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COMMENTARY

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The cognitive principles of learning underlying the 5E Model of Instruction

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Abstract

Over 34 years since its conception, research in educational settings has found evidence for the effectiveness of the 5E Instructional Model. Indeed, several studies have reported evidence of a better conceptual understanding of scientific ideas and models, positive effects on general achievement in science, and positive attitudes toward science. In this commentary, we would like to put forward the principles from cognitive sciences on how people learn which may underlie the 5E Model and that could theoretically contribute to the model's effectiveness as a learning sequence. Connections to conceptual change theory are especially highlighted.

Keywords: 5E Model, Cognitive sciences, Constructivism, Conceptual change, Learning theory, Learning sequence

Introduction

The 5E Instructional Model is an approach to science teaching and learning developed by the Biological Sciences Curriculum Study (BSCS) in 1987. As a learning sequence, the 5E Model builds on the work of other instructional models, such as the Atkin and Karplus Learning Cycle or the Science Curriculum Improvement Study (SCIS) Learning Cycle, with which it shares some steps (Bybee, 2015; Bybee et al., 2006). The 5E Model consists of five phases: engagement, exploration, explanation, elaboration, and evaluation. A description of the phases can be found in Table 1. Each phase has a specific function and overall they aim to help the teacher provide coherent instruction and the learner to engage in appropriate activities that will presumably promote a better understanding and retention of scientific knowledge.

The effectiveness of the 5E Model regarding the improvement of several science education outcomes has been supported by research conducted in schools over the last decades, mainly with primary and secondary school students from different socioeconomic backgrounds (for a review, see Bybee et al., 2006 and Bybee, 2015). Several studies have provided evidence of a better conceptual understanding of scientific ideas and models, long-term decreases in the prevalence of alternative conceptions, positive effects on general achievement in science, gains in students' self-expressed interest and confidence in science and scientific careers, and positive attitudes toward science (Kilavuz, 2005; Bybee et al., 2006; Cardak et al., 2008; Garcia-Grau, 2021; Hokkanen, 2011).

In this commentary, we would like to put forward the cognitive principles of learning that may underlie the 5E Model and that could theoretically explain its effectiveness as a learning sequence, according to basic research in cognitive science of learning and memory. By 'cognitive principles of learning', we mean theories and models of how learning works that have been developed by research mainly in cognitive psychology and cognitive neuroscience, although we also draw on research from developmental psychology and other behavioral disciplines that assume the cognitivist paradigm. Thus, our dissertation includes references to socio-cognitive theories of motivation and the conceptual change theory, for example.

Next, we highlight potentially plausible connections between the 5E Model and research literature from cognitive sciences for each of the stages of the Model.

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Table 1 Description of the phases of the 5E Model (from Bybee et al., 2006)

Phase	Description
Engage	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 organize students' thinking toward the learning outcomes of current activities
Explore	Exploration experiences provide students with a common base of activities within which current concepts (i.e., alternative conceptions), 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
Explain	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 behaviors. 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
Elaborate	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
Evaluate	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

Engage

In the first stage of the 5E Model, called *Engage*, the teacher introduces a problem or a discrepant event in a familiar context that students cannot explain with their current knowledge because it falls too short or does not fit in with their new experiences. As a result of this, a cognitive conflict arises. This conflict plays a motivational role and provides an opportunity to activate and elicit the students' prior knowledge.

From the cognitive perspective, the *Engage* stage of the 5E Model is exceptionally important because it addresses several processes which have proven critical for enhancing meaningful, durable, and transferable learning.

Firstly, research has shown that encouraging students to recall relevant knowledge from previous courses or their own lives (i.e., activating prior knowledge) can facilitate the integration of new material (Bransford & Johnson, 1972; Hattan et al., 2015; Peeck et al., 1982). In this regard, strategies such as asking students questions specifically designed to trigger recall or providing learners with a relevant context can help them use prior knowledge to aid the integration and retention of new information (Wetzels et al., 2011; Woloshyn et al., 1994).

