

International Journal of Science Education

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tsed20

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To cite this article: Zeynep Koyunlu Ünlü & İlbilge Dökme (2022): A systematic review of 5E model in science education: proposing a skill-based STEM instructional model within the 21-st century skills, International Journal of Science Education, DOI: 10.1080/09500693.2022.2114031

To link to this article: https://doi.org/10.1080/09500693.2022.2114031

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INTERNATIONAL JOURNAL OF SCIENCE EDUCATION
https://doi.org/10.1080/09500693.2022.2114031

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A systematic review of 5E model in science education: proposing a skill-based STEM instructional model within the 21-st century skills

Zeynep Koyunlu Ünlü [a] and İlbilge Dökme [b]

[a]Yozgat Bozok University, Faculty of Education, Primary School Department, Yozgat, Turkey; [b]Gazi University, Gazi Faculty of Education, Science Education Department, Ankara, Turkey

ABSTRACT

The first purpose of this systematic review is to describe how empirical studies on the applications of the 5E instructional model are distributed according to certain variables. The second purpose is to determine how the 5E model has shown a trend in empirical studies in the transition from inquiry-based teaching to STEM education over the years within the scope of learning outcomes of the 5E model. A total of 74 empirical articles out of the 201 obtained from the initial search with the keyword '5E model' in the Web of Science (WoS) and Education Resources Information Center (ERIC) databases were subjected to descriptive and content analysis. The outstanding conclusion from the synthesis of these empirical studies in which the 5E model was implemented is that the 5E model, which has had a broad impact for a long time, focused on its effects on sublevel thinking levels of Bloom's taxonomy (knowledge, understand), and its effects on higher-order thinking levels, which have a crucial place in science education, are overshadowed. Based on these results, a 'skill-based STEM instructional model' with an activity set prepared by the model has been proposed in this study concerning 21-st century skills based on the 5E model.

ARTICLE HISTORY
Received 17 January 2022
Accepted 13 August 2022

KEYWORDS
5E model; systematic review; skill-based STEM instructional model; 21-st century skills

Introduction

Before the turn of the twentieth century, science education was primarily content-oriented and based on transferring science-related concepts and principles from teacher to student. The science topics to be taught had turned into a train of knowledge headed into students' minds. However, the knowledge boom in natural sciences led to inquiry learning as a learning approach in science education that focuses on learning processes rather than science content (Barrow, 2006). In other words, there has been a shift from instructional approaches rooted in behavioural theories to first cognitive and then constructivist teaching approaches and models (Cooper, 1993). The science inquiry approach that emerged in this context adopted the motto 'Let us teach students the process of knowledge discovery rather than knowledge itself' and resulted in a reduction

CONTACT Zeynep Koyunlu Ünlü zeynepko.unlu@yobu.edu.tr
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Supplemental data for this article can be accessed online at https://doi.org/10.1080/09500693.2022.2114031
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in content knowledge in the curriculum with an emphasis on learning processes. The most important contribution of this approach to science education is that it reveals that scientific thinking skills can be taught to students at an early age and can be developed over time (Zimmerman, 2000). In recent years, however, there has been a shift in the literature to inquiry approaches updated with STEM education (Cairns & Areepattamannil, 2019; International Technology and Engineering Educators Association [ITEEA], 2009). In the context of STEM education, the motto 'knowing is not enough; we must apply' has frequently appeared in relation to classroom pedagogy. As the motto suggests, knowledge is just the beginning of a quality learning experience. If we want to actually learn, we must apply the knowledge we have. In STEM education, knowledge in science has been enriched by including mathematics and technology, and the pinnacle of cognition is represented by an engineering product (National Science Board [NSB], 2008). STEM education allows students to transform knowledge into a product by effectively using their higher-order thinking skills (scientific process skills, scientific reasoning skills, and critical thinking skills) ([Next Generation Science Standards NGSS], 2013; Özkul & Özden, 2020).

The 5E model, which was developed based on the science inquiry approach by the Biological Sciences Curriculum Study (BSCS) in 1987, is the most widely used model in the long-term process (Bybee, 1997) in both inquiry approach and STEM education. Since its development, a huge body of empirical study on the 5E model has revealed the positive effects of the 5E model on the learning outcomes from conceptual change to higher-order thinking levels (e.g. Artun & Coştu, 2013; Gökalp & Adem, 2020; Suwito et al., 2020; Taşlıdere, 2015). 5E model consists of five stages: engage, explore, explain, elaborate, and evaluate (Table 1). Effective completion of the phases in Table 1 provides a coherent instruction to the learner for a better understanding of scientific knowledge, attitude, and skills within an excellent progression of cognition (Garcia et al., 2021). The 'engage' phase includes activities to arouse curiosity about the new subject that students will learn based on their prior knowledge. During exploration and explanation activities, students are expected to discover knowledge, and they are expected to do so by using scientific process skills. These phases are very important for cognition at the understanding, application, and analysis levels of Bloom's taxonomy, although they are not separated by sharp boundaries. In the elaboration and evaluation stages of 5E, students are expected to use higher-order thinking skills (Bybee, 1997) because these stages are very precious for Bloom's cognitive levels of evaluating and creating. These last two phases of the 5E model are of critical importance, especially in the engineering dimension of STEM education, in other words, in the realisation of the motto 'knowing is not enough, we must apply'.

Has the conversion of the long-existing inquiry-based approach to STEM education led to an update to the popular 5E teaching model? This question was the main driving force for this systematic review study. Therefore, the main research questions in this systematic review were determined as follows:

(RQ1) How are empirical studies on the applications of the 5E instructional model distributed by year, methodology, participant grade level, subject area, learning environment, effects on learning outcomes, and relevance to STEM education?

(RQ2) How did the 5E instructional model used in empirical studies transform over the years? What are the trends in 5E instructional model applications?

Table 1. The phases of the 5E model (from Bybee et al., 2006, p. 2) and associated skills.

Phase	Summary	Associated skills and Bloom Taxonomy	
Engagement	'The teacher or a curriculum task accesses the learners' prior knowledge and helps them become engaged in a new concept through the use of short activities that promote curiosity and elicit prior knowledge. The activity should make connections between past and present learning experiences, expose prior conceptions, and organise students' thinking toward the learning outcomes of current activities.'	Remembering or recall	Knowledge
Exploration	'Exploration experiences provide students with a common base of activities within which current concepts (i.e. misconceptions), processes, and skills are identified and conceptual change is facilitated. Learners may complete lab activities that help them use prior knowledge to generate new ideas, explore questions and possibilities, and design and conduct a preliminary investigation.'	Scientific process skills (observing, inferring, measuring, communicating, classifying, predicting, controlling variables, defining operationally, formulating hypotheses, collecting data, recording data, interpreting data, experimenting, and formulating models)	Understand Apply Analyze
Explanation	'The explanation phase focuses students' attention on a particular aspect of their engagement and exploration experiences and provides opportunities to demonstrate their conceptual understanding, process skills, or behaviours. This phase also provides opportunities for teachers to directly introduce a concept, process, or skill. Learners explain their understanding of the concept. An explanation from the teacher or the curriculum may guide them toward a deeper understanding, which is a critical part of this phase.'		
Elaboration	'Teachers challenge and extend students' conceptual understanding and skills. Through new experiences, the students develop deeper and broader understanding, more information, and adequate skills. Students apply their understanding of the concept by conducting additional activities.'	Higher-order thinking skills (reasoning, critical, and creative thinking)	Evaluate Create
Evaluation	'The evaluation phase encourages students to assess their understanding and abilities and provides opportunities for teachers to evaluate student progress toward achieving the educational objectives.'		

