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Review

Thirty years of conceptual change research in biology – A review and meta-analysis of intervention studies

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ABSTRACT

As students learn biology at different levels of education, their tenacious and inaccurate prior conceptions pose a challenge to conceptual change. Educators and researchers have developed a variety of interventions to address these misinterpretations and promote the achievement of current scientific understanding. Despite an ever-growing body of literature, no study has been conducted to date that examines the quality of interventions or their effectiveness in terms of conceptual change. We conducted a systematic review and meta-analysis of intervention studies conducted in the field of biology in order to gain insight into this phenomenon. According to the results, evolution and photosynthesis are the most common topics investigated. Overall, the results of the meta-analysis indicate that conceptual change interventions result in large effects on conceptual understanding of biological topics when compared with traditional teaching, with refutational text being the most effective single type of intervention. However, the most effective interventions dealt with more simplified phenomena, such as the cardiovascular system of the human body. It was found that the effect sizes were strongly influenced by the number of participants in the samples, as well as publication bias. A striking number of the studies reported only superficial learning outcomes, such as knowledge enrichment rather than knowledge restructuring. It is possible to use the results of this study to inform instructional choices and to carry out further research.

1. Introduction

Today's global problems, such as species extinction and climate change, highlight the importance of proper biological understanding in society (e.g. Thacker & Sinatra, 2022). Young children construct naïve conceptions and often theory-like knowledge about everyday biological phenomena based not only on their observations but also on folk biological views in the context of lay culture (Carey, 1985; Hatano & Inagaki, 1994; Inagaki & Hatano, 2013). Thus, when starting school, children already possess a substantial amount of knowledge and conceptions related to biological topics. Some of these conceptions align with current scientific views, but very often, everyday experience can lead to systematic misinterpretations and misconceptions that have contradictory impacts on learning in science classrooms.

Several studies have demonstrated that established misconceptions about scientific phenomena are not confined to primary

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education but that adults, including university students, share many of the same misconceptions about science phenomena held by children (e.g. Chi, 2005a; Merenluoto & Lehtinen, 2004; Roth, 1990; Södervik et al., 2015). In the following, we use the term 'misconceptions' to refer to various terms for prior knowledge used in the literature, such as 'naïve concepts' and 'initial concepts', if they are known to be detrimental to learning correct scientific concepts or making scientifically correct interpretations of phenomena. Due to robust misconceptions developed by students during their earlier learning history, successful science learning is not usually achieved by piling facts on top of facts (i.e. enriching existing knowledge structures); rather, it often requires a profound restructuring of existing knowledge (Vosniadou, 2013). Theories of conceptual change describe the role of prior knowledge in learning and how previous knowledge structures should be restructured to reach a scientifically accepted understanding.

In science education research, a significant body of studies has focused on the challenge of conceptual change since the 1970s. Different conceptual change theories have been developed concerning how students construct and restructure their knowledge when aiming to understand complex scientific phenomena (for a review, see Potvin et al., 2020). Based on previous studies, it is understood that the process of conceptual change typically occurs gradually and requires special attention in teaching (Chi & Roscoe, 2002; Sinatra & Pintrich, 2003). In this regard, there has been significant progress in the search for instructional methods that facilitate conceptual change in science classrooms, and various interventions are being tested (see Vosniadou, 2013).

Despite the fact that many studies have been dedicated to investigating students' conceptions related to complex biological phenomena, overviews that systematically cover biology topics and intervention methods, as well as meta-analyses of the impact of interventions, are absent from the literature. The aim of this systematic review and meta-analysis is to summarise empirical research on conceptual change interventions in the field, including various biological topics, school levels, intervention methods, conceptual change theories and empirical methods. A further goal is to evaluate the impact of conceptual change interventions on the understanding of biological phenomena when compared with traditional teaching strategies. Thus, this review is of interest not only to researchers in the field of conceptual change but also to biology teachers and lecturers. The summaries and comparisons this review provides of intervention studies that have applied various theories and intervention methods to overcome misconceptions will be beneficial for developing biology teaching to better prepare new generations to meet the challenges of sustainable development.

1.1. Conceptual change challenges in learning biology

Even though the majority of conceptual change research has focused on learning concepts in physics and chemistry, during the last two decades, the literature on alternative conceptions in biology has expanded significantly (Tanner & Allen, 2005). Previous studies have established that learning complex and counterintuitive concepts regarding the biological world (e.g. photosynthesis, energy and evolution) is difficult, and misconceptions widely exist regarding these topics among both children and adults (Evans, 2013; McLure et al., 2020b; Mintzes & Wandersee, 2005; Roth, 1990; Wandersee et al., 1994). Surprisingly, the same kinds of misconceptions related to certain concepts, such as the cardiovascular system, photosynthesis and evolution, exist both in elementary and higher education (Chi, 2013; Södervik et al., 2017, 2019). This type of knowledge typically has its origin in everyday observations of the surrounding world or is learned from the everyday discourses of lay culture (Hatano & Inagaki, 2013).

Learning topics such as photosynthesis or Darwinian evolution typically require several fundamental conceptual changes, which require support and time. For example, very young children often categorise plants as non-living things, but then, even before entering school, they learn that plants can grow, need to be watered and can die, leading to a re-categorization of plants as living things like animals (Vosniadou et al., 2008). Later on, this unified category of living organisms turns out to be another misunderstanding because of the missed ontological differences between plants and animals. The photosynthesis process that allows green plants to be autotrophic (produce their own nourishment) competes with the intuitive grasp of the commonality of living things (Inagaki & Hatano, 2013). Consequently, for a learner who does not know about the concept of photosynthesis, the crucial difference between animals and plants is unintelligible.

Nevertheless, a conceptual understanding of photosynthesis is a prerequisite for understanding its role at the ecosystem level, which again seems to be a true learning challenge, even for university biology students (Södervik et al., 2015, 2021). Further, for a lay adult to understand climate change and questions related to nourishment production for growing populations, it is necessary to have a basic knowledge of photosynthesis, which provides all the energy sources essential to life as well as regulates the budgets of atmospheric gases, such as carbon dioxide (Mambrey et al., 2020).

Darwinian evolution is an example of another concept that is problematic to learn based on naïve biology (Inagaki & Hatano, 2013; Ummels et al., 2015). Typical misconceptions of evolution relate to the strong tendency of humans to explain natural phenomena in terms of goal-oriented, anthropocentric views (Evans, 2013; Inagaki & Hatano, 2013). The basic idea of Darwinian evolution requires understanding that it is not about the changes that happen in living organisms but about covert and gradual adaptations at the molecular and population levels. The above are examples of certain well-investigated topics in biology education; however, there are many other biology topics in which robust misconceptions have been observed.

Current ecological crises have prompted societies and government bodies to emphasise the need for all citizens to understand basic biological concepts. Current sustainability challenges can be explained through several biological content areas, and it is necessary to have a basic understanding of these areas to be able to take meaningful, informed action and make responsible choices in our daily lives, such as those related to nourishment, medication and consuming other goods (Mambrey et al., 2020). Broadly speaking, in this era of climatic, environmental and societal changes, at least a basic understanding of such fundamental processes as photosynthesis and evolution is necessary for all citizens.

1.2. Different theories of conceptual change

Theories of conceptual change differ from other explanations of learning challenges in their particular focus on the relationship between prior knowledge and new concepts to be learned. However, different theories highlight different aspects of this relationship. There are some situations in which a coherent set of everyday knowledge and beliefs conflicts with scientific explanations (e.g. Vosniadou & Skopeliti, 2014). In other cases, the conflict with the scientific viewpoint stems from general ways of explaining and categorising phenomena (Chi, 1992) or from prior knowledge that is too fragmented to form a proper conceptual understanding (diSessa, 1993). These differences are also relevant in designing teaching strategies for enhancing conceptual change.

A review of 245 conceptual change articles by Potvin et al. (2020) identified 86 at least slightly different models or theories of conceptual change. However, only a few theories are widely used in conceptual change research. The most frequently referred to are Posner's 'general model of conceptual change' and Vosniadou's 'framework theory'. In addition, Chi's ontological category shift, Hewson's conceptual capture and conceptual exchange, diSessa's p-prim reorganisation, Carey's strong restructuring of theories, Pintrich's model of moving beyond cold conceptual change and Driver's epistemological reasoning characterisation are frequently mentioned in the articles included in the Potvin et al. (2020) review.

Posner et al.'s (1982) theory focuses primarily on the conditions under which learners change their conceptualisations. If their conceptions successfully explain situations, the individual does not feel the need to change them. However, learning correct scientific concepts often requires deeper changes in conceptual knowledge and beliefs. For conceptual change to occur, learners must be dissatisfied with existing conceptions and view scientific concepts as meaningful, plausible and fruitful (Posner et al., 1982). Posner's theory does not refer to any deeper cognitive mechanism of knowledge restructuring but to general experiences in educational situations which emphasise the necessity of change. These can be seen as guidelines for conceptual change interventions.

There are also theories that focus on the nature of mental models and cognitive processes related to conceptual change (diSessa et al., 2004). In particular, Vosniadou (1994) and Carey (1985) have shown that children already have coherent theory-like models, which they use to interpret and explain phenomena based on everyday experiences, whereas diSessa (1993) has emphasised the fragmentary nature of prior knowledge when learning scientific concepts.

A key feature of Carey's (1985) conceptual change approach is that both adults' and children's concepts are theory-like models but are mutually incommensurable. Children develop these coherent models well before they are formally educated, for example, about biological phenomena (Carey, 1999; Hatano & Inagaki, 1996). Vosniadou's (1994) framework theory of conceptual change shares some features with Carey's theory, and both can be characterised as 'theory theories' (diSessa, 2017). Children develop mental models about phenomena, and these models are embedded within larger, at least partly coherent frameworks that also include epistemic and ontological beliefs. This general framework also explains why children often construct synthetic models that incorporate the initial models and features of the scientific models that they have been taught. Interventions based on theory theories should make learners aware of the conflict between their prior thinking and new concepts and help them to change these larger frameworks. In 'regular' teaching, students can learn to recall correct answers but do not necessarily change their initial thinking.

The difference between the typical ontological categories used to categorise phenomena in everyday life and the ontological categories of scientific concepts forms the basis of Chi's (Chi, 1992; Chi et al., 1994) explanation of difficulties in learning many scientific concepts. For example, it is impossible to understand the theory of evolution when viewed from the ontological perspective of a causal event. This would require shifting one's ontological perspective from direct causality to emergent systems. Interventions based on Chi's theory should help students to create new categories that are typical of scientific explanations, which they usually do not encounter in everyday thinking.