Supported by decades of empirical research in psychology and neuroscience, the cognitive theories of learning state that prior knowledge plays an essential role in the processing and retention of new information (Ausubel, 2012; Brod et al., 2013; Shing & Brod, 2016). In short, that which students can learn depends greatly on what they already know because learning is a constructive process: much of what they learn is built on the prior knowledge in their long-term memory. But, according to this view, having relevant knowledge is not enough: it needs to be prompted to become useful during the learning episode. This means that it must be activated in long-term memory and enter working memory, the "mental space" where the learner holds and manipulates the information they attend to. When this happens, new learning is generated: some pieces of the new information are connected to semantically related pieces of knowledge that the learner had retrieved from long-term memory. Later, when the learner wants to retrieve what has been learned, they will reconstruct the memories using the related knowledge from different learning episodes. In other words, research suggests that human memory does not store redundant information. Instead, it uses information that is already consolidated in long-term memory to build on new memories that share those features. That is why learning would involve connecting prior knowledge to new information.

However, students may not spontaneously bring their prior knowledge to working memory in learning situations. In light of this, it has proved useful to provide explicit opportunities for students to activate their prior knowledge so they can build on it (Bransford & Johnson, 1972; Dooling & Lachman, 1971; Hattan et al., 2015). For instance, some students can spontaneously activate their prior knowledge while learning, while others need support and guidance (Carr & Thompson, 1996). These latter students can benefit from teacher prompting to activate prior knowledge (Carr & Thompson, 1996). The *Engage* stage of the 5E Model encourages teachers to assist their students to purposely and actively use their prior knowledge. In fact, since generating prior knowledge can be a double-edged sword, e.g., if the knowledge students generate is inappropriate for the context or inaccurate (Alvermann et al., 1985; van Loon et al., 2013), the role of the teacher as a guide is critical: they encourage students to openly voice their ideas, promote reflection, steer the students' thoughts in the right direction, and guide classroom discussions. It is important not only to activate prior knowledge, but also to direct students' attention to those aspects of their prior knowledge that will be relevant to the learning task.

Educational researchers and science educators do not only describe learning as an *assimilation* process, that is, as the incorporation of new information into the existing and appropriate knowledge structures without changing them (also known as knowledge accretion). Learning usually requires an *accommodation* process, where the pre-instructional conceptual structures of the learner need to be fundamentally restructured to allow understanding of the intended knowledge (Hanfstingl et al., 2021; Posner et al., 1982). Some authors in science education and developmental psychology refer to this as a 'proper' conceptual change (although most of them also consider knowledge accretion—assimilation—to be a lower level of conceptual change) (Harrison & Treagust, 2000). Cognitive scientists, on the other hand, refer to any change in prior knowledge as a *memory updating process* which involves changes in the way pieces of information in memory are connected to each other to build meaning and guide recalling (Bjork, 1978; Lee et al., 2017).

When learning requires an accommodation process, activation of prior knowledge becomes even more important. From the science education perspective it has been suggested that activating prior knowledge is key for triggering conceptual change due to motivational reasons: the learner realizes that they cannot use their current conceptions to explain the available data and this creates the need for a more adequate mental model. Posner et al. (1982) pointed to the detection of anomalies as the first step in conceptual change: "There must be dissatisfaction with existing conceptions. Students are unlikely to make major changes in their concepts until they believe that less radical changes will not work […]. An individual must have collected a store of […] anomalies and lost faith in the capacity of his current concepts to solve these problems." However, although motivation is indeed a key mediator in the process of conceptual change (later we will discuss how the cognitive conflict implied in the *Engage* stage of the 5E Model can promote it), it should be noted that the activation of prior knowledge alone also contributes to conceptual change as a consequence of how memory works. Indeed, research in cognitive sciences suggests that activation of prior knowledge plays a key role in memory updating.

