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Learning in Earth and space science: a review of conceptual change instructional approaches

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ABSTRACT
In response to calls for research into effective instruction in the Earth and space sciences, and to identify directions for future research, this systematic review of the literature explores research into instructional approaches designed to facilitate conceptual change. In total, 52 studies were identified and analyzed. Analysis focused on the general characteristics of the research, the conceptual change instructional approaches that were used, and the methods employed to evaluate the effectiveness of these approaches. The findings of this review support four assertions about the existing research: (1) astronomical phenomena have received greater attention than geological phenomena; (2) most studies have viewed conceptual change from a cognitive perspective only; (3) data about conceptual change were generated pre- and post-intervention only; and (4) the interventions reviewed presented limited opportunities to involve students in the construction and manipulation of multiple representations of the phenomenon being investigated. Based upon these assertions, the authors recommend that new research in the Earth and space science disciplines challenges traditional notions of conceptual change by exploring the role of affective variables on learning, focuses on the learning of geological phenomena through the construction of multiple representations, and employs qualitative data collection throughout the implementation of an instructional approach.

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Introduction

Research in science education has consistently shown that students come to science classes with pre-instructional alternative conceptions. These alternative conceptions are often incomplete or incorrect and need to be better aligned with accepted scientific concepts through instruction. While there is much evidence in the literature to suggest that students hold alternative conceptions about geological and astronomical phenomena, there appears to be a paucity of intervention studies aimed specifically at correcting these ideas (Cheek, 2010; Francek, 2013; King, 2008; Lelliott & Rollnick, 2010). In response to this claim, and to identify action for the first author's future research, this review of the literature investigates the effectiveness of research-informed conceptual change instructional approaches in this context and the methods employed to evaluate their effectiveness.

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Learning for conceptual change in science

Conceptual change learning differs considerably from transmissive learning. Rather than an emphasis on content knowledge acquisition, notions of conceptual change consider the role of students' conceptions in learning science. The classical view of conceptual change holds that alternative conceptions can be altered by or replaced with more scientifically accurate understandings of phenomena (Hewson, 1981; Posner, Strike, Hewson, & Gertzog, 1982). Although this premise is simple, the interaction between existing and new conceptions is complex. The outcome of the interaction is dependent on an individual's 'conceptual ecology', a term that Posner et al. (1982) applied from earlier work in cognitive science (Toulmin, 1972). An individual's conceptual ecology refers to the 'conceptual framework by which he or she makes sense of the world' (Hewson, 1981, p. 392). It includes an individual's epistemological commitments and metaphysical beliefs about science (Posner et al., 1982), and has evolved over the past three decades to incorporate affective factors (Pintrich, Marx, & Boyle, 1993). The status afforded to a new conception is determined by the extent to which it is in accordance with existing cognitive frameworks, and therefore the degree to which an individual finds the conception intelligible, plausible, and fruitful. An individual may: (1) accept the new concept and replace their existing conceptions; (2) accept the new concept alongside their existing conceptions; (3) reject the new concept; or (4) compartmentalize the new concept so that it does not interact with existing conceptions (i.e. rote learn) (Hewson, 1981; Posner et al., 1982).

There are now multiple perspectives concerning the nature of conceptual change, and thus multiple conceptual change models exist. One variation on the classical conceptual change model suggests that alternative conceptions arise if students assign concepts to incorrect ontological categories (Chi, Slotta, & De Leeuw, 1994). From this perspective, conceptual change occurs when individuals change the way they perceive the nature of a concept. Another variation considers the role of affective factors, including motivation, interest, and self-efficacy, as variables that bring about conceptual change (Pintrich et al., 1993). Finally, some authors have advocated for a multidimensional model that views conceptual change from epistemological (classical), ontological, and affective perspectives (Tyson, Venville, Harrison, & Treagust, 1997).

Perhaps the most significant recent development in the field of conceptual change research is the 'warming trend' (Sinatra, 2005) that describes the move away from classical, cognition-only models of conceptual change, to an awareness of the influence of learner attributes on learning. Early studies that took affective variables into consideration sought evidence of conceptual change using qualitative research methods, such as interviews (Venville & Treagust, 1996). Recently, quantitative research methods have been employed successfully to demonstrate the relationship between affective variables and conceptual change (Cordova, Sinatra, Jones, Taasoobshirazi, & Lombardi, 2014; Linnenbrink-Garcia, Pugh, Koskey, & Stewart, 2012). The most recent research emerging shows that certain 'learner characteristics' appear to influence the occurrence of conceptual change (Sinatra & Mason, 2013). These include achievement goals (Taasoobshirazi & Sinatra, 2011), epistemic motivations and beliefs (Qian & Pan, 2002), interest (both individual and situational interest) (Andre & Windschitl, 2003; Mason, Gava, & Boldrin, 2008; Murphy & Alexander, 2004; Venville & Treagust, 1998), and self-efficacy (including commitment to or efficacy about alternative conceptions) (Linnenbrink-Garcia et al., 2012). It

also appears that a certain combination of affective characteristics—an 'affective profile'—might predict conceptual change (Cordova et al., 2014; Linnenbrink-Garcia et al., 2012).

A variety of conceptual change instructional approaches have been used in the science disciplines to challenge students' alternative conceptions. Recent approaches that have occurred in physics and chemistry education research include: conceptual change text (Şendur & Toprak, 2013; Ültay, Durukan, & Ültay, 2015); conceptual conflict-generating demonstration (often variations of the Predict–Observe–Explain approach) (Coştu, Ayas, & Niaz, 2010; Liaw, Chiu, & Chou, 2014); inquiry learning and laboratory investigations (Supasorn, 2015; Supasorn & Promarak, 2015); cooperative learning (Kırık & Boz, 2012); and computer simulations (Chang, Quintana, & Krajcik, 2010). Despite the merit of conceptual change instruction and its alignment with contemporary constructivist views of learning in science, classroom teachers continue to favor transmissive models of learning that promote knowledge acquisition (Duit, Widodo, & Wodzinski, 2007). This is often attributed to the complex nature of conceptual change and the difficulty experienced by both teachers and learners in implementing this type of instruction (Scott, Asoko, & Driver, 1991).