Based on his studies on the development of physics concepts, diSessa (1993) proposed an alternative explanation for conceptual change problems to the above-described theories that assume organised theory-like prior knowledge. The p-prim (phenomenological primitives) theory that he developed assumes that students have difficulties learning correct scientific concepts because they construct them using an unstructured accumulation of simple elements. Interventions can make use of these phenomenological primitives as building blocks in developing gradually more coherent scientific understanding (diSessa, 2004).

In addition to the most widely used approaches, some researchers have proposed elements related to conceptual change, such as motivational factors (Pintrich et al., 1993), fundamental epistemic differences between children's direct observations of the physical world and the way in which scientists view the world (Driver, 1978; Driver et al., 1996), and the role of intentionality in conceptual change (Sinatra et al., 2003). Several authors have focused on particular study processes, such as constructing scientific explanations through writing (Klein, 2004) or a particular type of educational discussion (Duit et al., 1998). In their multidimensional approach to conceptual chance, Tyson et al. (1997) incorporated several theories.

1.3. Types of conceptual change interventions

Conceptual change theories have inspired science educators and researchers to design various interventions aimed at enhancing conceptual change and overcoming misconceptions (Guzzetti, 2000; Sinatra & Seyranian, 2015). Widely used refutational texts (Guzzetti, 2000; sometimes also called 'conceptual change texts': Cetin et al., 2015) usually include the following elements: pointing out a typical misconception, a refutation of it and presenting a scientific explanation. Other frequently used types of conceptual change interventions include hands-on learning activities (e.g. Hynd, 2001; Weaver, 1998), simulations and games (e.g. Trundle & Bell, 2010), concept maps (e.g. Kinchin, 2000) and multiple representations and analogies (e.g. Çalik et al., 2011; Chiu & Lin, 2005; Jaakkola et al., 2010; Smith & Gentner, 2012).

Refutational texts aim to direct learners' focus explicitly onto the difference between students' prior knowledge and the correct scientific concepts (e.g. Mikkilä-Erdmann, 2001), whereas simulations and hands-on activities typically provide situations in which students are expected to experience the conflict without explicitly pointing it out (e.g. Trundle & Bell, 2010). In the same way, other interventions, such as problem- and case-based learning, collaborative learning, the use of concept maps, well-formulated traditional science texts and analogies, aim to facilitate conceptual change by supporting the construction of correct scientific understanding so that students experience dissatisfaction with their prior conceptions (e.g. Asshoff et al., 2019).

1.4. Assessing enrichment or knowledge restructuring

Assessing the effectiveness of interventions from a conceptual change perspective requires elucidating the outcome measures related to the quality of learning that has been captured. In conceptual change research, two major types of changes are typically distinguished: knowledge enrichment and knowledge restructuring (Carey, 1985; Posner et al., 1982; Vosniadou, 2013). Knowledge enrichment refers to learning in which new knowledge is simply added to existing knowledge structures, enriching the knowledge base. Knowledge restructuring (also called revision) is a more demanding process that requires fundamental changes and restructuring of one's existing knowledge structures. In the restructuring process, existing concepts may obtain new meanings in the learner's mind, and misconceptions may be revised. Knowledge tests in science education can focus on measuring the enrichment of knowledge in general or knowledge restructuring indicating conceptual change (e.g. Johnson & Carey, 1998; Nash et al., 2000). In conceptual change studies, both multiple-choice questions and open-ended questions are common; the selected data collection method does not determine which type of conceptual change is captured. However, it has been suggested that assessing knowledge restructuring with multiple-choice questions should require, for example, deliberately planned items that systematically focus on comparisons between correct scientific concepts with widely held misconceptions (e.g. Haslam & Treagust, 1987). In addition, complementary open-ended questions are often needed. Hence, educators' or researchers' choice of methodology determines a study's opportunities to capture either conceptual change or just an increase in knowledge.

1.5. Research questions

Different types of interventions in terms of materials and study methods have been tested to support deeper learning in science classrooms at different levels of education (e.g. Duit & Treagust, 2003; Guzzetti et al., 1993; Mills et al., 2016). Systematic reviews and meta-analyses have summarised the findings of these studies in different fields (e.g. Guzzetti et al., 1993; Mills et al., 2016; Murphy & Alexander, 2009). However, designing effective science instruction requires a domain-specific perspective that acknowledges the discipline-specific characteristics of an accurate understanding of pedagogical theories, in this case biology (Treagust & Duit, 2008). A large number of conceptual change interventions in biology have been published, but still today, there is no research synthesis which would provide research-based evidence supporting the development of high-level conceptual learning in biology classrooms among learners of different ages.

To summarise the findings of conceptual change intervention studies in biology education, this qualitative review and meta-analysis endeavour to answer the following research questions:

1. Which biological topics are investigated in conceptual change intervention studies?
2. At which educational levels have conceptual change interventions taken place?
3. Which conceptual change theories are used as a basis for interventions, and which are the most common?
4. What kinds of interventions are used to support conceptual change in biology?
5. Which kinds of research methods are used, and do the studies measure learning outcomes as enrichment or knowledge restructuring?
6. How effective are conceptual change interventions?
    - 6.1 Is there a difference in the effects of studies with different sample sizes?
    - 6.2 How effective are conceptual change interventions in various biological topics?
    - 6.3 Are there differences in the effectiveness of studies measuring knowledge enrichment and restructuring?
    - 6.4 How effective are different kinds of interventions in supporting conceptual change?
    - 6.5 Are there differences in the effectiveness of interventions at different educational levels?

2. Methods

2.1. Search procedure

In this systematic review and meta-analysis, critical review aspects are combined with comprehensive search processes. A systematic review and meta-analysis have been combined in order to produce the "best evidence synthesis." The review incorporates multiple study types rather than focusing solely on one preferred study design (Grant & Booth, 2009). The PRISMA statement (Page et al., 2021) and selection criteria presented by Thompson et al. (2012) were followed to ensure the external and internal validity of the review. Article and document searches of the following databases were conducted: Academic Search Premier, Education Source, ERIC, OpenDissertations, MEDLINE, Teacher Reference, APA PsychArticles and APA PsychInfo. The Academic Search Complete (EBSCO) search engine was used to conduct searches in these databases. In addition, searches were conducted using the Science Direct database. These databases were chosen because of their broad coverage of scientific journal articles and other document types. The sources include the following document types: academic journals, reports, e-books, conference materials, printed books, dissertations and others. Because the aim was to carry out the first comprehensive review of the use of conceptual change interventions in biology, the years of publication were not limited.

The following terms for the search procedure were chosen initially: 'misconceptions', 'conceptual change', and 'biology'. One additional term, 'teaching', was also included after scoping searches. It was necessary to conduct several iterations of the search using different terms to ensure that the results were comprehensive and yielded relevant evidence (Boland et al., 2017). In total, five combinations of search terms were used. The search syntaxes were as follows: 1. MISCONCEPTIONS AND TEACHING AND BIOLOGY; 2. 'CONCEPTUAL CHANGE' AND TEACHING AND BIOLOGY; 3. MISCONCEPTIONS AND INTERVENTION AND BIOLOGY; 4. 'CONCEPTUAL CHANGE' AND INTERVENTION AND BIOLOGY; and 5. 'CONCEPTUAL CHANGE' AND BIOLOGY. These terms were searched in titles, abstracts or keywords. The first and second authors worked independently and screened each record retrieved based on certain criteria (Table 1).

The initial search described above yielded 2679 results. The search procedure was conducted in February 2022. The selection procedure is shown in the PRISMA flow diagram (Moher et al., 2009) in Fig. 1.

Step 1: From the 2679 total retrieved records, 1025 duplicates were removed. This left 1654 articles.

Step 2: The authors assessed the records' eligibility by applying three inclusion and exclusion criteria to titles and keywords (Table 1). During the screening of titles and keywords, studies were excluded if they were clearly not about interventions related to misconceptions or conceptual change in the biology field. By using this criterion, 1335 papers were excluded.

Step 3: The authors assessed the abstracts' eligibility by applying three inclusion and exclusion criteria (Table 1). While applying these criteria to the screening of 319 abstracts, studies were included if 1) at least some information about an intervention used to enhance conceptual change or overcome misconceptions was found, and 2) the study topic seemed related to the biology field. Papers that dealt with misconceptions in general but did not include interventions, and papers of which the topics were not related to biology were excluded. Based on the screening of abstracts, 171 papers were excluded. The authors searched the full text versions of the 148 selected articles. Most of the articles were obtained from databases, journal web pages or after contacting the authors directly. It was not possible to obtain seven full texts, even after trying to contact the authors at least two times. Thus, the seven articles that were not available were excluded.

Step 4: The authors assessed the full texts of the remaining 141 records for eligibility by applying four inclusion and exclusion criteria (Table 1). Based on the analysis of the full texts, 45 papers that did not satisfy the inclusion criteria were excluded. The final sample used in the qualitative review consisted of 96 articles published between 1988 and 2021 (Table 2).

2.2. Preventing selection bias and ensuring validity of the selection

Several steps were taken to prevent selection bias. A comprehensive selection of major databases was used, and all three authors contributed to the development of the search strategy. Every single keyword in the search query was critically discussed by all three authors. The first and second authors participated in the eligibility-checking process. All papers were critically appraised based on inclusion–exclusion criteria. While checking the full texts, it was noted that some papers did not mention conceptual change theory, even though the aim was to overcome misconceptions. Discussions among all three authors were held regarding whether to include these papers in the review. It was decided to include them because they satisfied all of the inclusion criteria and their findings are important to conceptual change research – in some of studies, interventions to overcome misconceptions to achieve conceptual change were created and tested, although without using conceptual change theories.

The following additional inclusion criteria were used to select the articles for the meta-analysis:

Table 1

Inclusion and exclusion criteria used in selecting publications.