As said previously, activating prior knowledge appears to promote learning since, if interaction between new information and old knowledge is to take place, prior knowledge must be accessible. From the cognitive sciences perspective, activating prior knowledge may be essential for promoting conceptual change because only the memories that become activated are prone to change. We can even find evidence of this phenomenon in the cognitive neuroscience literature. For example, according to reconsolidation theory and the trace updating framework, when a memory is retrieved the synapses underlying the trace become unbound or weakened. Thus, reactivated memories are vulnerable to disruption and need to be reconsolidated (Finnie & Nader, 2012; Lee et al., 2017). However, since the retrieval episode is triggered and followed by related information in the environment, it provides an opportunity to update the memory trace: a reactivated trace is never just simply reconsolidated, it is modified to include information contained in the new experience (Dudai, 2004, 2012; Hupbach et al., 2007).

Therefore, the *Engage* phase of the 5E Model, which is where the learning sequence begins, is seen as highly relevant from the cognitive perspective because it provides time and explicit opportunities for prior knowledge to be activated, which is essential for memory updating. However, this is just half of the story. As mentioned previously, the *Engage* stage also plays a significant role in promoting student motivation, which is another key factor for learning and triggering conceptual change (Pintrich et al., 1993; Sinatra & Pintrich, 2003). Indeed, students' cognitive engagement is essential for attending to information, activating prior knowledge, monitoring comprehension, and persisting at the learning task. Regarding conceptual change, motivation is particularly important if the student is expected to abandon their prior conceptions and adopt new ones, a process that requires a substantial cognitive effort. That is why the *Engage* stage, as its name implies, aims to provide a motivational boost.

Indeed, the initial situation presented in the *Engage* stage involves two types of engagement: contextual and cognitive. Contextual engagement is based on the fact that students appreciate the real-life implications of the posed situation, that is, they recognize its instrumental value (Wigfield & Eccles, 2000). Clearly, learners are more motivated when they can see the usefulness of what they are learning (Maher & Midgley, 1991; McCombs, 1991). As for cognitive engagement, it is grounded in the curiosity that often arises when students realize that their current ideas cannot satisfactorily explain an observation that puzzles them, and therefore it is a consequence of the cognitive conflict or cognitive dissonance (Chaxel & Russo, 2015; Harmon-Jones et al., 2015; Kang et al., 2004; Posner et al., 1982). In a way, socio-cognitive theories of motivation suggest that people are motivated to learn from situations that pose problems that they believe they can solve (Barron & Hulleman, 2015; Wigfield & Eccles, 2000). At the same time, research showing that stories are "psychologically privileged"—because their structure enhances attention and memory—suggests that the introduction of a conflict to be solved is a key contributor to their effect (Ware & Young, 2010; Willingham, 2004). In sum, conflicts students believe they can solve are motivational.

The *Engage* stage is hugely important for the cognitive and the emotional (motivational) dimensions involved in the learning process. In addition, it also offers interesting opportunities for group discussions and cooperative learning, which, among others, are key socio-cognitive ways in which individuals learn and that may lead to more fruitful teaching and learning environments (Johnson & Johnson, 2009; Slavin, 2013).

Explore

The *Explore* stage consists of a guided inquiry activity that provides opportunities for students to address alternative conceptions and build new explanations that make sense to them. In the *Explore* stage students investigate phenomena, share their observations, suggest explanations, and discuss their interpretations. The role of the teacher is to act as a facilitator who guides and scaffolds students' thinking.

After the activation of prior knowledge in the previous stage, the *Explore* stage aims to promote connections between students' prior knowledge and the new information to be learned. To do so, the activities on this stage follow a guided inquiry-based approach (Gormally et al., 2009) that fosters thinking and sensemaking during the learning task. This contrasts with a type of learning that is only based on transmission, one in which the student often acts as a passive learner. From the cognitive perspective, this approach would be supported by one of the most basic findings of cognitive psychology: people learn and remember better when they think about what they are learning in terms of meaning, that is, when they are prompted to connect information in meaningful ways. This principle is related to the influential idea posited by Craik and Lockhart (1972), known as the *levels of processing model*, which describes memory encoding as a function of the depth of mental processing. According to this model, memory is the product of thought and deeper levels of processing during encoding produce more elaborate, longer-lasting, and stronger memory traces, where deep processing refers to greater degrees of semantic involvement—that is, thinking about meaning (for several perspectives on this topic, see Conway, 2002).