Students' alternative conceptions about Earth and space science

School and university students' alternative conceptions about astronomical phenomena are well researched. In a recent review of astronomy education research, Lelliott and Rollnick (2010) summarized research on conceptions held by school and university students, and their teachers. They found that the research focused on five main topics: the shape of the Earth, the Earth–moon–sun system, the day–night cycle, seasons, and gravity. Fewer studies have examined the sun and stars, the solar system, the concepts of size and distance, and cosmology. Some examples of common alternative conceptions of astronomical phenomena identified by three decades of research include: the Earth is flat (Nussbaum & Novak, 1976); the sun goes behind a hill at night time or it is covered by clouds (Baxter, 1989); Earth's shadow causes the moon's phases (Trundle, Atwood, & Christopher, 2002); and Earth's distance to the sun is the reason for the alternation of seasons (Tsai & Chang, 2005).

Alternative conceptions about geological phenomena have been researched to a lesser extent. Francek (2013) developed a comprehensive list of school and university students' alternative conceptions about Earth's structure, historical geology, plate tectonics, earthquakes, volcanoes, rocks and minerals, and weathering and erosion, finding that most alternative conceptions were about plate tectonics. Some examples of the most widely held alternative conceptions about geological phenomena include: Earth's crust is several hundred kilometers thick (Libarkin & Anderson, 2005; Steer, Knight, Owens, & McConnell, 2005); tectonic plates are underground and are not exposed at the Earth's surface (American Association for the Advancement of Science, 2015); volcanoes are found in places that have high temperatures, like at the equator (Dahl, Anderson, & Libarkin, 2005); and weathering and erosion are synonymous (King, 2010).

Researchers attribute these alternative conceptions to the difficulties that students have in comprehending the temporal and spatial scales associated with astronomical and geological phenomena (Dodick & Orion, 2003), as well as their frequent misrepresentation in textbooks (King, 2010) and popular culture (Barnett et al., 2006).

A timely review of instructional approaches

The identification of effective conceptual change instructional approaches in Earth and space science is important amid recent research that has highlighted a variety of issues, such as senior secondary students' perceptions that some topics, particularly geological concepts, are difficult, boring, and irrelevant (Dawson & Carson, 2013); concerns that teachers have poor knowledge of Earth and space science and may not be adequately trained to teach Earth and environmental science curricula (Dawson & Moore, 2011; King, 2001); teachers' resentment toward teaching Earth and space science, given their under-preparedness to do so (Jenkins, 2000); and teachers' perceptions that Earth and space science is less important than physics, chemistry, and biology (Betzner & Marek, 2014). In Australia, where this review was conducted, these concerns are significant, given that Earth and space science instruction has been recently mandated in the national science curriculum for all students in Preparatory to Year 10 (Australian Curriculum, Assessment and Reporting Authority, 2013).

Methodological approach

In the current study, procedures for reviewing the literature according to Randolph (2009) were adopted. As the process of conducting secondary research mirrors the process of conducting primary research, the tasks to conduct a systematic literature review include: (1) problem formation; (2) data collection; (3) data evaluation; (4) analysis; and (5) interpretation (Randolph, 2009). The researchers operationalized these five broad tasks as outlined below.

Problem formation

The first task in problem formation is to develop questions that will guide the literature review. In this review, the two research foci are the instructional interventions and methods of conceptual change literature within the Earth and space science disciplines. It was the researchers' aim to integrate findings from multiple approaches and contexts. As such, the following questions were developed to guide the literature review:

(1) What are the general characteristics of the literature?
(2) What conceptual change instructional approaches have been used in an Earth and space science education context?
(3) What methods were used to evaluate the effectiveness of these approaches?
(4) What are the recommendations for future research synthesized from the existing literature?

For the purposes of this review, peer-reviewed empirical studies that (1) employed quantitative and/or qualitative methods to (2) generate data on the effectiveness of a conceptual change instructional approach used in the Earth and space science discipline were selected. The authors excluded research that listed students' alternative Earth and space science conceptions, or did not analyze learning from a conceptual change perspective.

Data collection

The studies included in this review were compiled from four sources: (1) a search of the *Education Resources Information Centre* (ERIC) and *PsychInfo* databases for studies published in 1980 onwards; (2) a manual search of recent issues of science education, educational psychology, and cognitive science journals for studies published in 2010 onwards (a shorter time span was chosen due to the time intense nature of manually searching journals); (3) the reference lists of studies identified as relevant; and (4) the reference lists of three existing literature reviews.

The first author began with a search of the two academic databases. The following search terms were used: ('Earth science*' OR Geoscience* OR Geolog* OR Astronom*) AND ('conceptual change*' OR 'conceptual development*' OR misconcept* OR 'alternative framework*' OR 'naïve idea*'). As much research now considers the impact of affective variables on students' conceptual change, follow-up searches using the above keywords in addition to (affect* OR emotion* OR interest* OR efficacy) were conducted. The number and specificity of the search terms was refined through input from all authors to ensure that the search results would be a robust representation of the existing research. As well, recent issues of particularly relevant journals were searched manually throughout the preparation of the review to ensure that data collection was thorough, namely the *International Journal of Science Education*, the *Journal of Research in Science Teaching*, the *Journal of Science Teacher Education, Learning and Instruction, Research in Science Education*, *Science Education*, *Studies in Science Education*, *Cognitive Psychology, Contemporary Educational Psychology*, *Educational Psychologist*, *Educational Psychology Review,* the *Journal of Educational Psychology*, and the *Journal of Learning Sciences*. Two discipline-specific science education journals were searched manually, namely the *Journal of Geoscience Education* and *Astronomy Education Review*.