(RQ3) Which thinking skills/higher-order thinking skills has the 5E instructional model developed among students in applications in empirical research?

In this systematic review of research related to empirical studies using the 5E model, the results obtained from analyzing the content of the collected literature in more depth are focused especially on the learning outcomes of the teaching carried out with the 5E model (thinking skills/higher-order thinking skills). Therefore, under the next heading, the skills in science education related to these learning outcomes are detailed.

Skills in science education

In instructional methods based on expository strategies, skills training is highly limited because courses based on these methods are taught deductively by moving from the general to the specific. However, instructional methods based on instructional strategies of discovery and science inquiry allow skills to be used and improved in classes. In inquiry-based instructional strategies, students learn by discovery. Such scientific instructional strategies can only be materialised through scientific thought, which includes many mental and menial skills ranging from simple to complex. Among them, scientific process skills are observing, inferring, measuring, communicating, classifying, predicting, controlling variables, defining operationally, formulating hypotheses, collecting data, recording data, interpreting data, experimenting, and formulating models (National Research Council [NRC], 1996).

Students with *observation skills* collect data from matter and events in science activities by using the five senses (Harlen, 1999; Rezba et al., 2003). In the discovery phase of the 5E model based on inquiry-based learning, students observe an object as if they are looking at it for the first time in their lives, as if they are on a nature walk and observe an interesting unfamiliar object among the bushes. They first observe the object with sight. They then, theoretically, want to touch it once they determine it is harmless. Later on, they engage other senses and want to detect the smell, want to shake it to see if it makes a sound, and may even want to taste it if they have enough evidence that it is safe to do so. *Classification* is a mental process that starts at the concrete operations stage of Piaget's cognitive development theory, between the ages of 7–11 (Piaget, 1965). Existence is based on multitude and diversity, rather than uniformity and uniqueness. This concept activates the skill of classification in the human mind. For example, if you give a child a single red ball (uniqueness), you cannot activate classification in the child's mind. Similarly, if you give him six similar red balls (uniformity) there is once again no need for classification. However, if you give him four green and two red similar balls, the child will classify and group them based on their colours. Similar to the folders in a computer's memory, the human mind also groups objects and events based on certain characteristics and stores them in different mental folders. Developing this skill early enables students to classify with more complex and systematic methods in future years. During science activities, students can classify events and objects based on their observations, measurement results, and experiment findings (NSTA, 2002). Students with *measuring* skills can measure the lengths of a geometric object by using a ruler and calculate its volume or surface area. With a non-geometric object, they can measure its volume by using containers and can express the result in appropriate units. Similarly, such students can measure the mass of objects by using a scale, their weight by using a dynamometer, the temperature by using a thermometer, the time by using a chronometer or watch, and distances by using a length gauge. This skill develops with experiences gained in the exploration activities in early childhood science classes (AAAS, 1993). Formulating questions in certain stages of the exploration activities helps students develop skills of *inferring* and *predicting* (Rezba et al., 2003). For example, 'What happens if you place the egg in a bucket of water? Does it float or sink? Guess before you try it (predicting). Then place the egg in the water and observe. Compare your observations with your guess. What were the reasons for your observations (inference)?'

Students with *interpreting data skills* use different methods in science activities to collect data and record them in writing. When necessary, they interpret the data by putting them in graphs, tables, diagrams, and reach the result (Rezba et al., 2003). At a basic level, students can collect data from observation and measurement results. At more advanced levels, they can identify variables from a hypothesis they have written, can control some of these variables, and conduct experiments. During the experiments, they obtain data from measurements and observations. Students with s*cientific communication skills* can verbally present their research; enrich their written presentations with graphs, tables, diagrams, symbols, mathematical equations, and other visuals, and use computer technologies for their presentations (Rezba et al., 2003). Students with o*perational definition skills* define scientific concepts and principles in their research by using scientific terminology. Students can *create models* to explain certain micro or macro events (Anderson, 2002).

According to Piaget's cognitive development theory, children can move into the formal operational stage from the concrete operational stage after the age of 11 (Piaget, 1970). This stage indicates that individuals have reached the maturity to perceive abstract concepts and to carry out more complex mental activities. Every child with normal mental development catches the path from concrete to abstract after the age of 11. As if there is a gateway opened to the abstract world, and behind this gateway, there is a path from sensations to perceptions, from perceptions to concepts, from concepts to judgments. The reasoning skills that students can learn and improve are determining and controlling variables by hypothetical', 'probabilistic thinking', 'combinational thinking', 'relational thinking', and 'proportional thinking' (Lawson, 2009). How can such thinking occur in secondary school students' minds? We can look for the answer to this question with an example.. Let us imagine students trying to solve the problem 'How to increase the brightness of a lightbulb?' in a simple electrical circuit made of batteries, battery bed, lightbulb, key, and connection cables. If students foresee that 'When more batteries are used, the brightness of the bulb will increase', they have taken the first step towards hypothetical thinking. Students capable of probabilistic thinking consider the probabilities of both of the following hypotheses: 'When more batteries are used, the brightness of the bulb may increase' and 'When more batteries are used, the brightness of the bulb may decrease'. Combinational thinking allows students to foresee all components that may act as a response to the problem as hypotheses. Students then design experiments to test all their hypotheses. In these experiments, they use the skill of ***identifying and controlling variables*** to see the effect of an independent variable on the dependent variable, but while doing so, they keep all other variables under control. After completing the experiments, they conclude. In the meantime, they obtain results such as 'As the number of batteries increases, the brightness of the bulb also increases' or 'The number of batteries increases in direct proportion to the brightness of the bulb' by using relational thinking and proportional thinking skills. Scientific reasoning skills are largely examined under the umbrella term 'critical thinking' (Dewey, 1933). In its most general sense, critical thinking refers to an individual not accepting a piece of information as it is, but filtering it through their cognitive processes and evaluating it based on certain criteria (Bailin et al. 1999) As a result of the developments in science and technology, critical thinking has become an important characteristic that twenty-first century people should have. In part, critical thinking increases an

individual's knowledge by enabling them to look at an event from different angles. Critical thinking includes analysis, synthesis, evaluation, application, idea generation and expression, and problem solving skills (Scriven & Paul 1987; Dewey, 1933). According to Dewey (1933), the way to make students think critically in science lessons is to drag them into a problem. Students form hypotheses to solve the problem and engage in mental pursuits by using their reasoning skills to test the hypotheses. They try to solve the problem by interpreting the data they collect in an unbiased and deterministic way.