Regarding conceptual change, the *Explore* stage provides students with opportunities to reformulate their explanations by inferring them from new experiences and observations (Hewson, 1981). According to the classical model of conceptual change (Posner et al., 1982) after recognizing that prior conceptions are inconsistent in a given situation, students need to find an adequate new conception that successfully explains it. This new explanation must be "intelligible" (the learner must grasp its meaning) and "plausible" (the learner must see how it is consistent with other knowledge and explains the available data). Therefore, the *Explore* stage provides the chance for students to propose new explanations grounded on their understanding and test them empirically.

From the socio-cognitive perspective, in this stage, which can be accomplished with the whole class group or in small groups, the teacher's role is to make sure students help one another solve problems by building on each other's knowledge, by asking questions to clarify explanations, and by suggesting avenues that would move the group toward its goal (Brown & Campione, 1994). Research shows that both cooperation in problem-solving activities (Newstead & Evans, 1995) and argumentation (Youniss & Damon, 1992) among students enhance students' cognitive development (i.e., their ability to learn, think, and reason).

Actually, the role of the teacher during the *Explore* stage is really important if the cognitive principles supporting learning are to be complied with. According to cognitive load theory (Sweller, 2011), inquiry-based learning activities must be carefully guided and extensively scaffolded by the teacher in order to facilitate students' learning (Hmelo-Silver et al., 2007; Kirschner et al., 2006). Learning through investigations promotes students being cognitively engaged in sensemaking, developing evidence-based explanations, collaborating, and communicating their ideas. But it also places a huge burden on working memory. This working memory load does not contribute to the accumulation of knowledge in long-term memory because while working memory is being used to search for explanations, it is not available and cannot be used to learn (Kirschner et al., 2006). Scaffolded inquiry environments provide learners with opportunities to engage in complex tasks that would otherwise be beyond their current abilities and overwhelm working memory. Scaffolding keeps cognitive load at bay and makes the learning more manageable for students by modifying complex and difficult tasks in ways that make them within the student's zone of proximal development (Vygotsky, 1978). In this regard, scaffolding is a key element of cognitive apprenticeship, whereby students become increasingly knowledgeable given structure and guidance from mentors who scaffold them through task structuring and sequencing, questions, and hints, but without explicitly giving students the final answers (Quintana et al., 2004).

Finally, the *Explore* stage provides students with opportunities to grapple with specific information relevant to the learning objectives, which is known to create a "time for telling", that is, a situation that activates the students' prior knowledge and that therefore enables them to learn much more from an organized explanation (Edelson, 2001; Schwartz & Bransford, 1998), such as those provided in the following *Explain* stage.

Explain

When students understand the necessity of new information and its relevance to their explorational practices, a just-in-time explanation can promote knowledge construction in a way that makes it available for future use in relevant contexts (Edelson, 2001). Therefore, the new concepts grasped in the *Explore* stage are formalized in the *Explain* stage, which provides opportunities for teachers or the curriculum to directly and formally introduce those concepts and help students organize their new knowledge in ways that facilitate encoding and later retrieval. The way students organize knowledge influences how they learn and apply what they know (Ambrose et al., 2010). Research shows that when students are provided with an organizational structure in which to fit new knowledge, they learn more effectively than when they are left to deduce this conceptual structure for themselves (Ausubel, 1960, 1978; Bower et al., 1969; Kirschner et al., 2006). Of course, formal definitions and explanations of the intended models and concepts can also be cooperatively built by students with the close guidance of their teacher.

Elaborate

The *Elaborate* stage includes activities that require students to apply the concepts and procedures they have learned to solve new problems in new contexts. Here the new concepts will have the chance to prove they are "fruitful", as Posner's conceptual change model suggests: "if the new conception not only resolves its predecessor's anomalies but also leads to new insights and discoveries, then the new conception will appear fruitful and the accommodation of it will seem persuasive" (Posner et al., 1982).

Therefore, the activities in the *Elaborate* stage provide opportunities for students to transfer their new knowledge to a wide diversity of contexts. Research suggests that exposing students to multiple contexts promotes deeper understanding, maybe because they are more likely to abstract the relevant features of concepts and to develop a flexible representation of knowledge (Bransford et al., 1990; Gentner et al., 1993; Gick & Holyoak, 1983; Kimball & Holyoak, 2000).