Criteria related to:	Inclusion	Exclusion
Second step (title and keywords evaluation)		
Intervention	Mentioned	Not mentioned
Misconceptions or conceptual change	Mentioned	Not mentioned
Topic	Related to biology	Related to other fields than biology
Third step (abstract evaluation)		
Intervention	Mentioned	Not mentioned
Misconceptions or conceptual change	Mentioned	Not mentioned
Topic	Related to biology	Related to other fields than biology
Fourth step (full text evaluation)		
Field of misconceptions	The focus of the research is on overcoming misconceptions in biology field.	The focus of the research is on overcoming misconceptions not in biology field.
Intervention	The study explicitly explains the use of intervention dedicated to overcome misconceptions in biology field	The study does not explicitly explains the use of intervention dedicated to overcome misconceptions or only mentions the type of intervention
Results	The study clearly presents results related to the use of intervention	The study not clearly presents results related to the use of intervention or only shortly mentions the results
Language of full text	English	Other than English

Table 2
Years of publication of the selected articles.

Years	Number of published papers
1988–1991	1
1992–1997	11
1998–2003	12
2004–2009	18
2010–2015	25
2016–2021	29

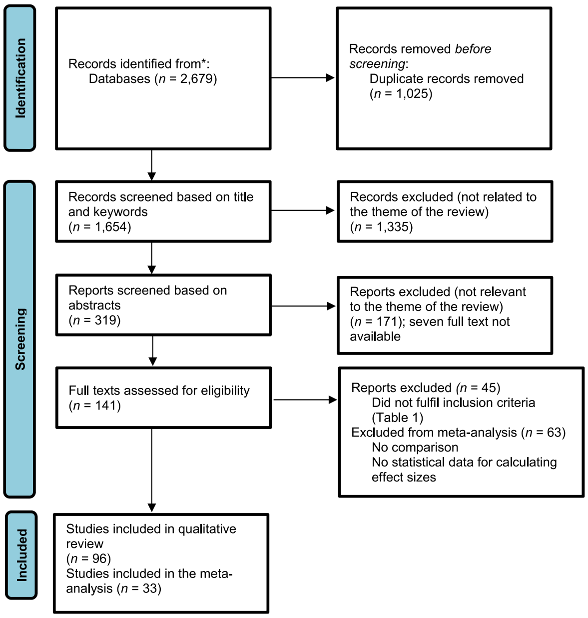

Fig. 1. Flow diagram of the selection procedure for publications.

1. The conceptual change intervention was compared with 'traditional' teaching that did not explicitly focus on the problem of possible misleading prior knowledge.
2. In the article, sufficient statistical information was present to calculate effect sizes.

Of the 96 articles included in the qualitative review, 45 did not have a control group. In two studies, two conceptual change interventions were compared. In 16 articles, there was not enough information to calculate effect sizes. For example, the articles either presented only percentages, did not present any data from the control group or supplied no information about the number of participants. Altogether, 33 studies with 3841 participants were included in the meta-analysis.

2.3. *Data analysis*

2.3.1. *Qualitative analysis*

For the data synthesis, a thematic analysis was conducted (Braun & Clarke, 2012). The research team prepared a coding form to retrieve information from articles assessed as eligible (Table 3). All selected papers were coded by two researchers who worked independently (the first and third authors, who hold higher-education degrees in biology and have experience with conceptual change studies). Papers were examined in terms of the domains of topic, education level, sample size, intervention type, theoretical framework, research design, data collection and analysis methods, and learning outcome measures. Any missing information was marked as 'not mentioned'. However, almost all selected papers were informative, and there was very little missing data.

To answer the first research question, papers were coded according to their topics into seven categories (e.g., 'Genetic' covers topics such as inheritance mechanisms and DNA). According to population type, papers were assigned to one or several of six groups: kindergarteners, primary school students, lower secondary school students (Grades 5 through 8), upper secondary school students (Grades 9 through 12), university students of natural sciences (majors or non-majors) and university student teachers. Further, all papers were divided into 14 groups according to the theoretical framework: Posner, Chi, Vosniadou, diSessa, Carey, Driver, Nussbaum and Novick, Clement, Klein, Duit, Pintrich, Sinatra, multidimensional CC (conceptual change) theory and no CC theory. If a paper used more than one CC theory, it was assigned to several groups. Coding was conducted on the basis of the comprehensive list of conceptual change

Table 3
Summary of the main characteristics of the selected studies.

Author(s), years	Topic	Intervention type (s)	Population and sample size	Theory	Methodology	Research design	CC measuring
Adcock (2003)	Photosynthesis	Refutational text	Upper second. N = 64	CCT, Posner	Mixed	Pre-post Control group	Enrichment
Ahopelto et al. (2011)	Photosynthesis	Traditional text	Teacher students N = 18	CCT, Chi, Vosniadou	Mixed	Pre-post-delayed No control group	Restructuring
Al Khawaldeh, 2007	Human circulatory systems	Refutational text	Upper second. N = 73	CCT, Posner	Quanti	Pre-post-delayed Control group	Restructuring
Al Khawaldeh, 2013	Genetic	Refutational text; Other (Prediction/ Discussion Learning Cycle)	Upper second. N = 112	CCT, Posner	Quanti	Pre-post Control group	Restructuring
Al Khawaldeh et al., 2010	Respiration	Refutational text; Concept maps	Upper second. N = 70	CCT, Posner	Quanti	Pre-post-delayed Control group	Restructuring
Alparslan et al. (2003)	Respiration	Refutational text	Upper second. N = 68	CCT, Posner, Vosniadou	Quanti	Pre-post Control group	Enrichment
Amir et al., 1994	Photosynthesis and respiration	Other (A graph of experiment analyzis)	Upper second. N = 516	No CCT	Mixed	Pre-post Control group	Restructuring
Amir et al., 1995	Photosynthesis and respiration	Writing	Upper second. N = 663	No CCT	Quanti	Pre-post Control group	Restructuring
Asshoff et al. (2019)	Photosynthesis and respiration	Problem-based learning	Upper second. N = 15	CCT, Posner	Quali	Pre-post No control group	Enrichment
Asterhan and Resnick, 2020	Evolution	Refutational text	Higher N = 100	CCT, Chi, Vosniadou	Mixed	Pre-post-delayed Control group	Restructuring
Atav and Acarlı, 2020	Microbiology	Hands-on	Teacher students N = 32	No CCT	Quali	Pre-post No control group	Enrichment
Balci et al. (2006)	Photosynthesis and respiration	Refutational text; 5E learning cycle	Lower second. N = 101	CCT, Posner	Quanti	Pre-post Control group	Restructuring
Ben-Nun et al., 2009	Genetic	Hands-on	Upper second. N = 181	CCT, Posner	Mixed	Pre-post No control group	Restructuring
Çakir et al. (2002)	Respiration	Refutational text	Upper second. N = 84	CCT, Posner	Quanti	Pre-post Control group	Enrichment
Cetin et al. (2004)	Ecology	Refutational text	Upper second. N = 78	No CCT	Mixed	Pre-post Control group	Restructuring
Cetin et al. (2015)	Ecology	Refutational text	Upper second. N = 82	CCT, Posner	Mixed	Pre-post Control group	Restructuring
Chan et al., 1992	Evolution	Game/simulation	Upper second. N = 108	CCT, Posner	Mixed	Pre-post Control group	Restructuring
Chirillo et al. (2021)	Human circulatory systems	Other (Reflex patterns)	Higher N = 72	No CCT	Mixed	Pre-post No control group	Restructuring
Cliff (2006)	Respiration	Case based learning	Higher N = 42	CCT, Posner	Quanti	Pre-mid-post No control group	Restructuring
Dickes et al., 2012	Evolution	Game/simulation	Primary edu. N = 10	CCT, Carey, Chi	Mixed	Pre-post No control group	Enrichment

(*continued on next page*)

Table 3 (*continued*)

Author(s), years	Topic	Intervention type (s)	Population and sample size	Theory	Methodology	Research design	CC measuring
Dumais et al., 2009	Virus and infection	Analogies	Upper second. N = 35	CCT, Chi, diSessa, Vosniadou	Mixed	Pre-post No control group	Restructuring
Emmons et al. (2017)	Evolution	Traditional text	Kindergarden N = 20 Primary edu. N = 17	CCT, Carey, Chi	Mixed	Pre-post-delayed No control group	Enrichment
Fan et al. (2018)	Respiration	Analogies	Upper second. N = n. m.	No CCT	Mixed	Pre-post No control group	Restructuring
Franke et al., 2011	Genetic	Hands-on	Upper second. N = 294	Multidimensional CCT	Quanti	Pre-post-delayed Control group	Enrichment
Fulford (2016)	Evolution	Historical science based learning	Higher N = 144	CCT, Driver	Mixed	Pre-post No control group	Restructuring
Gallucci (2007)	Evolution, genetic	Case based learning	Higher N = 64	CCT, Posner	Mixed	Pre-post No control group	Restructuring
Garcia i Grau et al., 2021	Kinetic-molecular theory	5E learning cycle	Upper second. N = 725	CCT, diSessa, Posner, Vosniadou	Mixed	Pre-post Control group	Enrichment
Gauthier et al., 2017	Molecular movements	Game/simulation	Higher N = 526	CCT, Chi	Mixed	Pre-post Control group	Restructuring
Griffiths et al. (1988)	Ecology	Refutational text	Higher N = 226	No CCT	Quanti	Pre-post Control group	Restructuring
Hand et al. (2007)	Molecular biology	Writing	Upper second. N = 87	CCT, Klein	Mixed	Pre-post Control group	Restructuring
Heddy et al., 2013	Evolution	TTES model	Teacher students N = 55	CCT, Chi, Sinatra	Mixed	Pre-post Control group	Restructuring
Henry (2005)	Evolution	Other (Course based on scientific method)	Upper second. N = 28	CCT, Posner	Quali	Pre-post No control group	Restructuring
Herrmann-Abell et al. (2012)	Photosynthesis	Other (Course based on question and modelling tasks)	Lower second. N = 120	No CCT	Quanti	Pre-post No control group	Restructuring
Herrmann-Abell et al. (2016)	Chemical Reactions and Conservation of Mass	Analogies	Lower second. N = 574	CCT, Posner, Chi, DiSessa	Mixed	Pre-post Control group	Restructuring
Jacobson et al., 2000	Evolution	Game/simulation	Lower second. N = 8	CCT, Posner, Chi, Vosniadou	Quali	Pre-post-delayed No control group	Restructuring
Jensen et al., 1995	Evolution	Historical science based learning	Higher N = 42	CCT, Posner	Mixed	Pre-post No control group	Restructuring
Jones et al., 1998	Molecular biology	Hands-on	Higher N = 4	CCT, Posner	Quali	Post only No control group	Restructuring
Kalinowski et al. (2013)	Evolution	General active learning strategy	Higher N = 88	CCT, Posner, Vosniadou,	Mixed	Pre-post No control group	Restructuring
Kampourakis et al., 2009	Evolution	Other (Course based on special teaching sequence)	Upper second. N = 98	CCT, Posner	Quali	Pre-post No control group	Restructuring
Karpudewan et al. (2015)	Ecology	Hands-on	Upper second. N = 73	CCT, Posner	Mixed	Pre-post Control group	Restructuring