Finally, the reference lists of relevant studies were analyzed to identify any further relevant studies, and so on, until a point of saturation was reached where the first author was certain that no more relevant studies could be obtained from this process. Particular attention was given to three existing literature reviews in this process (Cheek, 2010; Francek, 2013; Lelliott & Rollnick, 2010).

Data evaluation

The overall approach to data collection and evaluation is shown in Figure 1. The first author identified potentially relevant studies from hundreds of search results by first reading their title and abstract. Following this, many of the studies were read in full to determine their relevance. Information was extracted from 52 studies only. The remaining studies were excluded from the review for two main reasons. First, these studies did not analyze learning from a conceptual change perspective. Instead, they presented interventions that increased students' conceptual knowledge, but were not specifically designed to address students' alternative conceptions nor measure conceptual change (e.g. Gobert & Clement, 1999). Second, these studies were theoretical discussions or simply identified students' alternative conceptions and did not evaluate an intervention specifically designed to change them (e.g. Blown & Bryce, 2006; Vosniadou & Brewer, 1992).

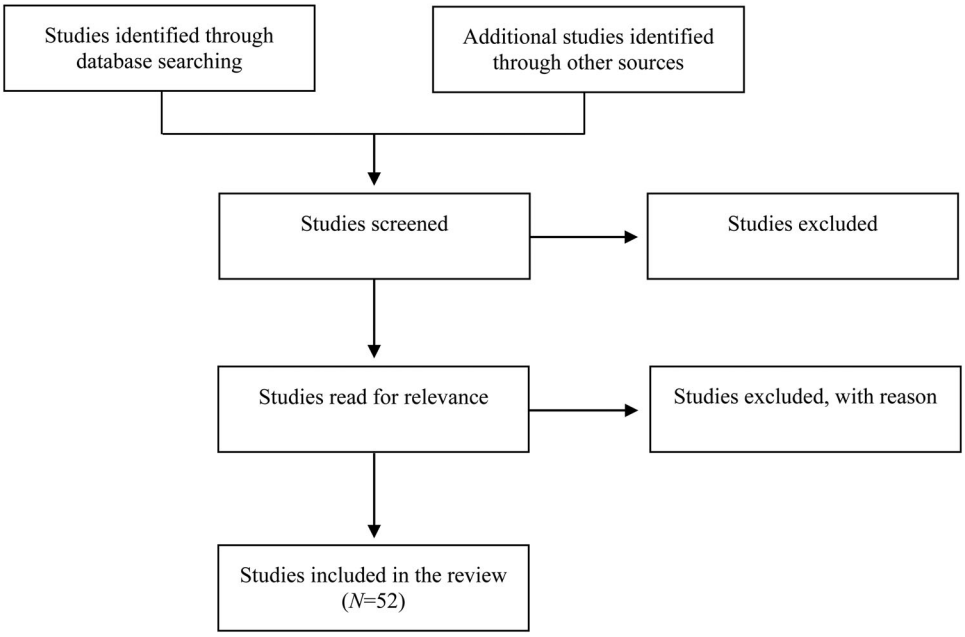

Figure 1. A summary of the process of selecting studies to include in this review.

Information extracted from the relevant studies was organized in an electronic database. This included information about each study's author and date of publication, journal of publication, geographical location, research design, theoretical view of conceptual change adopted in the study, setting and participants, methods of data generation and analysis, findings, data that support the findings, limitations of the study, and finally recommendations for further research. All authors looked for commonalities among instructional approaches to identify themes and gaps in the existing literature.

Analysis

Studies that investigated conceptual change instructional approaches in the Earth and space sciences have increased over the past 25 years. The majority of instructional interventions over this time have moved from the natural observation of phenomena and the use of physical models, to the use of computer simulations as technological advancement and access to technology increase. The most effective instructional approaches appear to be those where students physically constructed multiple representations of the phenomena. Although the development of instructional approaches has progressed, there have been limited theoretical and methodological progressions during this transition. This is reflected in four assertions, evidenced by the findings of this review, as follows:

(1) Astronomical phenomena have received greater attention than geological phenomena;
(2) Studies have viewed conceptual change from a cognitive perspective only;

(3) Data about conceptual change were generated pre- and post-intervention only; and
(4) The interventions reviewed present limited opportunities to involve students in the physical construction of multiple representations.

The findings that support each of these assertions are presented below.

General characteristics of the research

The following section presents a summary of the general characteristics of the studies included in this review.

Publisher, date, and location of research. Most of the studies were published in leading science education journals such as the *Journal of Research in Science Teaching*, rather than discipline-specific journals, such as the *Journal of Geoscience Education* or *Astronomy Education Review*. Even fewer studies were published in educational psychology journals. The number of intervention studies has increased over the past 25 years; of the 52 studies included in this review, the majority were published in the previous decade. Most of the research was conducted in the United States. Research has also been carried out to a lesser extent in Australia, Canada, Cyprus, Finland, Greece, Israel, Italy, Portugal, New Zealand, Taiwan, Turkey, and the United Kingdom.

Earth and space science topics. Of all the studies included in the review, the majority reported on an instructional approach designed to facilitate participants' accurate conceptions of astronomical phenomena. Fewer investigated instructional approaches designed to facilitate participants' accurate conceptions of geological phenomena or other Earth science-related phenomena, such as climate change science. The most widely researched astronomical phenomenon was the Earth–moon–sun system, including the causes of moon phases and seasons. Other astronomical phenomena researched are participants' conceptions of Earth; the alternation of day and night; the solar system; planetary motion; stars and the sun; light; galaxies; astronomical size and scale; and tides.

Participants. A large proportion of studies were conducted with primary and secondary school students. Some studies were conducted with undergraduate students or pre-service teachers. Very few studies evaluated interventions targeting teachers' alternative conceptions. All of the studies that did so targeted primary school teachers; no studies were aimed at facilitating secondary school teachers' scientific conceptions.