There often is a tendency to think that once students have the basic knowledge needed for an adequate understanding of a phenomenon, then it is relatively simple to apply that knowledge to the solution of practical problems. Unfortunately, transfer is not that straightforward. We've long known, since Thorndike and Woodworth's pioneering experiments (1901a, b, c), that transfer is very difficult to occur. The degree of similarity between learning and transfer contexts is critical (Barnett & Ceci, 2002). However, the way students learn is equally important in that it determines the potential for transfer to occur (Butler, 2010). If learning activities, by providing multiple contexts of applicability for the same concepts, create several retrieval routes to access the learned information, then the probability of finding a match between the cues given in the transfer task and the stored memory trace should be greater, thereby increasing the potential for transfer to occur. For example, asking students a series of questions that target the same concept and giving them feedback—hence encouraging students to think about that concept in different contexts—significantly increases the chances of transferring knowledge to new situations (Pan & Rickard, 2018).

To sum up, the *Elaborate* stage provides a space for extended practice applying the learned concepts and procedures in multiple situations. Extended practice is essential if something new is to be learned, especially if the goal is for that new knowledge to be retained over time and transferred to new situations (Healy et al., 1993).

Evaluate

Finally, in the *Evaluate* stage, the knowledge and abilities acquired by each student are assessed through an activity that challenges their understanding. Of course, evaluation can already take place during the previous stages of the instructional sequence as a formative assessment that provides opportunities for feedback throughout the whole learning process (Wiliam, 2011). Indeed, designers of the 5E Model recommend integrating the *Evaluate* stage throughout the whole learning sequence (Bybee, 2015). However, responding to a practical educational matter, science teachers must assess educational outcomes and assign students grades. Therefore, if this phase is applied at the end of the learning sequence, teachers can administer tests or other types of evaluative activities to determine the individual students' level of understanding and abilities. This is also an important opportunity for students to use the skills they have acquired and evaluate their own understanding.

As a side note, it is important to underscore the fact that since the 5E Model aims to promote learning with understanding, the evaluative activities should be designed accordingly. In this regard, tests requiring transfer help assess the quality of students' learning experiences. As stated in NRC's *How People Learn*, a synthesis of decades of research across many different disciplines about the science of learning, "different kinds of learning experiences can look equivalent when tests of learning focus solely on remembering, but they can look quite different when tests of transfer are used" (Bransford et al., 2000). Therefore, the design of the assessment tool will be key to revealing students' genuine understanding and thus appreciating the contribution of the 5E sequence to learning.

From a cognitive perspective, evaluation is not only useful for assessing learning and providing timely feedback. Cognitive psychologists have shown that retrieving information from long-term memory is one of the most effective actions for strengthening learning, even more than restudying (i.e., reactivating the memory trace by reviewing the information) for an equivalent amount of time (Karpicke & Roediger, 2008; Rowland, 2014). Although testing is not usually understood as part of the learning process but as means to assess what has been learned, the act of retrieving information from memory actually changes memory, increasing the probability of successful retrieval in the future (Roediger & Butler, 2011). This was already noticed in 1890 by psychologist William James, who, probably relying on introspection, wrote:

> *A curious peculiarity of our memory is that things are impressed better by active than by passive repetition. I mean that in learning (by heart, for example), when we almost know the piece, it pays better to wait and recollect by an effort from within, than to look at the book again. If we recover the words in the former way, we shall probably know them the next time; if in the latter way, we shall very likely need the book once more.*

Experimental reports from the beginning of the twentieth century through to today have proven him right: retrieval enhances retention (Karpicke & Roediger, 2008). Interestingly, according to several studies, retrieval may not merely produce transient, rote knowledge, but promote long-term, meaningful knowledge that can be retrieved flexibly and transferred to new situations (Karpicke, 2012; McDaniel et al., 2013). In addition, retrieval can help students organize information and form a coherent knowledge base (Roediger et al., 2011). Thus, the act of retrieval itself, which is central in an evaluative activity, is a powerful tool for enhancing learning. The 5E *Evaluate* phase, therefore, is also a learning phase, especially if it is applied not just at the end, but throughout the whole learning sequence.