Through these mental pursuits, students can use their *analysis skills* (Paul, 1981) and identify the relationship between whole events, phenomena, concepts, and their parts, and also see the relationships among the parts. Using *synthesis skills* (Ennis, 1987), they can integrate principles, concepts, and theories related to a topic and create a new and original product or idea. With *evaluation skills*, they can evaluate information to make a judgment using certain criteria (Paul, 1981). *Application skills* within the scope of critical thinking require students to solve problems by using the concepts, principles, and ideas they have learned, while *idea generation skills* require them to create original ideas in response to a problem. All the above-mentioned skills are intertwined with creative thinking and innovative application skills, which are because according to cognitive development theorists, creativity and innovative application skills may be defined as rationalism in the organisation of information, flexibility in problem solving, and originality in the end product (Runco & Chand, 1995). In this sense, STEM education, which uses scientific process, reasoning, and critical thinking skills, is crucial to fully integrate individuals into society who are equipped with twenty-first century skills. Figure 1 shows how the scientific process, reasoning and critical thinking skills, and twenty-first century skills intersect and complement each other.

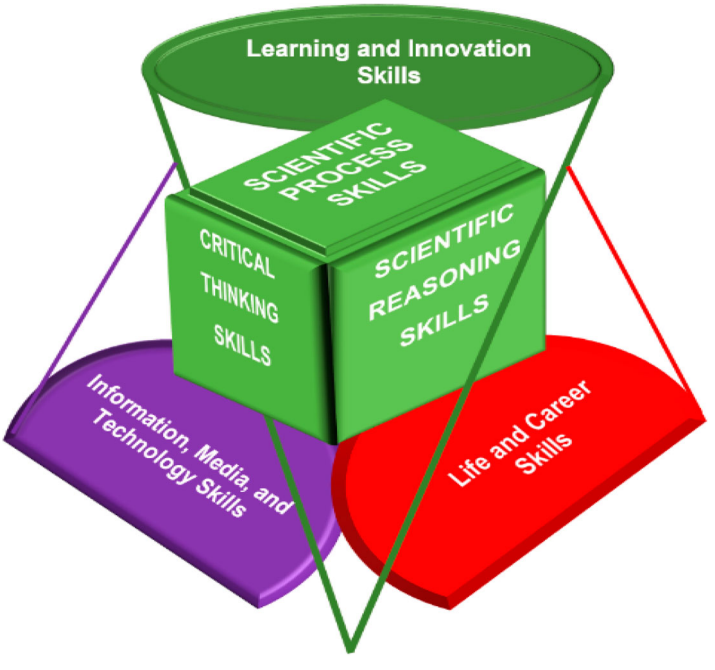

Figure 1. The place of science education skills among twenty-first century skills.

In our rapidly changing and transforming world, individuals equipped with twenty-first century skills are seen as a requirement by business leaders, governmental institutions and academic circles. The Partnership for 21-st Century Learning (2017) education project, which is implemented and supported by various institutions in many states in the USA, defines the twenty-first century skills that an individual should have as follows:

> *Learning and Innovation Skills:* Critical thinking and problem-solving skills, creativity and innovation skills, communication and collaboration skills.
>
> *Information, Media, and Technology Skills:* Information literacy, media literacy, and ICT literacy
>
> *Life and Career Skills:* Flexibility and adaptation, initiative and self-direction, social and cross-cultural interaction, productivity and accountability, leadership and responsibility.

Methods

In this study, the aim was to determine the trends in empirical studies in which the 5E model was used and to reach a general overview. A total of 74 articles were included in the analyses. The method used in the study was a systematic review that consists of three stages: search, selection, and synthesis (Galvan & Galvan, 2017). In the search stage, articles on the 5E model were searched in the relevant databases. In the selection stage, empirical articles on the 5E model is included in the analysis. In the synthesis stage, the articles were analyzed according to the criteria specified in Figure 2 and a new model (STEM-SBM) was created based on the analysis results. The stages of the research are described in more detail below.

Stage 1: search

In this systematic review study, the Web of Science (WoS) and Education Resources Information Center (ERIC) databases were used. In both databases, data for the initial search were obtained using the keyword '5E model'. The 'Document Types' criterion was refined for articles in the WoS search and 809 articles were found. The 'WoS categories' was then limited to 'Education educational research' and a total of 80 articles were reached. In ERIC, the search was limited to articles alone, and 136 articles were found. The distribution of articles into article sources was examined in both databases and intersecting journals in the two were determined. The titles of the intersecting journals in ERIC and WoS databases and the number of articles found in these journals can be seen in Table 2.

Stage 2: selection

First, the full texts of 22 articles in intersecting journals in the two databases were put into a folder called 'intersecting'. The database that found the most articles were taken into account when filing the articles in the database (Table 2). Then in the WoS database, intersecting journals were excluded and the full texts of the remaining 59 articles were collected in a folder named 'non-intersecting WoS'. In the ERIC database too, the full