Research design. The majority of studies were small-scale research projects conducted with small groups of students, such as intact classes of primary school students. Most adopted some sort of single case study research design. As such, the research was mostly exploratory and interpretive in nature. A smaller number of studies were quasi-experimental and aimed to compare intervention and comparison groups.

Theoretical perspective of conceptual change. Almost all of the research conducted viewed conceptual change from a cognitive perspective. Only two studies adopted an affective perspective (Broughton, Sinatra, & Nussbaum, 2013; Cordova et al., 2014). In these studies, the researchers aimed to determine the influence of affective variables on participants' conceptual change. Apart from these instances, no further studies considered how an intervention impacted students' perception of a given concept (i.e. ontological conceptual change), or how learner characteristics may have contributed to their knowledge reconstruction (i.e. affective conceptual change).

Conceptual change instructional approaches and methods employed to evaluate their effectiveness

The reviewed studies employed several conceptual change approaches to align better the participants' alternative conceptions of astronomical or geological phenomena with accepted scientific concepts. These included: natural observations, physical models, simulations, student-generated animations, analogy, cognitive conflict, refutational text, and other specific teaching and learning sequences (Table 1). These studies are marked with an * in the reference list. In this section, each instructional approach and its effectiveness are reviewed in turn.

Natural observation. Almost all of the eight studies in this category employed a similar intervention whereby the participants observed astronomical phenomena either directly or using secondary data. A similar instructional sequence was adopted in these studies. In groups, students: (1) gathered, recorded, and shared data about the moon; (2) analyzed their data, looking for patterns; and (3) modeled the cause of moon phases (e.g. Trundle et al., 2002). Two studies used this instructional sequence to learn about tides by accessing tidal data online (Ucar & Trundle, 2011; Ucar et al., 2011). One of these studies compared this inquiry-based approach with traditional instruction that included lectures and group discussions (Ucar & Trundle, 2011). No studies targeted participants' alternative conceptions about geological phenomena, perhaps due to the fact that many geological processes cannot be directly observed, or occur so slowly that direct observation is not possible.

Data generation was almost exclusively qualitative, relying mostly on structured interviews with participants. During interviews, participants generally completed drawing or modeling tasks. Two studies relied on students' diagrams only, as they investigated the effect of the instruction on students' ability to draw the moon's phases (Trundle et al., 2006, 2007a). One study adopted a mixed-methods approach and relied on qualitative and quantitative data to determine the effectiveness of the intervention (Ucar et al., 2011). Structured interviews and a multiple-choice test were the primary sources of data in this study. In all of the studies, data collection occurred exclusively pre- and post-intervention. No studies collected data throughout the intervention, thus preventing any insight into the nature/process of conceptual change. Additionally, this meant that there was no indication of how social interactions may have influenced students' conceptual change, despite the fact that group work was an important component of all of the instructional approaches. One study was unique in that the authors conducted interviews six months after the intervention to determine its effectiveness (Trundle et al., 2007b). Many studies claimed to have sourced data from classroom observations, document analysis, and participants' journals; however, these data were rarely analyzed and used as evidence to support the findings of the study (e.g. Trundle et al., 2002; Ucar et al., 2011).

In all studies, a constant-comparative approach to data analysis was used to identify trends in the participants' understanding about moon phases and tides. Participants' pre- and post-instructional conceptions were coded using a framework that categorized their ideas on a continuum that included 'no conception', 'incomplete or alternative conceptions', and 'scientific conceptions'. In most cases, this was quantified by assigning a score to the nature of students' conceptions, allowing a percent increase from pre- to post-instruction to be calculated. A paired samples *t*-test was used in the one study that

Table 1. A summary of the conceptual change instructional approaches and studies included in this review ($N = 52$).

Instructional approach	Number of studies	References
Natural observation	8	Lee, Lester, Ma, Lambert, and Jean-Baptiste (2007) Trundle et al. (2002) Trundle, Atwood, and Christopher (2006) Trundle, Atwood, and Christopher (2007a) Trundle, Atwood, and Christopher (2007b) Trundle, Atwood, Christopher, and Saçkes (2010) Ucar and Trundle (2011) Ucar, Trundle, and Krissek (2011)
Physical models	3	Ogan-Bekiroglu (2007) Shen and Confrey (2007) Steer et al. (2005)
Simulations	10	Bakas and Mikropoulos (2003) Bell and Trundle (2008) Binns, Bell, and Smetana (2010) Gazit, Yair, and Chen (2005) Hobson, Trundle, and Saçkes (2010) Keating, Barnett, Barab, and Hay (2002) Küçüközer (2008) Küçüközer, Korkusuz, Küçüközer, and Yürümezoglu (2009) Schneps et al. (2014) Trundle and Bell (2010)
Student-generated animation	1	Nielsen and Hoban (2015)
Analogy	2	Blake (2001) Blake (2004)
Cognitive conflict	1	Tsai and Chang (2005)
Refutation text	4	Broughton et al. (2013) Broughton, Sinatra, and Reynolds (2010) Cordova et al. (2014) McCuin, Hayhoe, and Hayhoe (2014)
Other specific teaching and learning sequences	23	Barnett and Morran (2002) Bezzi (1996) Bulunuz and Jarrett (2010) Celikten, Ipekciouglu, Ertepinar, and Geban (2012) Chang and Barufaldi (1999) Chastenay (2016) Diakidoy and Kendeou (2001) Hayes, Goodhew, Heit, and Gillan (2003) Hsu (2008) Kali, Orion, and Eylon (2003) Lombardi, Sinatra, and Nussbaum (2013) Marques and Thompson (1997) Martinez, Bannan, and Kitsantas (2012) Nussbaum and Sharoni-Dagan (1983) Rebich and Gautier (2005) Salierno, Edelson, and Sherin (2005) Sharp and Sharp (2007) Sneider and Ohadi (1998) Stover and Saunders (2000) Taylor, Barker, and Jones (2003) Trumper (2006) Viiri and Saari (2004) Zelik, Schau, and Mattern (1999)

employed a multiple-choice test instrument to measure conceptual change (Ucar et al., 2011).