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Table 3 (*continued*)

Author(s), years	Topic	Intervention type (s)	Population and sample size	Theory	Methodology	Research design	CC measuring
Keleş et al. (2011)	Birds	Refutational text	Lower second. N = 26	Driver	Mixed	Pre-post No control group	Restructuring
Kopecki-Fjetland et al., 2021	Molecular biology	Problem-based learning	Higher N = n.m.	No CCT	Quanti	Pre-post No control group	Enrichment
Kuisma et al., 2021	Human senses	Other (Course based on Cross-curricular approach)	Upper second. N = 10	CCT, Chi, Vosniadou	Mixed	Post only No control group	Restructuring
Larsson et al., 2015	Molecular movements	Hands-on; Analogies	Higher N = 35	CCT, Nussbaum & Novick	Quali	Pre-post-delayed No control group	Restructuring
Law et al., 2004	Genetic	Game/simulation	Upper second. N = 16	CCT, Posner	Quali	Pre-post No control group	Enrichment
Lawson et al. (1993)	Diffusion, molecular polarity and bonding	Analogies	Higher N = 77	CCT, Clement	Mixed	Pre-post Control group	Enrichment
Lumpe et al., 1995	Photosynthesis	Hands-on	Upper second. N = 25	CCT, Posner	Mixed	Pre-post Control group	Restructuring
Luz et al. (2013)	Human circulatory systems	Other (Course based on proposing hypothesis)	Upper second. N = 85	CCT, Posner	Mixed	Pre-post-delayed No control group	Enrichment
Malone et al. (2018)	Evolution	Game/simulation	Upper second. N = 424	No CCT	Quanti	Pre-post Control group	Enrichment
Mason (1994)	Human circulatory systems	Analogies	Lower second. N = 60	CCT, Chi	Qual	Pre-post No control group	Restructuring
Matthews (2001)	Evolution	Writing	Higher N = 37	CCT, Posner	Quanti	Pre-post-delayed No control group	Enrichment
McKenzie (1996)	Species classification	Problem-based learning	Higher N = 20	CCT, Posner	Quanti	Pre-post No control	Restructuring
McLaughlin et al. (2016)	Evolution	Hands-on	Upper second. N = 17	No CCT	Quali	Pre-post No control group	Enrichment
McLure et al., 2020	Evolution	Other (Thinking Frames Approach (TFA))	Upper second. N = 104	Multidimensional CCT	Mixed	Pre-post Control group	Restructuring
Menia et al. (2017)	Ecology	Analogies	Lower second. N = 70	CCT, Posner	Mixed	Pre-post Control group	Enrichment
Mikkilä-Erdmann (2001)	Photosynthesis	Refutational text	Primary edu. N = 209	CCT, Vosniadou	Quali	Pre-post Control group	Restructuring
Muis et al. (2018)	Genetically modified food	Refutational text	Higher N = 120	CCT, Sinatra, Pintrich et al.	Quanti	Pre-post Control group	Restructuring
Murtonen et al. (2018)	Genetic	Other (Drawing task)	Higher N = 82	CCT, Posner, Chi, Vosniadou	Mixed	Pre-post Control group	Restructuring
Naz et al., 2013	Species classification	General active learning strategy	Lower second. N = 80	CCT, Posner, Carey, Vosniadou	Quali	Pre-post Control group	Enrichment
Nehm et al., 2007	Evolution	General active learning strategy	Higher N = 182	CCT, Posner	Mixed	Pre-post Control group	Enrichment
Oliver (2011)	Evolution	Problem-based learning	Upper second. N = 16	No CCT	Mixed	Pre-post No control group	Enrichment

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Table 3 (*continued*)

Author(s), years	Topic	Intervention type (s)	Population and sample size	Theory	Methodology	Research design	CC measuring
Opfer et al., 2004	Categorization of life status	Other (Picture-question-answer-feedback cycle)	Kindergarden N = 80	CCT, Carey	Mixed	Pre-post No control group	Restructuring
Ozkan et al. (2004)	Ecology	Refutational text	Lower second. N = 58	CCT, Posner	Mixed	Pre-post Control group	Enrichment
Pearsall et al. (1998)	Molecular biology	Hands-on; Concept maps	Higher N = 161	CCT, Carey, Chi, Posner	Mixed	Pre-post No control group	Restructuring
Pekel et al., 2015	Genetic	Refutational text; Analogies	Upper second. N = 52	CCT, Posner	Quanti	Pre-post Control group	Restructuring
Poehnl et al., 2013	Genetic	Modified ref. text	Upper second. N = 195	CCT, Posner, Vosniadou	Quanti	Pre-post-delayed Control group	Enrichment
Pugh et al. (2010)	Evolution	TTES model	Upper second. N = 126	CCT, Posner	Mixed	Pre-post-delayed Control group	Enrichment
Rates et al. (2016)	Ecology	Game/simulation	Higher N = 32	CCT, Chi	Quali	Pre-post No control group	Restructuring
Riemeier et al., 2008	Molecular biology	Hands-on	Upper second. N = 15	CCT, Posner	Quali	Pre-post No control group	Restructuring
Robson et al., 2011	Evolution	Hands-on	Higher N = 82	No CCT	Quanti	Pre-post No control group	Enrichment
Ronfard et al. (2021)	Evolution	Traditional text	Primary edu N = 68	CCT, Carey, Vosniadou	Mixed	Pre-post-delayed Control group	Restructuring
Rose (2012)	Evolution	Other (Course based on reflective discourse)	Upper second. N = 12	Multidimensional CCT	Mixed	Pre-post Control group	Restructuring
Schwendimann et al., 2016	Evolution	Concept maps	Upper second. N = 81	CCT, Chi	Mixed	Pre-post Control group	Restructuring
Sellmann et al. (2015)	Ecology	Hands-on	Upper second. N = 95	CCT, Posner	Mixed	Pre-post Control group	Restructuring
Sert Çibik et al. (2008)	Photosynthesis and respiration	Hands-on	Teacher students N = 78	CCT, Posner	Quanti	Pre-post Control group	Restructuring
Shi et al. (2017)	Molecular movements	Game/simulation	Higher N = 279	CCT, Posner	Quanti	Pre-post No control group	Restructuring
Smith et al. (1993)	Photosynthesis and respiration	Traditional text	Lower second. N = n.m.	CCT, Posner	Mixed	Pre-post Control group	Restructuring
Södervik et al. (2015)	Photosynthesis	Refutational text	Higher N = 171	CCT, Posner, Vosniadou	Mixed	Pre-post Control group	Restructuring
Sparks et al., 2020	Evolution	TTES model	Higher N = 16	CCT, Posner	Mixed	Post only No control group	Enrichment
Sungur et al. (2001)	Human circulatory systems	Refutational text; Concept maps	Upper second. N = 49	CCT, Posner, Pintrich et al.	Quanti	Post only Control group	Enrichment
Terrell et al. (2021)	Molecular biology	Analogies	Higher N = 125	No CCT	Quanti	Pre-post Control group	Enrichment
Tran et al. (2014)	Evolution	Hands-on	Higher N = 66	CCT, Posner	Mixed	Pre-post No control group	Enrichment

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Table 3 (*continued*)

Author(s), years	Topic	Intervention type (s)	Population and sample size	Theory	Methodology	Research design	CC measuring
Tsoi (2013)	Species classification	Game/simulation	Teacher students N = 84	CCT, Posner	Quanti	Pre-post No control group	Enrichment
Udovic et al. (2002)	Evolution	General active learning strategy	Higher N = 375	No CCT	Mixed	Pre-post Control group	Enrichment
Vaughn et al., 2017	Evolution	Traditional text; Writing; Other (Field trips)	Teacher students N = 51	CCT, Sinatra	Quanti	Pre-post No control group	Enrichment
Venville et al., 1996	Human circulatory systems, classification of living things, cell membranes, heart	Analogies	Upper second. N = 15	CCT, Posner, Chi, Vosniadou	Quali	Post only No control group	Restructuring
Wasmann-Frahm (2009)	Species classification	Historical science based learning	Lower second. N = 76	CCT, Posner	Mixed	Pre-post-delayed Control group	Enrichment
Wernecke et al. (2018)	Ecology	Other (Incorrect presentations)	Upper second. N = 304	CCT, Posner	Quanti	Pre-post Control group	Restructuring
Wichaidit et al. (2011)	Photosynthesis	Analogies	Lower second. N = 58	CCT, Duit	Quanti	Pre-post No control group	Enrichment
Williams (2009)	Evolution	Game/simulation	Upper second. N = 16	No CCT	Quali	Pre-post No control group	Enrichment
Williams et al., 2000	Genetic	Traditional text	Primary edu. N = 24	CCT, Carey	Quali	Pre-post No control group	Restructuring
Windschitl (1997)	Photosynthesis and respiration	Game/simulation	Higher N = 255	No CCT	Mixed	Pre-post No control group	Enrichment
Windschitl et al., 1998	Human circulatory systems	Game/simulation	Higher N = 205	CCT, Posner, Pintrich et al.	Quanti	Pre-post Control group	Restructuring
Wodaj et al., 2021	Human circulatory systems	5E instructional model	Upper second. N = 164	CCT, Posner	Quanti	Pre-post Control group	Restructuring
Wright et al. (2021)	Genetic	Analogies	Higher N = 83	No CCT	Quanti	Pre-post-delayed No control group	Enrichment
Yurtyapan et al., 2021	Many topics (photosynthesis, ecology, etc.)	Other (Concept cartoons)	Teacher students N = 79	No CCT	Quanti	Pre-post Control group	Enrichment

theories presented in Potvin et al.'s (2020) review. According to the type of intervention, papers were assigned to one or several of 14 groups: text (refutational), text (traditional), hands-on, analogies, game/simulation, concept maps, writing, problem-based learning, case-based learning, general active learning strategies, historical science-based learning, TTES model, 5E learning cycle and 'other'. The group 'other' included interventions used only in one paper. Finally, the quality of outcome measures was coded into two categories: enrichment and knowledge restructuring.