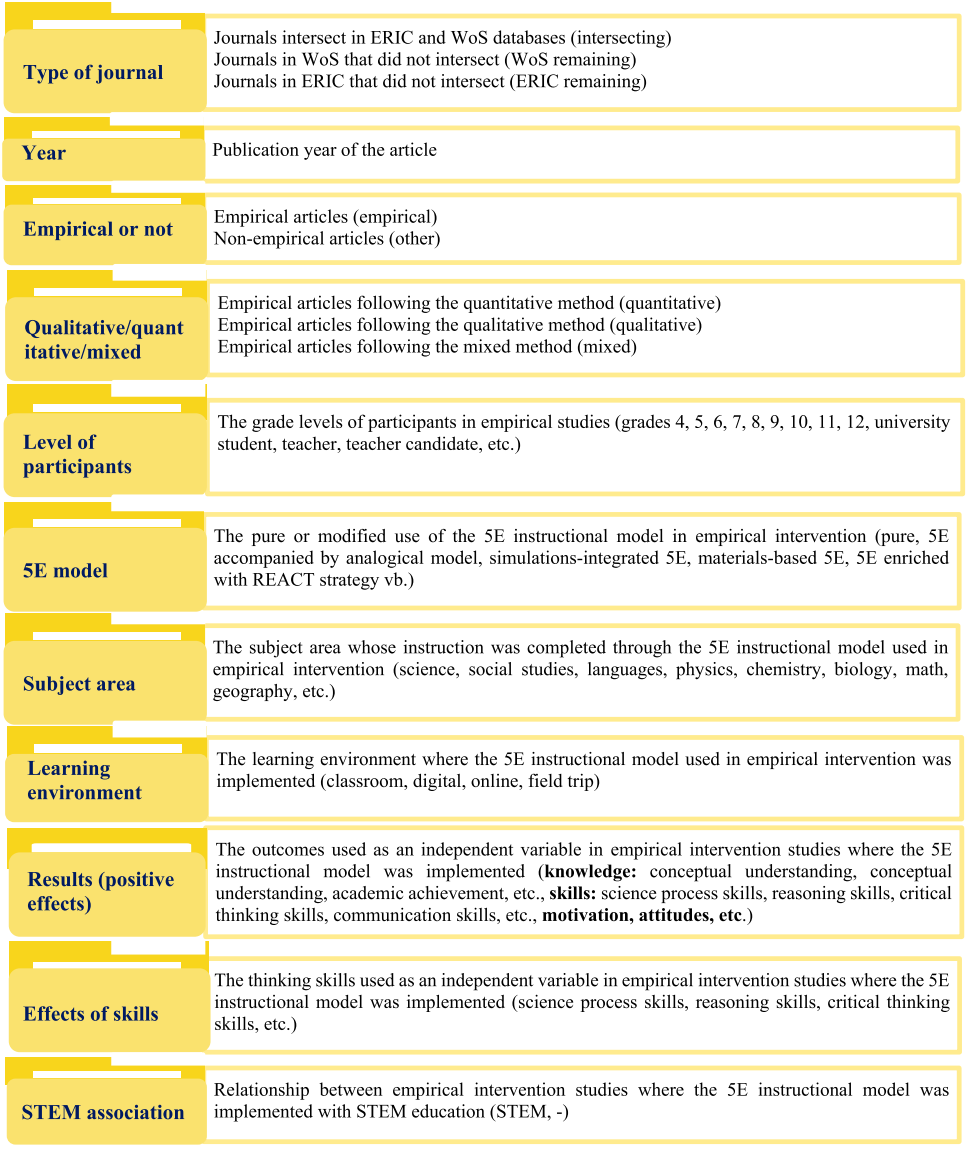

Figure 2. Initial review criteria for articles and their explanations (statements in parentheses show the codes in Excel).

texts of a total of 120 articles in journals other than intersecting ones were collected in the 'non-intersecting ERIC' folder. The number of these articles filed for initial review and the names of the folders are given in Table 3.

A total of 201 articles collected in three folders were initially reviewed by two authors and empirical ones were selected. It was determined that 14 out of 22 articles in the 'Intersecting' folder, 28 out of 59 articles in the 'Non-Intersecting WoS' folder, and 32 out of 120 articles in the 'Non-Intersecting ERIC' file were empirical. These empirical articles were examined in more detail and saved in an Excel file according to the specified review criteria (Figure 2). Within the scope of the research, articles on

Table 2. Intersecting journals in ERIC and WoS and the number of articles found in these journals.

Intersecting journals in ERIC and WoS	Number of articles in ERIC	Number of articles in WoS	Number of filed articles
American Biology Teacher	3	2	3
EURASIA Journal of Mathematics, Science & Technology Education	3	5	5
Journal of Science Education and Technology	3	4	4
Science Activities: Projects and Curriculum Ideas in STEM Classrooms	3	4	4
Education Sciences	2	3	3
International Journal of Science Education	2	3	3
Total	**16**	**21**	**22**

document analysis, descriptive research, activity, meta-analysis, lesson plan preparation and the 5E model in which no application was made were not selected for analysis and were excluded. The inclusion criteria is an empirical article on the 5E model. Hereby, a synthesis of 74 empirical articles about the 5E model was made (Appendix-1).

Stage 3: synthesis

The first column in the Excel file is 'folder name' and the later columns show examination criteria. The names, explanations and codes of the criteria written in the Excel column are shown in Figure 2. The empirical articles were examined in detail with these criteria for content analysis. Among the review criteria, there are type of journal, year, empirical or not, method, participants and subject area which are available in many systematic review studies and provide a general idea to the reader. Specific to this research, how 5E model is used, what it affects in terms of knowledge, skills and emotional (results of the research), and the status of being associated with STEM were analyzed in selected articles. During the analysis process, the researchers studied together and reached a consensus. The results are given in the findings section.

Results and discussion

Descriptive analysis of empirical intervention studies where the 5E instructional model was implemented

This systematic review study includes articles published from 2007 onwards describing empirical studies where the 5E model was used. The cutoff date for the later studies was January 2021. The distribution of these empirical studies using the 5E model by years can be seen in Figure 3.

Table 3. Filing of journals from initial search in WoS and ERIC databases with respect to intersections.

Name of folders where full texts were collected	Number of articles	Explanation
Intersecting	22	Total number of articles in intersecting journals in ERIC and WoS databases
Non-intersecting WoS	59	Total number of articles in non-intersecting journals in WoS database
Non-intersecting ERIC	120	Total number of articles in non-intersecting journals in ERIC database
201 (Total number of articles filed for initial review)		

As shown in Figure 3, empirical research on the 5E model started to increase after 2013. Even though the increase since that time has not been steady, it can be observed that empirical studies on the 5E model have become more popular since 2013. This finding shows that empirical studies on the 5E model are still trending, as the total number of articles published in 2021 was not included in our data set. In other words, the 5E model, which falls under inquiry-based learning, is still viewed as an important issue by researchers. The distribution of mixed, qualitative, and quantitative methods used in the articles is shown in Figure 4. The most popular method in the articles was the quantitative method, followed by mixed and qualitative methods, respectively.

The research participants in the 74 articles included students at various stages of education, teachers, and teacher candidates (see Figure 5). The distribution of participants covers almost all the stages of education, with a small number of total studies in elementary school and the highest number in secondary school. No empirical studies were found on the 5E model at the preschool level. This finding suggests that the 5E model is not suited for preschool participants, as the 3E model developed by Atkin and Karplus (1962) is thought to be more suitable for preschool and elementary school levels. Based on Piaget's mental operation processes, the 3E model consists of exploration, explanation (concept development), and expansion stages.

The majority of the studies carried out were in the field of science. In addition, there were empirical studies in which the 5E model was implemented in fields such as Turkish, English, STEM, and teacher education (Figure 6). The reason why most of the studies were done in the field of science is the suitability of the 5E model to science subjects. Furthermore, as science topics are related to daily life, they can be used in the entrance stage of 5E to make connections with students' lives to raise their motivation. Integrating science subjects with practice, experiment and activity constitutes the exploration stage of the model. The empirical structure of knowledge in science and the different dimensions of science subjects are ideal for the elaborate stages of the 5E model. In addition, the possible integration of alternative measurement and evaluation techniques with science education contributes to the formation of the evaluation stage. As noted earlier, the popularity of the 5E model in science education encouraged its use in other fields, too.