After instruction, most students in all studies showed evidence of holding more accurate scientific conceptions and fewer alternative conceptions. Participants in two studies were more likely to be able to draw a scientific diagram of the moon's phases as a result of the intervention (Trundle et al., 2006, 2007b). In the study that interviewed participants six months after the intervention, most participants had retained scientific conceptions of moon phases; however, some resorted back to their alternative conceptions (Trundle et al., 2007a). It seems that the participants' direct experience with the phenomena (i.e. conducting natural moon observations or accessing real-time tidal data) was a crucial aspect of the success of these instructional approaches. Also, as participants worked in groups in all of the studies, the 'interpretive, sense-making discussions' (Trundle et al., 2002, p. 653) between individuals may have also been important (although no evidence supports this claim). In the studies where participants analyzed tidal data, the fact that pre-service teachers were able to access data over a long period of time and from a range of geographical locations was considered a critical aspect of the instruction (Ucar et al., 2011). A possible explanation for students who did not have accurate scientific conceptions post-intervention, suggested in one study, was that these individuals were not metacognitively aware of the inconsistencies between their alternative conceptions and the scientific conception presented during instruction (Trundle et al., 2007a). Another possibility is that participants' alternative conceptions were reinforced during the physical modeling of phenomena (a part of the broader instructional sequence) due to limitations of the model used (Trundle et al., 2002).

Although the use of natural observation as an instructional strategy holds obvious merit, a variety of directions for future research were suggested. One such direction is that research is conducted with school-aged students (Ucar et al., 2011). To date, research has tended to investigate the effectiveness of this type of instructional approach on pre-service teachers only. Only three studies have extended research to school-aged students (Lee et al., 2007; Trundle et al., 2007b, 2010). It has also been suggested that research on a conceptual change intervention where participants are somehow metacognitively comparing their pre- and post-instructional ideas would be particularly insightful (Trundle et al., 2007a). Finally, Ucar et al. (2011) advise that any research that addresses pre-service teachers' alternative conceptions about tides would be beneficial due to the alarming number of non-scientific ideas held by soon-to-be teachers on this topic.

Physical models. This review identified three studies that investigated the use of physical models in facilitating scientific conceptions. In one study, pre-service teachers worked in groups to create models to represent the Earth–moon–sun system and presented their model to their peers (Ogan-Bekiroglu, 2007). In another study, undergraduate science students created multi-modal models of the Earth's interior (Steer et al., 2005). The final study was a phenomenological study that reported on a primary school teacher's experiences of conceptual change throughout a professional development program on the moon's phases (Shen & Confrey, 2007). Throughout the program, the teacher constructed a variety of physical models to represent the phases of the moon. Initially, she constructed a table using data on moon phases. She then transformed this table into a two-dimensional diagram, and finally a three-dimensional model.

Each of these studies employed different approaches to data generation. A range of data sources were drawn upon, including video recordings, interviews, diagrams, and questionnaires. While two studies utilized a typical qualitative approach to data analysis and coded participants' pre- and post-treatment responses on a questionnaire/drawing task (Ogan-Bekiroglu, 2007; Steer et al., 2005), one study took a novel approach and analyzed the participant's real-time conceptual change by video-recording her experience (Shen & Confrey, 2007). The authors of this study primarily looked for discussion and debate occurring during group discussions (often revealing the teacher's alternative conceptions and instances of conceptual change). This allowed the researchers to capture the cognitive processes embedded within social interactions, which they argued is the key to understanding conceptual change and is in accordance with the conditions of regular schooling. Despite the merit of video-recording participants during the intervention, this was an uncommon approach to data collection.

All of the instructional approaches where participants were constructing or manipulating physical models were found to be effective. A significant finding from one study was that profound conceptual development occurred when transforming information between models and constructing multiple representations (Shen & Confrey, 2007). This was attributed to the participant being actively involved in the modeling tasks, likening one representation to another, and resolving inconsistencies within and between models. Although the findings from another study suggested that such an approach is effective overall, the authors cautioned against the use of student-generated models (Ogan-Bekiroglu, 2007). Some pre-service teachers in this study retained their pre-instructional alternative conceptions due to limitations of the model they constructed, supporting an earlier finding by Trundle et al. (2002). This was probably because the teacher did not play an active role in checking that the models were scientifically accurate. Despite this, and based upon the positive results of the use of models as evidenced in these studies, it appears that a call for further research into the use of models in learning Earth and space science concepts, particularly geological phenomena such as plate tectonics, is justified (Steer et al., 2005).

Simulations. Ten studies investigated the effectiveness of simulations in facilitating participants' accurate conceptions of astronomical phenomena. It is apparent that technological advances and access to technology are allowing researchers (particularly in the last decade) to address the abstract nature of the Earth–moon–sun system and related astronomical phenomena. The research focused on three main simulations: *Starry Night*™ (Bell & Trundle, 2008; Binns et al., 2010; Hobson et al., 2010; Trundle & Bell, 2010), *Virtual Solar System*™ (Gazit et al., 2005; Keating et al., 2002), and *CosmoWorld*™ (Bakas & Mikropoulos, 2003). These simulations are interactive, allowing for students' direct manipulation of the phenomena under study. While *Starry Night*™ offers a two-dimensional representation of the night sky, both *Virtual Solar System*™ and *CosmoWorld*™ offer three-dimensional representations of the Earth–moon–sun system. One other general modeling program was used (Küçüközer, 2008; Küçüközer et al., 2009). The majority of this research followed the same inquiry-oriented teaching and learning sequence as Trundle et al. (2002) (see *Natural observation*).