In order to ensure the inter-rater reliability of the thematic analysis, 10 randomly selected papers were coded independently by the first and third authors (O'Connor & Joffe, 2020). The two independent coders classified the papers in a similar way, and in the first round, the inter-rater reliability was nearly 100%, with the exception of one coded dimension: knowledge enrichment versus knowledge restructuring, for which the independent coders initially agreed on 68.5% of the articles. A comprehensive discussion was conducted in order to reach a consensus as to how the two coders interpreted the information provided in these articles. All disagreements were discussed and resolved by consensus, and a third coder (the second author) also reviewed the disagreements about enrichment vs. knowledge restructuring. Once the first and third authors had established a common understanding and were in agreement, they proceeded to code the remainder of the articles. Thus, in the second round, the final inter-rater reliability was 100%.

2.3.2. Meta-analysis

Calculating effect sizes. Comprehensive Meta-Analysis software (version 3.3.070, Biostat, Englewood, NJ, USA) was used to calculate unbiased effect sizes (Hedges' *g*). For each independent sample, only one effect size was calculated. If an article presented several outcome estimates, the effect size was calculated on the basis of the estimate best indicating the level of understanding of the scientific concept after the intervention. In some studies, the positive effect size described an increase in correct scientific concepts, while in other studies, it described a decrease in misconceptions. Most of the effect sizes (16) were calculated on the basis of means, standard deviations and sample sizes of intervention and control groups in pre- and post-tests. In some cases, the descriptive statistics were available only from the post-test. *F*-values and sample sizes were used to calculate the eight effect sizes. Articles did not report pre-test and post-test correlations, but the correlation of 0.7 proposed by Borenstein (2009) was used in the calculations. Because of the differences in the biological topics and the nature of the interventions presented in the articles, it was assumed that there is no fixed true effect across the studies, but there are also sources of variation other than sampling error. Thus, random effect analysis was used to estimate the overall effect size across the studies.

Sensitivity and publication bias analysis. Sensitivity analysis was used to control for the impact of outliers (Thabane, 2013) using the 'remove one study' procedure of the Comprehensive Meta-Analysis programme. Publication bias was estimated using a funeral plot and Egger's test (Peters et al., 2006; Sterne et al., 2011).

Moderator analysis. In analysing the effects of moderators, a mixed-model procedure was used (Overton, 1998, p. 365). Effect sizes were calculated for the following moderator variables: sample size, biological topic of the study, quality of the outcome measure and type of intervention. Sample sizes were classified into small (below 60, $n = 10$), moderate (61–120, $n = 14$) and large (above 121, $n = 8$) samples. Biological topics included genetics ($n = 3$), photosynthesis and respiration ($n = 9$), the human circulatory system ($n = 3$), evolution and natural selection ($n = 6$), molecular biology ($n = 5$) and ecology ($n = 6$). The outcome quality variable included enrichment ($n = 11$) and restructuring ($n = 21$). The intervention type included analogy ($n = 5$), conceptual change text ($n = 11$), simulation/game ($n = 3$), hands-on activity ($n = 3$) and the group 'other' ($n = 10$), which consisted of individual methods used in only one or two studies.

3. Results

The main information for the included studies is presented in Table 3.

3.1. Biological topics of the interventions

The most common biological topic in conceptual change interventions was 'evolution' (Table 4). In most studies, the focus was on natural selection, but it was also on genetic aspects of evolution, such as random gamete sampling, mutation or the recombination and traits perspective – that is, variation for a trait within a population, heritability of the trait, evolution of new traits, evolution of selected animal traits or origin of new traits. Phylogeny and the phylogenetic nature of evolution have been the focus of certain studies. Concepts such as adaptation, variation, inheritance, speciation, domestication and extinction or competition and fitness were essential in some papers.

The second most frequently investigated topic was 'photosynthesis'. It was focused on as a part of carbon flow in a terrestrial ecosystem or studies highlighting the role of plants in food chains as autotrophic, self-sufficient organisms, the flow of energy in the food chain and the significance of photosynthesis to life on Earth. Other relatively common topics were cell respiration, the human cardiovascular system, ecological concepts such as climate change and genetic concepts such as meiosis.

3.2. Number of studies at different levels of education

Intervention studies were conducted at all levels of education (Table 5). The smallest number of studies took place in the kindergarten population. A few studies were conducted in primary schools, in teacher education and moderately frequently in the lower secondary level. Studies focusing on natural science majors or minor study students in higher education were common. The most common group to investigate conceptual change in the biology field was upper secondary school students. The sample size was another variable. The smallest sample size was eight students, while the largest sample size was 725 students. The mean sample size was 117 participants (*SD* = 139), whereas the median was 78 (the lower quartile, 37 participants; the upper quartile, 120 participants) and the mode was 82.

Table 4
Topics of the selected articles.

Topic	Number of papers
Evolution	28
Photosynthesis	15
Respiration	12
Ecological concepts	10
Genetics	10
Circulatory systems	8
Others	23

Note. Other topics: species classification, microbiology concepts, molecular biology concepts etc. The general number of papers is higher than 96 because some papers included more than one topic.

Table 5
Educational levels of the intervention studies.

Population	Number of papers
Kindergarten	2
Primary school	5
Lower secondary school	12
Upper secondary school	41
Natural sciences university students	30
Teacher students	7

Note. The general number of papers is higher than 96 because some papers included more than one population or topic.

3.3. Conceptual change theories applied in intervention studies

The authors of 19 intervention studies dealing with misconceptions or conceptual change did not refer to any specific theory of conceptual change (Fig. 2). Several of these studies focused exclusively on the knowledge and methods of a particular science content area (e.g. Wright et al., 2021) and did not explicitly refer to any educational or psychological theories. Many papers presented a practical model, such as school partnerships with scientists (e.g. McLaughlin et al., 2016) or referred to general educational or psychological theories, such as constructivism (e.g. Kopecki-Fjetland et al., 2021).

However, the majority of intervention studies in this review presented one or more of the theories included in Potvin et al.'s (2020) comprehensive list of conceptual change theories. In this review of studies on biology education, Posner's theory of conceptual change was the most frequently cited, which is consistent with Potvin et al.'s (2020) overall finding for conceptual change studies in any scientific field. Posner's theory has been applied as a basis for interventions in a variety of areas, including climate change, genetics and respiration, with a range of populations from lower secondary school students to college students. Many studies have combined Posner's theory with other conceptual change theories, such as those of Vosniadou, Chi, Carey and diSessa.

The general review of conceptual change theories (Potvin et al., 2020) indicates that Vosniadou's framework theory was the second most frequently used theory and Chi's ontological shift theory the third. In this review of biological intervention studies, Vosniadou's and Chi's theories were used equally frequently. Vosniadou's framework theory and Chi's ontological shift theories were used in interventions on various topics, but Chi's theory was particularly frequently used in interventions related to the theory of evolution. Ontological shift theory is more often combined with other CC theories, such as those of Posner, Carey, Vosniadou or diSessa, than used as the main and only CC theory forming the basis of interventions.

The multidimensional approach (Venville & Treagust, 1998), the intentional conceptual chance theory (Sinatra & Pintrich, 2003) and the model of moving beyond cold conceptual change (Pintrich et al., 1993) are also applied in several intervention studies. Other conceptual change theories, such as those of Driver et al. (1996), Duit et al. (1998), Klein (2004) and Nussbaum and Novick (1982), are used only in individual studies.

3.4. Intervention types and outcome measures

The most common intervention type was a text-reading intervention (25 studies). More specifically, most of the texts used were refutational texts (19 studies out of 25), including text types called conceptual change texts and refutational texts in the original papers (Fig. 3). For example, in the refutational text related to aerobic respiration, students were first given basic information related to respiration to read. Second, the misconception was presented as a belief held by some of the students. Third, the text explained why this belief is incorrect. Students were reminded of some facts that support the correct scientific concept (Al khawaldeh & Al Olaimat, 2010). Refutational texts were usually supplied for students to read individually and then discuss together with a teacher. One study (Poehnl & Bogner, 2013) used a modified refutational text design in which the alternative and scientific conceptions were not explicitly contrasted. In this case, the modified refutational text design was unsuccessful in supporting conceptual change.

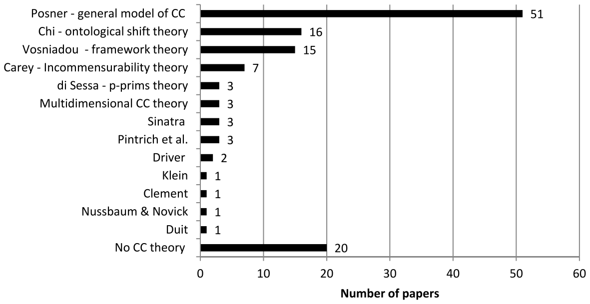


Fig. 2. Conceptual change theories applied in intervention studies.
Note. The general number of papers is higher than 96 because some papers included more than one CC theory.

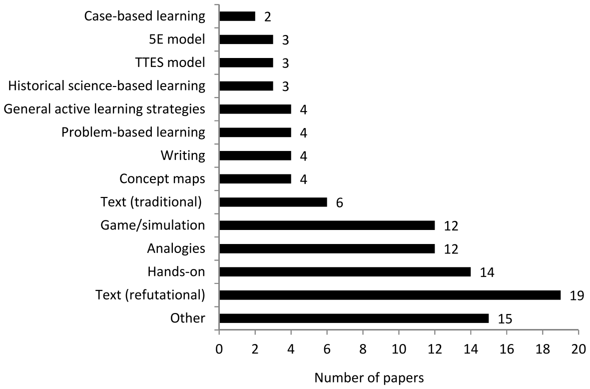


Fig. 3. Intervention types used in CC studies in the biology field.
Note. The general number of studies is higher than 96 because some studies used more than one intervention type.

In six studies, a traditional text was used in the intervention. The traditional texts were explanatory, explaining only scientific phenomena, but they did not provide any information about misconceptions and did not stimulate the reader to compare misconceptions and scientifically correct concepts. Examples include a text similar to a textbook text but more argumentative and coherent and better at explaining relations, such as causes and consequences, between concepts (Ahopelto et al., 2011); two custom-made picture storybooks that combined pictures with accurate, comprehensive mechanistic descriptions of a concept (Emmons et al., 2017); curriculum materials written by the research project staff (Smith et al., 1993); a 280-page workbook (created by the research authors) that was used instead of a textbook (Vaughn & Robbins, 2017); an instruction book with envelopes containing feedback statement ('correct answer') cards and individual multiple-choice judgement booklets (Williams & Tolmie, 2000) and a two-storybook sequence in which the first describes the logic of a concept and the second extends the concept's explanation (Ronfard et al., 2021).