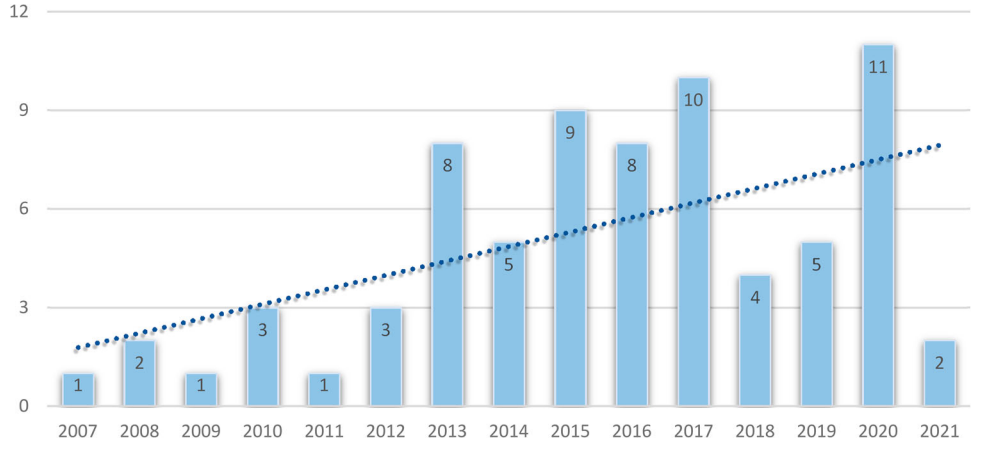

Figure 3. Number of studies using the 5E model from 2007 through January of 2021.

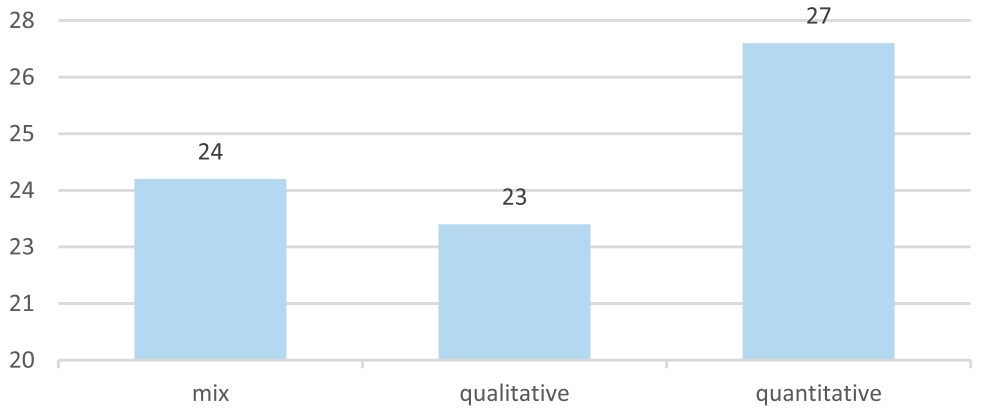

Figure 4. The distribution of research methods in empirical studies on the 5E model.

Indeed, there have recently been studies in the fields of social sciences (Suwito et al., 2020), Turkish (Özcan & Kırbaşoğlu Kılıç, 2017), English (Chen, 2021), STEM (Conradty et al., 2020; Güven et al., 2020) and math (Althauser, 2018; Kalantarnia et al., 2020; Turan & Matteson, 2021).

The environments in which the 5E model was implemented in the reviewed studies were categorised under the following headings:

(a) Classroom/laboratory: Studies where certain stages of the 5E model are implemented in the classroom while others are implemented in a lab environment.

(b) Computer: Studies in which certain stages or all of the 5E model are assisted by computer animations, simulations, videos, etc.

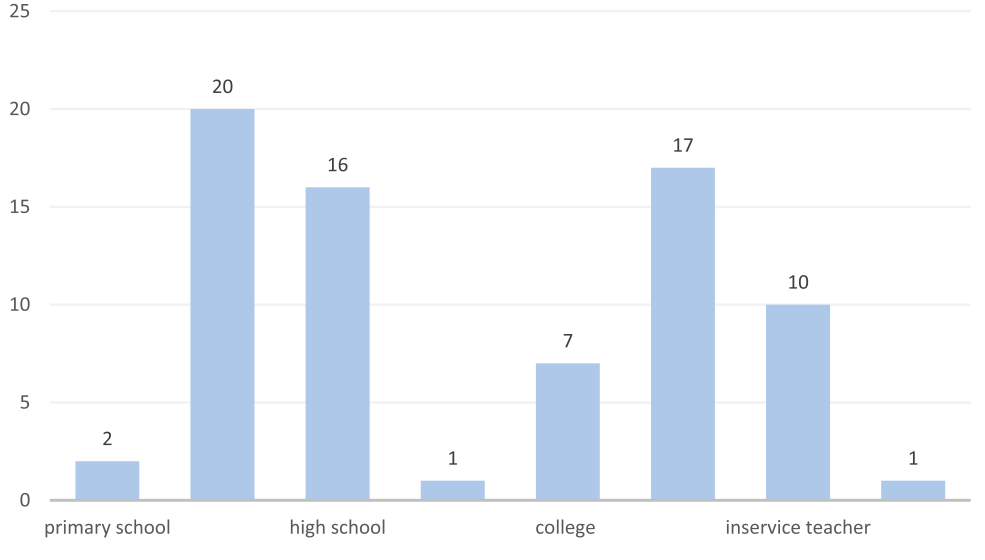

Figure 5. The distribution of the participants in empirical studies on the 5E model based on educational background.