Like the studies reviewed so far, data generation occurred pre- and post-intervention and was analyzed from a cognitive perspective. Data generation in simulation interventions was, again, typically qualitative. Pre- and post-interviews were by far the most

common method employed. At interview, students demonstrated their conceptual understanding by completing drawing or modeling tasks. Participants' pre- and post-instructional conceptions were generally coded using a framework that categorized their ideas, consistent with the constant-comparative method described previously (see *Natural observation*). Like Shen and Confrey (2007), Gazit et al. (2005) also employed an atypical approach by video-recording participants during instruction to capture students' interactions with the simulation.

The studies reviewed reported that there was typically an increase in the number of students who held more scientific conceptions of phenomena post-instruction. It is likely that simulations, being a simplified version of reality, provided access to phenomena that were otherwise unobservable. In the case of *Virtual Solar System*™, this may be due to the three-dimensional representation supporting students' ability to visualize abstract concepts from multiple viewpoints (Keating et al., 2002). This particular simulation, which is especially interactive, is deemed beneficial because of its descriptive and predictive ability; that is, it not only helps explain the Earth–moon–sun system, but through interaction and manipulation, it also helps to explain what might be expected when variables are changed (e.g. the time Earth takes to orbit the sun). One study found that the use of a simulation reinforced students' alternative conceptions (Gazit et al., 2005). The authors suggest a few reasons for this, including that students may have misinterpreted features of the simulation (e.g. the graphics) or experienced difficulty comprehending the multiple viewpoints (i.e. not having a fixed point of reference to view phenomena). Two studies had conflicting findings about the effectiveness of using *Starry Night*™ over natural moon observations (Binns et al., 2010; Trundle & Bell, 2010).

One methodological limitation associated with simulations was evident in most of the studies. In the many instances where simulations were embedded within a broader teaching and learning sequence, the single case study research design did not delineate the impact of individual instructional activities on the findings (e.g. Bell & Trundle, 2008). Therefore, any conceptual gains were not attributed to the use of the simulation alone, but rather, to the broader instructional approach. Opportunities for further research concern the optimal use of simulations, such as determining the minimum number of *Starry Night*™ moon observations needed for conceptual change to occur (Bell & Trundle, 2008).

Student-generated animation. Student-generated animations that do not require specially designed software, such as 'slowmation' (i.e. a from a stop-motion animation), is a new approach that has been researched from a conceptual change perspective very recently (Nielsen & Hoban, 2015). The construction of a slowmation representation is a process whereby an animation is created from a series of still digital photographs that are displayed in quick succession. The creation process involves three stages: (1) planning, (2) chunking and sequencing information, and (3) constructing and reconstructing (adapted from Nielsen & Hoban, 2015). In the slowmation construction process, the participants of this study researched a topic and then planned a storyboard. They used their own mobile phone or a digital camera to photograph a multi-modal two-dimensional or three-dimensional model as they manipulated it to demonstrate a concept or process. Their photographs were then displayed at two frames per second using software or an iPhone/iPad™ application.

This approach was effective in promoting pre-service teachers' scientific conceptions of moon phases from pre- to post-interview (Nielsen & Hoban, 2015). In creating a slowmation, the pre-service teachers demonstrated their understanding of moon phases using different modes; for example, research notes and storyboards, three-dimensional models, still images, and narration. This was particularly effective at bringing about conceptual change as the pre-service teachers were presented with multiple opportunities to consider and revise their own alternative conceptions. Comparing their own representations with expert representations was deemed essential in bringing about conceptual change, as was the process of constructing and manipulating physical models (Nielsen & Hoban, 2015).

Analogy. Two studies investigated the effect of teaching primary school students about the rock cycle using the analogy of aluminum can recycling (Blake, 2001; 2004). Students were introduced to the target (i.e. the rock cycle), taught the analog (i.e. aluminum can recycling, which students had leant about previously), and then connected the two. Afterwards, students pointed out some limitations of the analogy. Data were gained from multiple sources, including a rock sorting task, concept maps, and semi-structured interviews. Students who participated in this treatment were more able to scientifically describe and classify rocks. Blake (2004) suggested that the use of an analogy might have assisted students to construct scientific conceptions of the rock cycle by making links to their prior knowledge. However, one major limitation evident in this study is that the data generally failed to give information about if and how the use of an analogy facilitated conceptual development. This was perhaps because no data sources provided an in-depth examination of the learning occurring throughout the intervention. Repeating this type of research with a deliberate focus on audio-recording students during the learning episode is a possibility for future research.

Cognitive conflict. Tsai and Chang (2005) proposed a specific instruction based on creating cognitive conflict as an approach to bring about conceptual change. They carried out a quasi-experimental investigation to determine the effect of the instruction on Year 9 science students' conceptions about the cause of seasons. While students in one class experienced regular instruction, students in another class were presented with a 'discrepant statement' (e.g. 'in winter, the Earth is slightly further from the sun, whereas in summer the Earth is closer to the sun') and a 'critical statement' ('if seasons were caused by Earth's distance to the sun, the Northern and Southern Hemispheres would have the same season at the same time') (Tsai & Chang, 2005, p. 1093) at the beginning of instruction. Following this, the teacher presented both classes with a scientific explanation. During this part of instruction, students were engaged in modeling the Earth's rotation around the sun with balls. Interviews were conducted one week, two months, and eight months after the treatment. At each interview, students in the intervention class held more scientific conceptions and fewer alternative conceptions than those in the control class; therefore, this study endorses the use of cognitive conflict-based instructional approaches as an effective means of promoting conceptual change. The limited publications in this area and the promising results of this study warrant further research into cognitive conflict as a conceptual change approach in other Earth and space science education contexts.

Refutation text. Four studies employed a refutation text to bring about conceptual change (Broughton et al., 2010; Broughton et al., 2013; Cordova et al., 2014; McCuin et al., 2014). Of

particular interest is Broughton et al.'s (2013) approach to determine if a refutation text about Pluto's re-classification as a dwarf planet would change students' understanding of the definition of a planet. The text was constructed from a range of magazine articles to explain the changing nature of science, the role of evidence in making scientific decisions, and the history of Pluto's classification as a planet. Students' knowledge about the planets and the reclassification of Pluto were assessed using an open-ended questionnaire. It was found that students held alternative conceptions about the definition of a planet, and about Pluto's size and orbit. There was a significant change from pre- to post-test on students' understanding of why scientists changed the definition of a planet after they engaged with the text.