The second most popular intervention type utilised in the 14 studies was hands-on activities. The hands-on approach refers to teaching methods involving activity and direct experience with natural phenomena. It is defined as applying to educational experiences in which students actively engage in manipulating objects in the classroom (Haury & Rillero, 1994). Typically, hands-on interventions in this review study were laboratory work or experiments, for example, molecular genetics laboratory activities based on molecular biology methods, which enabled students to design and perform authentic experiments by themselves (Ben-Nun & Yarden, 2009), or small-group learning activities in introductory university biology laboratory classes performing experiments (Jones & Eichinger, 1998). Other hands-on type interventions included hands-on tasks focused on realistic approaches to solving real-world problems, such as activities that were controlled and mediated by the learners (Karpudewan et al., 2015) or working with real plants and other educational material in order to carry out tasks concerning the multiple consequences of global climate change (Sellmann et al., 2015).

The third most common type of intervention used to support conceptual change was analogies, which were used in 12 papers. Analogies can be described as tools for rendering counterintuitive ideas more intelligible and plausible (Dagher, 2005) or as a bridge through which new material, including abstract concepts, can be more easily assimilated by leveraging students' prior knowledge to facilitate their understanding of the material (Treagust, 1993). The studies included in this review used various analogies such as the following: an analogical model to explain the influenza virus structure, created using a limited number of viral components that are essential to the understanding of the mechanisms of antigenic shift and drift (Dumais & Hasni, 2009); Lego bricks and ball-and-stick models used in modelling underlying molecular events (Herrmann-Abell et al., 2016); a bottle containing layers of oil and water with some dye added to represent the process of diffusion (Lawson et al., 1993) or the use of the mail delivery system as an analogy for the human circulatory system (Mason, 1994).

Game/simulation interventions were used in 12 studies. The purpose of a simulation is to replace or amplify real experiences with guided ones, often of an 'immersive' nature, which evoke or replicate substantial aspects of the real world through a full range of interactive experiences (Lateef, 2010). In game-based learning, a number of gaming principles are applied for educational purposes in real-life settings to engage learners (Pho & Dinscore, 2015). The simulations and games were as follows: Excel-based modelling simulations (Malone et al., 2018); a computer-based cardiovascular simulation exercise in a context-bound framework (Windschitl & Andre, 1998); an agent-based participatory simulation (Rates et al., 2016); a computer simulation that models the photosynthetic and respiratory processes in plants (Windschitl, 1997); the simulation-based, platform-genre adventure game *Molworlds* (Gauthier & Jenkinson, 2017); a simulation built using a modelling tool (Law & Lee, 2004); a multi-agent-based computational model (Dickes & Sengupta, 2012) and a game-like activity based on showing pictures and asking students to assign each picture to one of two indicated groups (Tsoi, 2013). Of 12 game/simulation interventions, 11 were computer based.

Less popular intervention types were concept maps, writing, problem-based learning and general active learning strategies, which were used in four papers each. Concept maps are known to increase meaningful learning and can be used to represent the knowledge and/or experience of both individuals and groups (Katagall et al., 2015). In two of the four studies included in this review that used concept maps, they were used in combination with refutational texts. After students read refutational texts, the strategy of how to create a concept map was introduced, and they were asked to construct their own concept maps to show the interrelationships among concepts mentioned in refutational texts (Sungur et al., 2001; Al Khawaldeh & Al Olaimat, 2010). In Pearsall et al.'s (1998) study, students were instructed how to make a concept map and later were asked to show their understanding of a concept by creating a concept map. After several weeks, the concept maps were given back to the same students, and they were asked to make changes according to their current understanding. The use of any additional materials was not allowed. In Schwendimann and Linn's (2016) study, in addition to creating concept maps, students compared their concept maps against an expert's map or the map of another student.

Interventions of the writing type can be described as the 'writing to learn' (WTL) approach. WTL maintains that the writing process can be used to foster people's writing and understanding of content and concepts (Reynolds et al., 2012). Matthews (2001) asked students to compare three stories related to evolution in a two-page essay. Students in Hand et al.'s (2007) study were asked to write a textbook explanation for 11–12-year-old students or an article for the general public. Vaughn and Robbins (2017) asked pre-service teachers to write a paper describing the legal and philosophical foundations for teaching evolution to public school students. The students in Amir and Tamir's (1995) study were asked to write a proposition showing how photosynthesis and respiration are related.

Problem-based learning (PBL) is a method of learning in which the process starts with encountering a specially created real-life problem that students are tasked with solving. In the PBL studies included in this review, students were asked to work in groups and solve a certain issue. Tasks were related to the following issues: the impact of elevated CO2 concentrations on trees and carbon flows in a forest ecosystem (Asshoff et al., 2019), rodent control in cities (Oliver, 2011), issues related to hydrogen bonding and pH/pKa in a molecular biology context (Kopecki-Fjetlan & Steffenson, 2021) and six unidentified samples of aquatic arthropods (McKenzie, 1996).

Active learning strategies are strategies in which students actively participate in lessons and are involved in various activities. Strategies for active learning may vary; however, in three of the four papers in this review that included active learning strategies, the main strategy was student discussions. Discussions were related to dog breeding and human evolution (Kalinowski et al., 2013), the nature of science (Nehm & Reilly, 2007) or the evolution of flight in bats (Udovic et al., 2002).

Less popular intervention types were historical science-based learning, the 5E learning cycle and the teaching for transformative experiences in science (TTES) model, used in three studies each. Historical science-based teaching can be described as the process of learning by analysing the historical development of species. Two papers using this intervention type were dedicated to evolution and one to species classification, showing that this approach can be used to study phenomena (i.e. long-term and continuous processes) such as the natural history of vertebrates (Wasmann-Frahm, 2009), the differences between Darwin's and Lamarck's theories, including on the evolution of the giraffe's long neck (Jensen & Finley, 1995) or the history of the industrial melanism of moths (Fulford, 2016).

The TTES model is based on Dewey's idea that students' experiences and active engagement are the most important parts of changing the understanding they hold of a certain phenomenon. According to the TTES model, students experience situations in which they can apply scientific concepts to their everyday lives (Sparks & Darner, 2020). Studies in which the interventions were based on the TTES model used the following ideas: questions designed to prompt active use, the expansion of perception and increased experiential value (Sparks & Darner, 2020), lectures or small group and whole group discussions (Heddy & Sinatra, 2013).

The 5E learning cycle (i.e. the Engagement, Exploration, Explanation, Extension and Evaluation learning cycle) starts with active engagement in investigating the presented concept or phenomenon. In the exploration phase, the teacher is a facilitator who guides the process. During explanation, the teacher moderates a discussion about the phenomenon, and during the extension phase, students are given additional activities in which they apply their understanding to other tasks (Settlagh, 2000). The 5E learning model intervention was used in two ways: as the only intervention or in combination with another intervention (refutational texts). In addition, in one study, the 5E learning cycle was modified and called '7E'. The 7E model is an updated 5E model in which two new phases are added: elicitation and extension (Eisenkraft, 2003).

One of the least common interventions in the biology field is case-based learning. Case-based learning (CBL) is similar to PBL but has some differences. In CBL, groups of students concentrate on a specific issue, having already completed some advance preparation, and a specific issue is not necessarily a problem (Herreid, 1997; Slavin et al., 1995). Gallucci (2007) used stories, narratives, scenarios or articles to introduce biology content, and cases were used for homework, classwork and exams. Cliff (2006) used a case study about CO poisoning in order to teach respiration. Students were asked to work in groups on the given case study as homework after regular classes.

Many studies ($n = 15$) used interventions that were unique and found only in one paper during this literature review; these belonged to the group 'other'. Examples are as follows: learning from incorrect representation, the thinking frames approach (TFA), field trips, the picture–question–answer–feedback cycle, concept cartoons, the prediction–discussion learning cycle, a graph analysis, a drawing task, a consistent use of reflex patterns and specific unique courses. Learning from incorrect representations is based on the idea that errorful learning, which is necessarily followed by corrective explanation, is beneficial to learning (Metcalfe, 2017).

The TFA is a constructivist approach created to engage students in higher-order thinking and used to render students' misconceptions visible through cognitive conflict strategies following small group discussions (McLure et al., 2020a). Field trips can be described as class trips to various environments, such as zoos, museums or science centres, for educational purposes (Behrendt & Franklin, 2014). The picture–question–answer–feedback cycle is comprised of several steps, including showing a picture to a student, the examiner asking a question related to it, the student giving an answer and the examiner providing feedback on the student's answer (Opfer & Siegler, 2004). Concept cartoons are cartoons created in consideration of a scientific phenomenon and are used to engage students in overthinking their ideas by exploring different characters' ideas related to the phenomenon (Keogh & Naylor, 1999).

The prediction/discussion-based learning cycle (HPD-LC) combines prediction/discussion, exploration, term introduction and concept application steps (Lavoie, 1999). A graph analysis can be described as a remedial material activity that requires students to consider what they know about a scientific phenomenon by analysing a graph (Amir & Tamir, 1994). A drawing task is based on the idea that drawing has the potential to foster metaconceptual awareness and to help create cognitive conflict (Murtonen et al., 2018). The consistent use of reflex patterns is an approach based on the frequent reinforcement of basic reflex patterns and pattern recognition (Bransford et al., 2000). In six papers, the intervention was a specific unique course. The courses were based on the use of the scientific method, question and modelling tasks, a specially created teaching sequence, proposing hypotheses, reflective discourse or a cross-curricular approach.

The most common approach utilised in the studies was mixed methods (50%), typically combining multiple-choice questions and open-ended questions. Quantitative methodology was used in 33% of the papers, while 17% used qualitative methodology. Thirty-nine per cent (39%) of the papers were categorised as measuring knowledge enrichment, whereas 61% measured more profound changes in participants' understanding, which can be interpreted as knowledge restructuring.