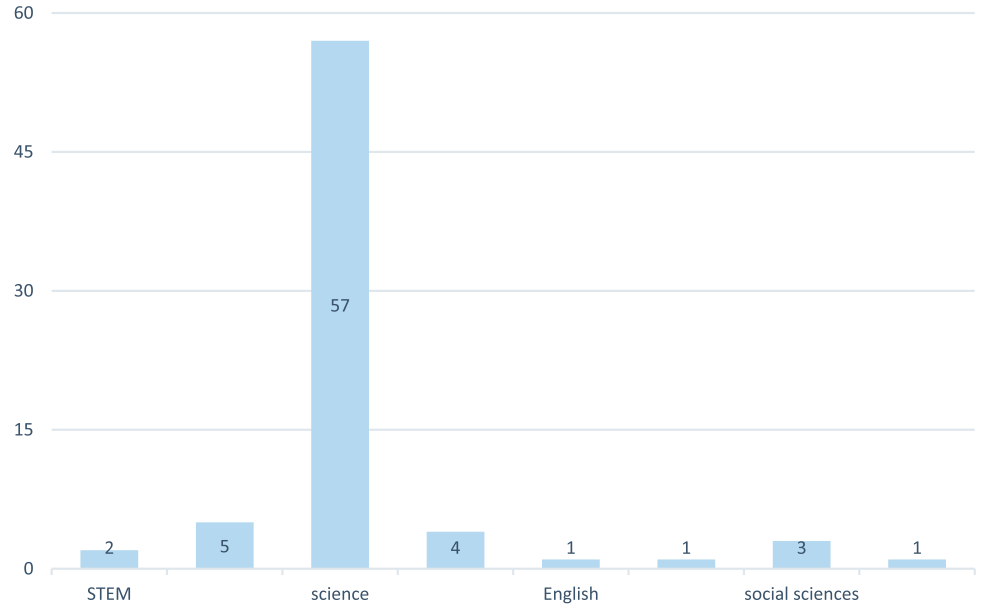

Figure 6. The distribution of empirical studies on the 5E model by subject area.

(c) Field trip: Studies where certain stages of the 5E model are implemented in out-of-school learning environments.

(d) Classroom/laboratory + computer: (a) and (b)
(e) Classroom/laboratory + computer + field trip: (a), (b) and (c)

The frequencies of the environments in which the 5E model is applied presented in Figure 7 show that it is possible to implement the model in different environments.

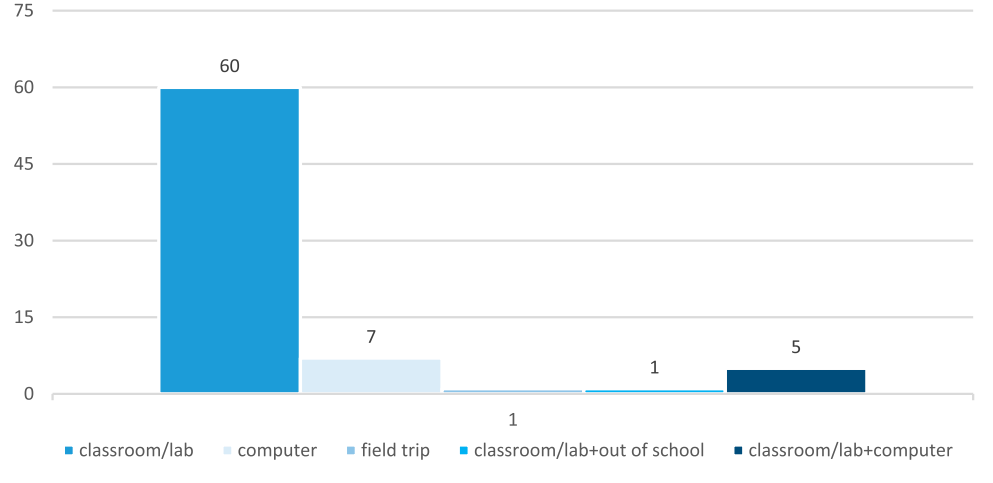

Figure 7. Environments where empirical studies on the 5E model were implemented.

Trends in 5E instructional model implementation

Here, the findings of the 74 empirical studies in which the 5E model was implemented are presented. In these empirical studies, the 5E model was most often used purely by itself following the steps without additional processes in 47 studies. On the other hand, in 27 studies, the model was enriched by using in combination with various processes. As shown in the first column of Table 4, these enrichments were categorised into three types. The first includes studies into which various simulations and animations were integrated at certain stages of the 5E model (n = 10). The second includes studies where the stages of the 5E instructional model were enriched with STEM applications (n = 3). Finally, the third category includes studies in which the 5E instructional model in the other category was enriched with in-class application processes (n = 13).

In 64% of the empirical studies, the 5E instructional model was used pure. This was the case for recent studies as well (Bezen & Bayrak, 2020a; Bezen & Bayrak, 2020b; Chaudhuri et al., 2019; Gillies & Rafter, 2020; Kalantarnia et al., 2020; Lara-Alecio et al., 2018; Namdar & Küçük, 2018; Suwito et al., 2020; Parsons et al., 2019; Ramlee et al., 2019; Şengül, 2020; Turan, & Matteson, 2021). Considering its effects on learning outcomes, this finding shows that the 5E model is a powerful instructional cycle even when used on its own. The remaining 36% of empirical studies, in which the 5E instructional model was combined with different processes, reveal the structure of the model that can be enriched with different processes. The 5E instructional model includes

Table 4. 5E model implementation styles.

Model	Source
Unenhanced 5E	Akerson et al., 2009; Akbulut et al., 2012; Althauser, 2018; Arslan et al., 2015; Artun & Coştu, 2013; Aydın & Yılmaz, 2010; Ayvacı et al., 2015; Bang, 2013; Bezen & Bayrak, 2020a; Bezen & Bayrak, 2020b; Bilgin et al., 2013; Ceylan & Geban, 2009; Chaudhuri et al., 2019; Chen, 2011; Çardak et al., 2008; Çetin-Dindar & Geban, 2017; Er Nas et al., 2012; Gillies & Rafter, 2020; Güzel, 2016; Hırça, 2015; Hu et al., 2017; Kalantarnia et al., 2020; Kim, 2016; Lara-Alecio et al., 2018; Lin et al., 2014; Manzo et al., 2016; Namdar & Küçük, 2018; Parveen, 2017; Parsons et al., 2019; Ramlee et al., 2019; Scott et al., 2014; Sickel et al., 2013; Supasorn, 2015; Suwito et al., 2020; Song & Schwenz, 2013; Svendsen, 2015; Şahin et al., 2017; Şengül, 2020; Taylor et al., 2007; Tezer & Cumhur, 2017; Turan & Matteson, 2021; Torun & Tekdere, 2015; Tortop & Özek, 2013; Walker, et al., 2008; Wilson et al., 2010; Uzunöz, 2011; Zhao, et al., 2012
STEM applications	Büyükdede & Tanel, 2019; Conradty et al., 2020; Güven et al., 2020
Computer and internet applications (simulation and animations)	Güzel, 2017; Cheng et al., 2016; Çepni et al., 2010; Daşdemir, 2016; Hırça, 2013; Koyunlu Ünlü & Dökme, 2020; Namgyel & Bauraphan, 2017; Özcan & Kırbaşoğlu Kılıç, 2017; Taşlıdere, 2015; Sezginsoy et al., 2017
Other	*5E supported context based/life based context*: Aydın Ceran & Ateş, 2019; Çiğdemoğlu & Geban, 2015 *5E learning model accompanied by analogical model*: Devecioglu-Kaymakcı, 2016 *5E + I/A inquiry model*: Zuiker & Whitaker, 2014 *5E enriched with REACT strategy*: Gökalp & Adem, 2020 *Materials based* 5E: Tural et al., 2010 *5E with flipped model:* Jensen et al., 2015 *Argumentation to the 5E model:* Chen et al., 2018 *5E with 3D role-playing game*: Chen et al., 2014 *5E incorporated scientific practices:* Şengül & Schwartz, 2020 *Guidance material based 5E*: Şenel Çoruhlu, 2017 *Experiencing 5E inquiry model*: Mustafa, 2016 *Extended worksheet developed 5E model*: Töman et al., 2013