This finding was accompanied by more positive emotion at post-test. This shift in students' emotions about Pluto's reclassification may have resulted from their reading of the refutation text and finding the scientific rationale for Pluto's reclassification acceptable. A series of regression tests revealed a relationship between students' emotions and their conceptual development. At post-test, positive emotion was a strong predictor of students' belief that Pluto should no longer be a planet, the accepted scientific viewpoint. Positive emotion was also a predictor of students providing scientific reasoning for their decision. In summary, if students felt positive emotions after engaging with the refutation text, they were more likely to hold scientifically accurate conceptions about the definition of a planet and Pluto's reclassification as a dwarf planet. This was one of only two studies reviewed to consider conceptual change from an affective perspective.

Other specific teaching and learning sequences. Twenty-three studies reported a variety of other instructional approaches that do not fit within the previous categories. Instructional interventions in this category were generally a mix of teaching and learning activities over a long period of time where the influence of a specific approach could not be delineated. Some examples included:

- An undergraduate astronomy course where an emphasis was placed on concept mapping and group discussions (Zelik et al., 1999);
- A unit of work on six astronomical concepts that spanned several weeks and included learning activities such as Internet-based research, observations of the moon, and the use of a three-dimensional computer model (Barnett & Morran, 2002);
- An excursion to a planetarium (Chastenay, 2016; Stover & Saunders, 2000);
- Diverse instruction that challenged more than one of students' alternative conceptions simultaneously (Hayes et al., 2003);
- An audio-tutorial that included explanations, guidance for analytical observation of visuals, and instructions for manipulating concrete props (Nussbaum & Sharoni-Dagan, 1983).

Interpretation

The most obvious trend in the existing literature is that intervention studies carried out in the Earth and space science discipline employed what are now considered outdated theoretical and methodological perspectives. The major theoretical shortcoming was that almost all of the studies viewed conceptual change from a cognition-only perspective. Although this approach is now being challenged in other science disciplines, researchers

are yet to substantially challenge traditional notions of conceptual change in the Earth and space science disciplines. Only two studies considered conceptual change from an affective perspective; the remaining studies viewed conceptual change from a cognition-only perspective. There were also a number of methodological shortcomings. First, the learning of astronomical phenomena received significantly greater attention than geological phenomena. Of the 52 studies included in this review, only eight studies investigated the effectiveness of an intervention designed to facilitate scientifically accurate conceptions of geological phenomena. Second, intervention studies in the Earth and space science disciplines have generally only investigated conceptual change by measuring students' conceptions pre- and post-intervention. The few studies that generated data throughout the implementation of an instructional approach had a more robust evaluation of the intervention, and provided additional insight into how the instructional approach influenced students' conceptual change. This was an atypical approach to data collection; only three studies included in this review video-recorded participants while they were learning. Third, intervention studies primarily required participants to view or manipulate representations of phenomena. Notwithstanding the effectiveness of this approach, in studies where conceptual change was most profound, participants were creating representations (or multiple representations) of phenomena.

Recommendations for future research synthesized from the literature

In light of these assertions, the authors have identified the need for conceptual change research in the Earth and space science disciplines that:

(1) Challenges traditional notions of conceptual change by considering data from affective perspectives;
(2) Focuses on the learning of geological phenomena through the construction of multiple representations; and
(3) Employs qualitative data collection methods throughout the implementation of an instructional approach.

The theoretical and methodological implications of these recommendations are discussed below.

The need for research that challenges traditional notions of conceptual change. Despite the overwhelming and long-standing argument for further research into the interplay between affective variables and conceptual change (Cobern, 1994; Pintrich et al., 1993; Sinatra & Mason, 2013; Treagust & Duit, 2008; Tytler & Prain, 2010; West & Pines, 1983; Zembylas, 2005), only two studies included in this review took such an approach (Broughton et al., 2013; Cordova et al., 2014). As identified earlier, together these studies explored the relationships between prior knowledge, efficacy, interest, emotions, and conceptual change. The remainder of the studies viewed conceptual change as a purely cognitive construct.

Science education researchers have increasingly criticized a cognition-only approach to conceptual change learning. It has been suggested that cognition-only models of conceptual change present an over-rationalized view of learning that fail to consider the role of factors such as motivation, interest, self-efficacy, feelings, and emotions as conceptual

supports for new knowledge (Pintrich et al., 1993). In fact, it has been acknowledged that adopting a purely cognitive perspective of conceptual change can constrain the interpretation of the learning process (Caravita & Hallden, 1994; Duit & Treagust, 2003). If new research in Earth and space science education continues to ignore the influence of affective variables on conceptual change, the assumption that affective variables are irrelevant to teaching and learning in a cognitively demanding discipline like science will remain unchallenged (Zembylas, 2005). Research that adopts an affective or multidimensional perspective of conceptual change, therefore, is crucial within this discipline where studies of this nature are virtually non-existent.

An in-depth examination of whether interest plays a role in students' conceptual change is an example of the type of research that is needed. There have been efforts to explore this in other science disciplines. A common theme emerging from the findings is that this area is under-researched and results are contradictory, substantiating the need for ongoing research. Few studies have investigated how individual or situational interest may bring about conceptual change (Sinatra & Mason, 2013; Treagust & Duit, 2008). Of those that do, some authors report that students' interest relates positively to conceptual change (Andre & Windschitl, 2003), while others argue that highly interested students may be more resistant to change (Dole & Sinatra, 1998). Further research of this nature will challenge traditional notions of knowledge reconstruction and help to clarify the opposing results reported to date. The findings from this type of research can also inform teachers' choice of instructional approach so that classroom environments are conducive to conceptual change.