3.5. *Impact of conceptual change interventions*

3.5.1. *Description of the studies included in the meta-analysis*

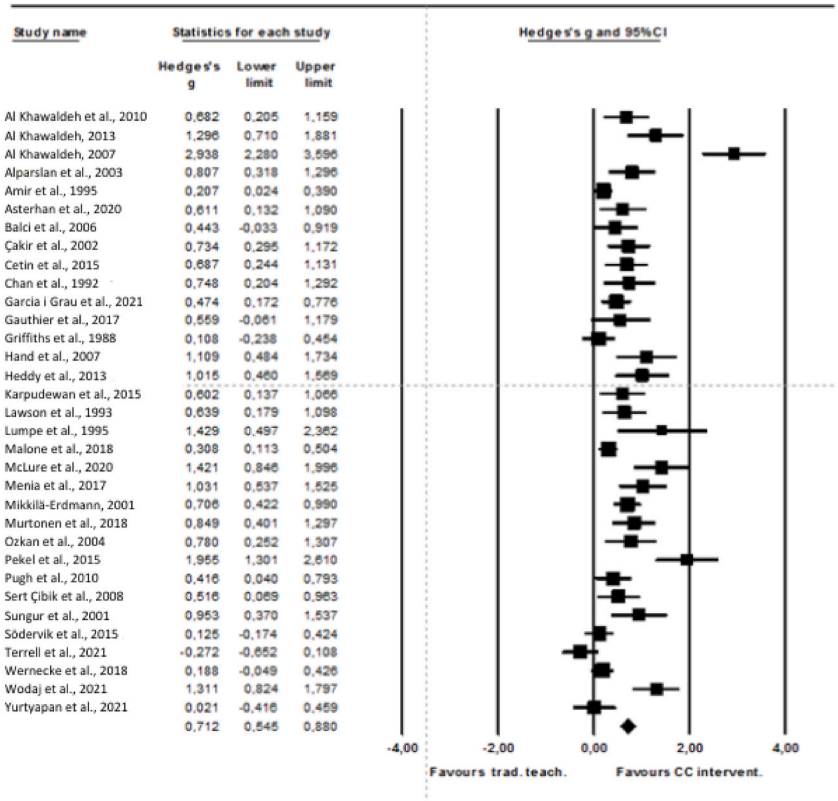
A forest plot of the studies is presented in Fig. 4. The overall effect size of 0.748 shows that conceptual change interventions have a large effect on the conceptual understanding of biological topics when compared with traditional teaching. A sensitivity test showed that the effect size estimate was robust. However, visual publication bias analysis with a funnel plot indicates that small and midsize studies with miniscule or negative results are missing. Egger's regression test (intercept = 4.67, $p < .001$) confirms that there is a publication bias.

Heterogeneity tests (*I*-squared = 84.13) indicate that sampling errors do not explain the variation of individual studies' effects, meaning that with high probability, the effect sizes of individual studies are not estimates of the true effect size of the same population. Thus, there is a need to continue the analysis with moderators.

3.5.2. *Moderator analysis*

The main analysis was based on the four moderator variables (sample size, biological topic, outcome measure and intervention type) using a mixed-effects model. Because of the small number of studies in some of the subgroups, pooled within-group estimates of tau-squared were used to estimate the mean effect sizes of the subgroups.

The moderator analysis (Table 6) shows that the effect sizes in all sample size groups are positive and differ significantly from zero;



Study name	Statistics for each study		
	Hedges's g	Lower limit	Upper limit
Al Khawaldeh et al., 2010	0,682	0,205	1,159
Al Khawaldeh, 2013	1,296	0,710	1,881
Al Khawaldeh, 2007	2,938	2,280	3,596
Alparslan et al., 2003	0,807	0,318	1,296
Amir et al., 1995	0,207	0,024	0,390
Asterhan et al., 2020	0,611	0,132	1,090
Balci et al., 2006	0,443	-0,033	0,919
Çakir et al., 2002	0,734	0,295	1,172
Cetin et al., 2015	0,687	0,244	1,131
Chan et al., 1992	0,748	0,204	1,292
Garcia i Grau et al., 2021	0,474	0,172	0,776
Gauthier et al., 2017	0,559	-0,061	1,179
Griffiths et al., 1988	0,108	-0,238	0,454
Hand et al., 2007	1,109	0,484	1,734
Heddy et al., 2013	1,015	0,460	1,569
Karpudewan et al., 2015	0,602	0,137	1,066
Lawson et al., 1993	0,639	0,179	1,098
Lumpe et al., 1995	1,429	0,497	2,362
Malone et al., 2018	0,308	0,113	0,504
McLure et al., 2020	1,421	0,846	1,996
Menia et al., 2017	1,031	0,537	1,525
Mikkilä-Erdmann, 2001	0,706	0,422	0,990
Murtonen et al., 2018	0,849	0,401	1,297
Ozkan et al., 2004	0,780	0,252	1,307
Pekel et al., 2015	1,955	1,301	2,610
Pugh et al., 2010	0,416	0,040	0,793
Sert Çibik et al., 2008	0,516	0,069	0,963
Sungur et al., 2001	0,953	0,370	1,537
Södervik et al., 2015	0,125	-0,174	0,424
Terrell et al., 2021	-0,272	-0,652	0,108
Wernecke et al., 2018	0,188	-0,049	0,426
Wodaj et al., 2021	1,311	0,824	1,797
Yurtyapan et al., 2021	0,021	-0,416	0,459
	0,712	0,545	0,880

Fig. 4. Forest plot of 33 studies comparing conceptual change interventions with traditional teaching.

Table 6
Effect size estimates and heterogeneity indicators by moderator variables.

Moderator	N of studies	Mean effect size	Standard error	Lower limit	Upper limit	p	τ^2	I^2
Sample size								
Small	10	1.102	0.144	0.820	1384	<.001	0.062	39.662%
Midsize	15	0.750	0.105	0.543	0.956	<.001	0.241	81.42%
Big	8	0.274	0.128	0.023	0.524	.032	0.036	66.84%
Biological topic								
Circular system	3	1.675	0.268	1.150	2.200	<.001	0.850	90.89%
Ecology	6	0.533	0.171	0.198	0.868	.002	0.090	69,44%
Evolution	6	0.703	0.171	0.360	1.045	<.001	0.111	72,29%
Genetics	3	1.315	0.265	0.796	1.835	<.001	0.224	73.51%
Molecular Biol.	5	0.457	0.194	0.077	0.837	.018	0.184	78.30%
Photosynthesis	10	0.507	0.134	0.244	0.769	<.001	0.066	65.42%
Outcome measure								
Enrichment	12	0.529	0.142	0.250	0.808	<.001	0.083	68.07%
Restructuring	21	0.827	0.111	0.610	1.044	<.001	0.260	85.95%
Intervention type								
Analogy	5	0.645	0.240	0.175	1.114	.007	0.359	91.05%
Refutational text	12	0.809	0.156	0.502	1.115	<.001	0.286	85.41%
Game/simulation	3	0.525	0.313	−0,088	1.137	.093	0.017	24.90%
Hands-On	3	0.777	0.333	0.124	1.431	.020	0.050	36.98%
Other	10	0.725	0.170	0.392	1.059	<.001	0.160	78.33%
School level *								
Higher education	10	0.401	0.159	0.088	0.713	.012	0.113	70.24%
Upper secondary	19	0.885	0.118	0.664	1.127	<.001	0.247	86.58%
Lower secondary	3	0.758	0.298	0.173	1.343	.011	0.028	29.79%

Note. *One study with primary school students was excluded from the analysis.

however, they are strongly dependent on the number of participants in the samples. The effect size is very large in studies with small samples, large in studies with midsize samples and small in studies with large samples. The effect size difference between various samples is significant (Q-value = 21.803, df = 2, p < .001).

Sample size is clearly related to effect size ($Q = 83.560$, $df = 2$, $p = .000$), so the effect size is smaller in larger samples. There were also significant differences in the effect sizes of interventions for various biological topics ($Q = 74.974$, $df = 5$, $p = .000$). Interventions related to circular systems and genetics resulted in higher effect sizes than interventions related to other biological topics. The differences in the mean effect sizes of studies measuring knowledge enrichment or knowledge restructuring did not differ significantly from each other ($Q = 1.563$, $df = 1$, $p = .211$). The difference between the mean effect sizes of various intervention types is significant ($Q = 14{,}569$, $df = 4$, $p = .006$), indicating that the interventions in the group 'other' and conceptual change texts are the most effective. School-level mean effect size difference is significant, showing that interventions in upper secondary school are the most effective, and the effect size is smallest in studies conducted in higher education (Q = 8.895, df = 2, p = .012).

4. Discussion

This systematic review and meta-analysis study was undertaken to analyse interventions targeting conceptual change in biology education. Our purpose was to gain understanding of which biological topics have been most studied, which types of interventions and measures have been utilised among students of different ages and on which conceptual change theories the studies are mainly based. Additionally, we endeavoured to investigate the effectiveness of these interventions in promoting high-level learning, both generally and for sample size, biological topic, school level, intervention type and measure of outcomes. To this end, we carefully reviewed 96 scientific research papers and conducted a meta-analysis of 33 of these papers.

4.1. *Findings of the systematic review in relation to previous literature*

The results of the systematic review show that the biological topics of evolution and photosynthesis have gained the most attention in intervention studies. These topics are indisputably among the most challenging topics in biology for students to learn at any level of education, requiring fundamental conceptual changes (Chi, 2013). These phenomena also lay the foundation for and tie together many concepts in biology (Mayr, 1997). Biology educators all over the world have sought long and feverishly the best ways to teach these fundamental phenomena, knowing that understanding the basics of these concepts is important for all citizens for protecting both nature and human well-being. Evolutionary mechanisms and processes help, for example, to understand why a new flu shot is needed every year and why the inappropriate use of antibiotics is a serious threat to humankind. In addition, understanding the basics of photosynthesis helps to understand, for example, why a vegetable-rich diet is a planet-friendly option and why the burning of fossil fuels is harmful for the climate. However, there is much research-based evidence on typical misconceptions that learners have related to the phenomena of evolution and photosynthesis, which provides a solid basis for designing conceptual change interventions (Evans, 2013; Ummels et al., 2015).

The majority of the intervention studies were conducted at the upper secondary school level, and the most common intervention type was ‘refutational texts’. Based on previous studies, we know that refutational texts seem to be particularly effective in supporting adolescents’ and adults’ learning, although they are not equally powerful among young children (Tippett, 2010). In addition, hands-on activities, simulations and the use of analogies seem to be suitable methods for teaching biology concepts and thus are widely used in the interventions. One of the important findings of this review is the richness of interventions that have been used to enhance conceptual change in biology concepts.