steps that will enable effective learning through research. This multi-step structure makes it possible to integrate different processes into all, one or more of these steps. For example, when teaching the solar system, Devecioglu-Kaymakcı (2016) supported the 5E model with analogies in all stages of the model, including engage, explore, explanation, elaborate, and evaluate. Considering the enrichment of the 5E model, our findings show the most preferred process combined with 5E are animation and simulation used in certain stage(s) (Güzel, 2017; Hırça, 2013; Koyunlu Ünlü & Dökme, 2020; Taşlıdere, 2015). In some of the studies we reviewed, the 5E instructional model was combined with only one additional type of process (e.g. Chen et al., 2018), while in others it was combined with more than one process (Çepni et al., 2010; Namgyel & Bauraphan, 2017; Sezginsoy Şeker & Erdem, 2017). In empirical studies that fall under the category of others, it can be seen that the 5E instructional model was enriched with popular applications such as argumentation and REACT. However, the most striking finding was the limited number of empirical studies in which the 5E model was adapted to STEM education, a popular recent choice for science education (Büyükdede & Tanel, 2019; Conradty et al., 2020). For example, Conradty et al. (2020) integrated 'the potential role of art STEM module' with the 5E model to enhance creativity by designing activities to foster creativity which were implemented in the exploration stage. In another study (Büyükdede & Tanel, 2019), the effects of the 'STEM-based 5E model' on the success and views of teacher candidates were examined. In this experimental study, the topic 'work-energy' was taught using the 'STEM-based 5E model', and the mean achievement level of the experimental group was found to be higher than the control group. During the elaboration phase of the model, teacher candidates were asked to design a product related to the topic (Büyükdede & Tanel, 2019). As the 5E model was integrated into STEM education in these articles, the skeleton of the model was not structurally harmed, but some processes were added to certain stages.

Bybee (2019)'s non-empirical study entitled 'Using the BSCS 5E Instructional Model to Introduce STEM Disciplines' presented a STEM-integrated 5E Instructional Model. Unfortunately, no empirical studies using the 5E method and applying Bybee's (2019) model have been published after 2019. In Bybee (2019)'s STEM education including the stages of the 5E Instructional Model, Phase 1 is 'Introducing Students to Place-Based and Problem-Based Situations (Engage)'. This phase is an adaptation of the engage stage of the 5E model. The STEM unit begins with students being introduced to a problem situation. Phase 2 is named 'Exploring the STEM Disciplines (Explore)'. This stage requires the use of science, technology, engineering, and math to understand and solve the problem in Phase 1. In Phase 3, 'Explaining the STEM Disciplines', students are expected to advance their understanding of the STEM disciplines. Phase 4 is 'Applying the STEM Disciplines to the Problem Situation' is an adaptation of the elaboration stage in the 5E model. Examined carefully, teacher and student guidelines in Bybee (2019)'s model suggest that they can be influential in science classes.

The effects of the 5E instructional model

In the empirical studies reviewed, the 5E model as an instructional tool is the independent variable. The dependent variables in five categories which are affected by the 5E model are given in Table 5. Cognitive development theories (Piaget & Inhelder, 1969;

Sinnott, 1998) emphasise the importance of contextual variables in developmental change. Empirical studies that use the 5E model as an independent variable are supposed to add new skills to students' existing thinking modes and advance them cognitively. The cognitive effects of the 5E model in the articles reviewed were considered in two groups based on Bloom's taxonomy. Studies investigating the effects of the model only at the levels of knowledge and understanding were included in the 'pre-cognition effect' (n = 56). Studies that require certain thinking skills beyond knowledge and understand were included in the 'cognition effect' (n = 17). A noteworthy number of articles (n = 15) examining the effects of the 5E model on attitude were categorised under 'affective effect'. Curiosity and motivational effects that determine the direction of behaviour by organising cognitive, affective, and behavioural variables (n = 5) were placed in a separate group. Collaboration, communication, pedagogical effects, etc. were given in the category named 'others' (Table 5).

The most striking characteristic in Table 5 is that the 5E model had a high working frequency on pre-cognition effects (n = 56). In the 56 articles reviewed, measurements/observations were made about learning and exemplifying scientific concepts and the positive effects of the 5E model on cognition were revealed. Although 5E instructional applications can prompt students to use many cognitive skills, including the stages of 'application, analysis, synthesis, evaluation' in Bloom's taxonomy, the effects on these cognitive skills were studied only in approximately 23% of the empirical articles (n = 17). Even though this low rate may be surprising, these 17 articles were examined in more detail to identify the reasons for the determined low rate. In 12 of these articles, the 5E model was implemented without enrichment. In the remaining 5, the 5E model was enriched by adding only extra processes to certain stages. This finding reveals that there is no need for extra enrichment of the 5E model for cognitive learning beyond knowledge and comprehension. The enrichment made to the 5E model in these studies generally involved the integration of computer and internet technology applications into the stages of the model. For example, Cheng et al. (2016), used internet search instead of hands-on activities in the exploration phase in learning nanotechnology topics with the 5E model. In articles investigating the cognitive effect of the 5E model beyond knowledge and comprehension, no structural changes were made to the skeleton of the current 5E model. The low rate in this finding may be attributed to the measurement tool, because it is much easier to develop multiple-choice tests that measure development at the level of knowledge and comprehension than it is to develop tests that measure thinking skills at higher levels of Bloom's taxonomy. Moreover, basic scientific process skills such as 'observing, classifying, measuring, predicting and inferring' used in the exploration phase of the 5E model improve cognition with the coordinated use of both thinking and hand skills. The multiple choice tests used to measure these skills must be supported by performance assessment tools. To illustrate, 4 of the 5 articles that investigated the effects of the 5E model on scientific inquiry and scientific process skills (Devecioglu Kaymakcı, 2016; Hırça, 2015; Koyunlu Ünlü & Dökme, 2020; Song & Schwenz, 2013) evaluated the impact with qualitative measurement tools, while only one (Cheng et al., 2016) used a quantitative measurement tool. Studies which evaluated the effects of the 5E model on problem-solving skills beyond knowledge and comprehension via quantitative measurement tools generally came from the field of mathematics (Kalantarnia et al., 2020; Tezer & Cumhur, 2017). In two of the three studies investigating

Table 5. The effects of the 5E model on learning outcomes.