The need for research that focuses on the learning of geological phenomena through the construction of multiple representations. As already reported, the majority of studies included in this review investigated the effectiveness of an intervention designed to facilitate accurate conceptions of astronomical phenomena. Although important, this is not a surprising finding. Traditionally, both students and teachers have not regarded Earth science as prestigiously as the other 'hard' science disciplines, such as physics and chemistry (Dawson & Carson, 2013). Similarly, Earth science has received little attention in conceptual change literature compared to the physics and chemistry disciplines, where research of this nature originated. Like these disciplines, however, Earth science deals with abstract and unobservable concepts and processes that students hold many alternative conceptions about. The construct of geological time, for instance, is particularly difficult for individuals to comprehend (Dodick & Orion, 2003). The design of instructional approaches that facilitate accurate conceptions of geological phenomena, therefore, is a broad avenue for future research.

In this review, the instructional approaches where conceptual change appeared to be most profound were those that required the physical construction of multiple representations (Nielsen & Hoban, 2015; Shen & Confrey, 2007). In these instances, there were many opportunities for participants to consider and revise their alternative conceptions. This finding supports an emerging way of thinking in science education research. Researchers have suggested that 'representational negotiation' should be a significant focus in the science classroom (Klein, 2006; Tytler & Prain, 2010). That is, students should have many opportunities to 'integrate, refine, and translate ideas across representations' (Tytler & Prain, 2010, p. 2074). While this is not an entirely new idea and has been researched in other science disciplines such as chemistry, instructional approaches that

emphasize opportunities to construct multiple representations of Earth science phenomena are almost non-existent. The use of student-generated animation such as slowmation, however, is one example of how this gap in the research is being addressed.

There is a paucity of research on the learning potential of student-generated animations, making it a valuable avenue for future research, particularly from a conceptual change perspective. A number of studies have noted the educational value of students creating animations in chemistry (Chang et al., 2010; Schank & Kozma, 2002; Stieff & Wilensky, 2003; Wilder & Brinkerhoff, 2007; Wu, Krajcik, & Soloway, 2001), while another has examined the learning potential of creating animations in mathematics (Hubscher-Younger & Narayanan, 2007). In these studies, the use of specially designed software packages increased students' conceptual understanding. For example, Year 7 students who used *Chemation*™ software to generate and explain an animation of a chemical reaction had significantly higher post-test scores than students who viewed and explained a teacher-generated animation (Chang et al., 2010). Other specially designed software (*ChemSense*™, *Connected Chemistry*™, *Chemscape Chime*™ and *eChem*™) has also yielded positive learning outcomes when students created their own animation (Schank & Kozma, 2002; Stieff & Wilensky, 2003; Wilder & Brinkerhoff, 2007; Wu et al., 2001).

Student-generated animation that does not require special software, such as slowmation, has been researched to a lesser extent. Research on slowmation outside of the Earth and space science disciplines has been situated in pre-service teacher education contexts. Studies have found that slowmation is highly effective in supporting science pre-service teachers to identify and change their own alternative conceptions of science concepts or processes (Hoban, Loughran, & Nielsen, 2011; Hoban & Nielsen, 2012; Nielsen & Hoban, 2015). An approach such as this, where students are creating multiple representations of science phenomena, appears to be well aligned with contemporary perspectives of learning in science and at the cutting edge of conceptual change research in this discipline.

The need for research that employs qualitative data collection throughout the implementation of the instructional approach. Although each study had a unique methodological approach to determine the effectiveness of an intervention, most data were generated pre- and post-intervention only. While this provides a broad insight into the effectiveness of an instructional approach, a fine-grained analysis on the causal mechanisms of conceptual change is not possible. For example, many interventions discussed in this review were carried out in a group setting. Much of the conceptual change that was taking place, then, was embedded within a broader social context. The socially driven knowledge reconstruction, probably occurring from dialogue, scientific reasoning, and argumentation between participants or between participants and the teacher, could have provided valuable information about how an intervention influenced conceptual change.

Three studies that adopted this approach were able to provide a more robust evaluation of the effectiveness of an instructional approach (Gazit et al., 2005; Nielsen & Hoban, 2015; Shen & Confrey, 2007). These studies also aligned better with contemporary views on cognitive science, such as the view that learning should support collective knowledge construction (Klein, 2006). By capturing students' real-time conceptual change, the researchers were able to very specifically determine how the instructional approach influenced participants' conceptual change. This is in stark contrast to the studies that could only identify that conceptual change increased from pre- to post-intervention and then

speculate why this had occurred. Future research that employs qualitative data collection throughout instruction (e.g. audio- or video-recording) will significantly contribute to the conceptual change research in the Earth and space sciences and the conceptual change field more broadly.

Concluding remarks

This review has examined the existing body of research that explores instructional approaches designed to facilitate accurate conceptions of astronomical and geological phenomena. Overall, it appears that instructional interventions over the past three decades have moved from the natural observation of phenomena and the use of physical models to the use of computer simulations as technological advancement and access to technology have increased. Although the development of instructional approaches has progressed, there have been limited theoretical and methodological progressions during this transition.

The first author's ongoing research informed by this review now seeks to investigate the use of slowmation to promote junior secondary science students' scientific conceptions of plate tectonics. During the process of creating a slowmation, students will manipulate a range of materials to produce and narrate an animation that explains the processes that occur at tectonic plate boundaries. The researcher aims to determine: (1) whether the process of creating a slowmation has a significant effect on students' conceptual change; (2) how the process of creating a slowmation influences students' conceptual change; and (3) to what extent students' interest, generated by creating a slowmation, influences their conceptual change. As such, the research will respond to the theoretical and methodological concerns raised in the current review by challenging classical cognition-only views of knowledge reconstruction, extending conceptual change research in Earth and space science education, specifically of geological phenomena, and contributing to research that investigates the value of constructing multiple representations of a phenomenon through student-generated animation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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