It must be highlighted that, although evaluative activities can enhance learning by means of the retrieval practice effect (also known as the testing effect), tests can be stressful for students. This can have a negative impact on their memory and learning, which defeats the very purpose of assessing students for learning in the first place. In this regard, research suggests that the benefits of retrieval practice can be harnessed by using low stakes assessment activities (e.g., quizzing) that avoid the detrimental effects of stress associated with testing (McDaniel et al., 2011; Wenzel & Reinhard, 2021; Yang et al., 2021).

Neuroscientists have already suggested theoretical explanations of the neurocognitive mechanisms that may be underlying the retrieval effect (e.g., Antony et al., 2017). When an engram (the pattern of neural connections that represents a memory in the brain) is reactivated, it experiences a new round of consolidation processes. This eventually causes some strengthening of the original memory trace. However, it is also an opportunity for the trace to be modified since it becomes labile just before it is reconsolidated (Dudai, 2004, 2012). Regarding these mechanisms, some neuroscientists have suggested that unlike restudying (i.e., encoding the same information again), which only reactivates the specific engrams corresponding to the material that was studied initially, retrieval is an imprecise process that coactivates memories that are semantically linked to the target memory, thereby affording an opportunity to integrate the original engram into the coactivated knowledge structures (Antony et al., 2017). Therefore, according to these hypothesis, not only does retrieving strengthen parts of the original engram, but it also promotes further connections to prior knowledge, increasing its transferability. The fact that retrieving knowledge changes that knowledge and its connections with other semantic-related knowledge may have evident consequences for conceptual change theory. Retrieval practice (including prior knowledge activation) may be essential for conceptual change.

Finally, retrieval practice can also improve the conceptual organization of practiced materials, especially when the posed questions are open-ended. As already posited by Gates as early as 1917, one of the reasons retrieval practice enhances knowledge organization is that it requires students to organize information more than does reading alone. When students actively recall information, they need to give it a coherent structure (Roediger et al., 2011).

Conclusions

The 5E Model of Instruction was designed in the late 1980s with the idea of translating decades of research in science education into a learning cycle that instructors could effectively use in their classrooms (Bybee et al., 2006; Trowbridge & Bybee, 1996). The cycle was based on a model of learning understood as a conceptual change and, therefore, on the constructivist theory of learning (Mayer, 2009). With this in mind, one could easily assume that several cognitive principles of learning had to underlie the design of the model. Indeed, some of these principles had already been identified by cognitive scientists by the time the 5E Model was designed, such as the levels of processing effect or the fact that memory works by connecting pieces of information related by meaning. In contrast, other principles were derived from later research or were at least supported by ample evidence found later, such as the role of retrieval in learning. These later principles also help us account for the model's effectiveness.

Nevertheless, it should be highlighted that the learning principles that lay the foundations of the 5E Model are not only present in a collection of isolated actions that support learning, but also in the way they are sequenced. A quote from *How People Learn* (Bransford et al., 2000) seems especially germane to summarizing this point:

> *An alternative to simply progressing through a series of exercises that derive from a scope and sequence chart is to expose students to the major patterns of a subject domain as they arise naturally in problem situations. Activities can be structured so that students are able to explore, explain, extend, and evaluate their progress. Ideas are best introduced when students see a need or a reason for their use—this helps them see relevant uses of the knowledge to make sense of what they are learning. (p. 127)*

Here is a research-based recommendation for a structure and sequence of instruction that exposes students to problem situations (i.e., engages student thinking) and then provides opportunities to explore, explain, extend, and evaluate their learning. This research summary from the NRC report supports the sequence of the 5E Instructional Model, and it even uses very similar terms.

Overall, one could argue that the 5E Model is effective because students are provided with time, prompts, and several opportunities to deeply engage with the learning object in a way that promotes connections between what is known and what is meant to be learned.

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Competing interests
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