Most of the intervention studies drew upon the common conceptual change theories that are the most emblematic and have been identified as being widely used in conceptual change studies in various scientific fields (Potvin et al., 2020). The most common theory referred to in the papers was that of Posner and colleagues (1982). It is natural that as the first widely known theory directly focused on the educational context, Posner’s theory, is so often referred to in biology learning intervention papers. Chi’s (1992) ontological shift theory was frequently used, particularly in studies on evolutionary theory. This is natural because the scientific explanation of evolution is one example of an ontological category that is not normally used in everyday reasoning. In addition, Vosniadou’s (1994) theory was widely cited in the intervention studies in this review.

Carey’s (1985) theory was used with biological concepts to explain conceptual change challenges in learning; however, it was not commonly cited. The reason may be that Carey’s studies have mainly focused on young children and that primary school was not a common context in the reviewed studies. The theory of Hewson (1980) regarding conceptual exchange and conceptual capture, which was highly cited in Potvin and colleagues’ (2020) review study, did not explicitly appear in the studies analysed in this review. It was also noteworthy that diSessa’s theory (1993) was not very often cited, although it is one of the leading theories in the conceptual change research tradition. The reason for this probably lies both in traditions – diSessa (1993) is very much cited in physics education – and also in the nature of biological concepts. It might be that for learning biology concepts, Vosniadou’s and Chi’s theories provide more explanatory power than diSessa’s idea of fragmented pieces of knowledge. However, surprisingly many papers did not refer to any conceptual change theories, although the aim of particular papers stated that the intervention targeted overcoming misconceptions and/or fostering conceptual change. The weakness of these papers is that the designs of the interventions or measurements were not justified with relevant theoretical framing.

In spite of the fact that all studies selected for this review stated their aim as enhancing learners’ conceptual change, in 39% of the papers, the outcome measures managed to capture more knowledge enrichment types of learning instead of knowledge restructuring. Measuring knowledge restructuring requires sophisticated theory-based research instruments, and developing such instruments is laborious but of the utmost importance. Overall, surprisingly few studies utilised a large-scale randomised controlled trial with control and experimental groups.

4.2. *Findings of the meta-analysis in relation to previous literature*

The overall meta-analysis showed a large effect of conceptual change interventions when compared with traditional teaching. It is important to note here, however, that the effect varies according to the sample size, topic, school level, outcome measurement and intervention type. The results indicated large heterogeneity among the studies, though, and one explanation for this was the large differences between small-scale and large-scale studies. Studies with small sample sizes had very large effects, whereas the mean effect of large studies was small. There were also differences in the mean effect sizes of studies on various biological topics. The largest mean effect sizes were in studies on circulatory systems and the smallest in those on evolution, photosynthesis and molecular biology. These results may derive from the different nature of these processes. The misconceptions related to the circulatory system typically require only mental model-level transformation, instead of the fundamental knowledge structuring that is typically required in the learning of evolution and photosynthesis (Murtonen et al., 2018). According to Chi (2005b), emergent processes that are systemic in nature are typically more challenging to learn than so-called direct processes that have a clear direction and steps. Thus, perhaps circulatory systems represent a less challenging topic to learn from the conceptual change point of view than photosynthesis or evolution because they represent a direct process, whereas evolution is an emergent process. Photosynthesis, on the other hand, is a concept that has elements of both a direct and an emergent process. The chemical equation ($6CO_2 + 6H_2O = 6O_2$ and $C_6H_{12}O_6$) is a direct process, and it is typically rather easily learned that carbon dioxide and water are the raw materials converted into oxygen and chemical energy in a solar-powered process called photosynthesis. However, when the concept is considered from a larger, ecological perspective, it has an emergent, systemic and hence very complex nature, making it remarkably more difficult to learn.

Interventions that applied refutational texts were the most effective. However, the differences in the mean effect sizes between the various intervention types were not very large. Interventions using refutational texts explicitly highlight the need to restructure prior knowledge. Perhaps this more direct pedagogical guidance in refutational text interventions explains the stronger effects (see Kirschner et al., 2006). The hands-on interventions were almost as effective as refutational text interventions. It may be that hands-on activities are engaging and manage to make the difference between prior conceptions and empirical evidence so salient that it leads to conceptual change. However, interventions using simulations and learning games, which, in theory, share similarities with hands-on activities, had the lowest effect sizes. The reason may be that simulations or games failed to make the discrepancy between prior knowledge-based expectations and events in the simulations explicit. Hence, in these less effective interventions, the students are expected to discover the difference between their prior knowledge and scientific concepts more independently by themselves.

In conceptual change research, it is assumed that knowledge enrichment is easier to achieve than deeper knowledge restructuring. Surprisingly, studies measuring knowledge restructuring had higher mean effect sizes than studies focusing on knowledge enrichment. It may be that measures focusing on the knowledge restructuring of theoretically described initial conceptions (or misconceptions) towards correct scientific concepts are more directly related to the content of the interventions than more general knowledge tests measuring enrichment.

Additionally, the effect size was highest in studies conducted among adolescents compared to those conducted among lower secondary school pupils or higher education students. Secondary school was also the most common study context. Previous empirical evidence has shown that texts that refute the learner's prior knowledge with scientific knowledge are more effective among adolescents and adults due to their better metacognitive abilities compared to young children (Tippett, 2010). Thus, presumably, the two results found in the review are connected.

4.3. Limitations of the study and suggestions for future studies

As indicated in the publication bias analysis, the selection process and criteria for the articles included in the review and in the meta-analysis may have resulted in a number of relevant articles not being included. For example, the exclusive use of English language studies may have led to biases. Moreover, in interpreting the results of the meta-analysis, it is important to consider publication bias. It is likely that the unbiased mean effect sizes are somewhat lower than the reported effect sizes.

In several papers, the interventions were relatively short, although we know that conceptual change typically requires intentional study over longer periods. In the studies analysed in this review, the length of the intervention varied from a single lesson to an entire one-semester course, and we did not control for the length of the intervention. In addition, misconceptions can be extremely persistent, and learners often have a tendency to return to their previous, naïve conceptions after some time; yet, conducting a delayed post-test was rare (16%) in the analysed papers, and we did not analyse the long-term effects separately. Including a delayed post-test would be advisable for future studies, as it would provide important information related to the stability of the learned scientific view.

In addition, almost half of the studies (47%) did not include a control group, although utilising a quasi-experimental or experimental research design would be crucial in determining the effectiveness of the intervention. All things considered, there is a need for large-scale randomised controlled trials to test the effectiveness of conceptual change interventions related to key biological concepts, such as photosynthesis and evolution. Current research on conceptual change highlights the role of students' epistemic beliefs (Thacker & Sinatra, 2022) and affective factors (Gill et al., 2022). Studies also show that conceptual change does not always mean replacing prior conceptions but that they typically co-exist with scientific concepts (Shtulman & Legare, 2020). These trends were not yet applied in the studies in this review but should be taken into account in future studies.

4.4. Pedagogical implications

Science teachers at all educational levels still need concrete and effective pedagogical advice and suggestions on how to best promote conceptual change in science classrooms. Duit et al., (2013) stated that there remains a large gap between what is known in the research domain of conceptual change and what may be set into practice in normal science classrooms. Our analysis of conceptual change interventions provides some perspectives that can inform instructional choices. Overall, the results of the study show that conceptual change interventions have a large effect on the conceptual understanding of biological topics when compared with traditional teaching, with the single most effective intervention type being refutational texts. This result also has pedagogical implications because texts are still vital resources in teaching and learning and are often used as the basis of instruction in science education (Mason et al., 2008). In addition to refutational texts, hands-on activities seemed to be a relatively powerful way to foster conceptual change. In most of the hands-on activities, the students had an opportunity to generate hypotheses and test their prior conceptions by conducting experiments and drawing conclusions. Engaging in these activities can help to promote conceptual change because concrete experiences activate multiple pathways to process things to be learned.

Taken together, the results of this systematic review and meta-analysis indicate that explicitly contrasting common misconceptions with scientific conceptions holds a lot of persuasive power to support the learning of counterintuitive scientific content. Clear and powerful contradiction of typical, strongly held prior misconceptions and scientific ideas is needed because learners often merely ignore, trivialise, compartmentalise or hold in abeyance new knowledge that does not fit into their previous knowledge structures as such (Chinn & Brewer, 1993). Prior misconceptions are typically tenacious; therefore, learning activities that optimise student involvement in the learning process and provide repeated challenges in different contexts have a positive impact on learning.

Furthermore, students' prior conceptions and ways of thinking should be made visible to the learners themselves so that they can feel dissatisfaction towards their existing conceptions and be motivated to strive to substitute a scientific understanding (Posner et al., 1982). Students' prior conceptions and modes of thought should also be made visible to the teacher, who can then design more effective learning activities based on the background knowledge that students bring to the classroom. The teacher should select strategies that engage students to think about their initial ideas, make connections and weigh their old ideas against new knowledge. Most of the interventions handled topics such as evolution and photosynthesis, but there are several other counterintuitive and complex concepts in biology that could benefit from this conceptual change-informed teaching approach. For example, concepts such as energy and reproduction relate to biodiversity loss and climate change but are often misunderstood.

It is also important to note that the sample size played a role in the effectiveness of the interventions. In small samples, the effect sizes were remarkably higher than in the studies with larger sample sizes. This indicates that there is a challenge to scaling up successful interventions within education systems. More research is needed that focuses on large-scale transformations of educational practices.

4.5. Conclusion

This systematic review and meta-analysis were conducted to gain insight into the types and settings of different conceptual change interventions and their effectiveness in the biology domain. This study, which includes a systematic review and meta-analysis, is one of the first to investigate not only the types of interventions that have been conducted in different contexts and domains but also the effectiveness of these interventions. This review fulfilled its general aims, and the results can inform both biology educators and researchers from kindergarten to higher education. In this study, we have seen that conceptual change-informed interventions are, in general, effective in supporting high-level learning of complex biological phenomena, particularly at the secondary school level and principally in classrooms with a small group size. Yet, there is still a need to develop more effective interventions to support the learning of the most challenging biological topics, also including those other than photosynthesis and evolution, that typically require several profound conceptual changes among learners of different ages. Grasping basic and fundamental biological phenomena is a prerequisite for understanding and fighting against several current ecological hazards, which is why future efforts to promote conceptual change in biology classrooms are of crucial societal importance.

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Authors statement

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Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

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