	Learning outcomes	Source
Pre-cognition effect	Achievement (in knowledge and comprehension dimension)-conceptual understanding-conceptual change	Akbulut et al., 2012; Akerson et al., 2009; Aydın Ceran & Ateş, 2019; Arslan et al., 2015; Artun & Coştu, 2013; Ayvacı &Yıldız, 2015; Bezen & Bayrak, 2020; Bilgin et al., 2013; Büyükdede & Tanel, 2019; Ceylan & Geban, 2009; Chaudhuri et al., 2019; Chen et al., 2014; Chen et al., 2018; Çardak et al., 2008; Çepni et al., 2010; Çetin-Dindar & Geban, 2017; Çiğdemoğlu & Geban, 2015; Conradty et al., 2020; Devecioglu-Kaymakcı, 2016; Daşdemir, 2016; Er Nas et al., 2012; Gillies & Rafter, 2020; Gökalp & Adem, 2020; Güzel, 2016; Güzel, 2017; Hırça, 2013; Jensen et al., 2015; Kalantarnia et al., 2020; Kim, 2016; Koyunlu Ünlü & Dökme, 2020; Lara-Alecio et al., 2018; Manzo et al., 2016; Mustafa, 2016; Namdar & Küçük, 2018; Namgyel & Bauraphan, 2017; Parveen, 2017; Parsons et al., 2019; Song & Schwenz, 2013; Supasorn, 2015; Scott et al., 2014; Suwito et al., 2020; Şahin et al., 2017; Şenel Çoruhlu, 2017; Şengül, 2020; Taylor et al., 2007; Töman et al., 2013; Walker, et al., 2008; Taşlıdere, 2015; Turan & Matteson, 2021; Tural et al., 2010; Tezer & Cumhur, 2017; Tortop & Özek, 2013; Withers, 2016; Wilson et al., 2010; Zhao, et al., 2012; Zuiker & Whitaker, 2014
Cogniton effect	Scientific inquiry skills, science process skills	Cheng et al., 2016; Devecioglu-Kaymakcı, 2016; Hırça, 2015; Koyunlu Ünlü & Dökme, 2020; Song & Schwenz, 2013
	Problem-solving skills	Kalantarnia et al., 2020; Tezer & Cumhur, 2017; Svendsen, 2015
	Higher-order thinking/cognitive skills	Aydın & Yılmaz, 2010; Çetin-Dindar & Geban, 2017; Ramlee et al., 2019
	Mental ability	Bilgin et al., 2013
	Creativity	Conradty et al., 2020; Güven et al., 2020; Kalantarnia et al., 2020
	Critical thinking	Chen, 2021
	Mental model	Supasorn, 2015
Affective effect	Attitude	Aydın & Yılmaz, 2010; Ayvacı et al., 2015; Bezen & Bayrak, 2020b; Daşdemir, 2016; Güven et al., 2020; Güzel, 2016; Güzel, 2017; Jensen et al., 2015; Kim, 2016; Lin et al., 2014; Namgyel & Bauraphan, 2017; Özcan & Kırbaşoğlu Kılıç, 2017; Tortop & Özek, 2013; Uzunöz, 2011; Walker et al., 2008
Curiosity and motivation	Motivation	Chen et al., 2014; Cheng et al., 2016; Çetin-Dindar & Geban, 2017; Parsons et al., 2019
	Curiosity	Gillies & Rafter, 2020
Others	Mathematical efficacy	Althauser, 2018
	Views regarding the nature of science	Akerson et al., 2009; Bang, 2013; Song & Schwenz, 2013; Zuiker & Whitaker, 2014
	Opinions on class	Bezen & Bayrak, 2020; Özcan & Kırbaşoğlu Kılıç, 2017
	Collaboration	Chen, 2021
	Communication	Chen, 2021
	Technical skills	Hırça, 2013
	Instructional design processes	Hu et al., 2017
	Instructional skills	Şengül & Schwartz, 2020
	Research opportunities	Sickel et al., 2013
	Usability of the developed e-learning environment	Torun & Tekdere, 2015

the effects of the 5E model on creative skills (Conradty et al., 2020; Güven et al., 2020), the model was enriched with additional processes, while the model was used without enrichment in the third (Kalantarnia et al., 2020). Conradty et al. (2020) included several processes that require creative skills in all phases of the model. Güven et al. (2020) enriched the model by including the engineering design process in STEM education into the elaboration phase of the 5E model. In the engineering dimension of STEM education, the product design process requires top cognition skills including the synthesis of everything learned as well as creativity. In the two articles, creative skills were measured and evaluated by using tools providing quantitative data, and in the remaining one (Güven et al., 2020) by a tool providing raw qualitative data.

As a structural change in the model skeleton would be required, no empirical article investigating the effects of the 5E model on higher-order scientific reasoning skills was found. The teaching of scientific reasoning skills within the scope of critical thinking (Dewey, 1933) usually takes place when faced with a problem. Hypotheses for the problem are established, and experiments are designed in which dependent, independent and controlled variables are defined to test the hypotheses. How the independent variable affects the dependent variable is found by interpreting the obtained data with proportional, probabilistic or correlational thinking in an unbiased and deterministic fashion (Lawson, 2009). At the end of the interpretation process, a reasonable conclusion is reached by making a judgment. This is in fact a process of knowledge generation. In this way, students produce existing knowledge as if they were discovering it for the first time; that is, they learn by exploring. Based on our analysis, it does not seem possible that the learning of scientific reasoning skills will take place with the unenhanced 5E model. However, structural changes to the model's skeleton may facilitate this.

In the light of these discussions, two conditions emerge for the 5E model to be able to create a significant cognitive effect covering higher order thinking skills in students. First, the skeletal structure of the 5E model needs to be developed to include higher-order thinking skills. This can only happen with a serious transformation of the 5E model, which has had a broad impact for many years as a pedagogical approach designed to meet the needs of the twenty-first century. The second condition is to enrich the performance measurement tools that measure the effects of the model on reasoning thinking skills by adding new criteria. It is believed that the focus in these empirical studies on students' cognitive output (at the level of knowledge and comprehension) and the low number of studies on students' cognitive outcomes related to higher-order thinking skills is a direct result of the difficulties teachers face in measuring thinking skills.

As a result of our synthesising the literature review, 'Skills-Based STEM Instructional Model for the twenty-first Century' where the 5E model can be used much more effectively (Appendix-2) has been proposed. Additionally, an activity set, and a skill performance evaluation set prepared in accordance with the model are also given in Appendix-3 and 4.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Zeynep Koyunlu Ünlü http://orcid.org/0000-0003-3627-1809
İlbilge Dökme http://orcid.org/0000-0003-0227-6193

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