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Instructional design of scaffolded online learning modules for self-directed and inquiry-based learning environments

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ABSTRACT

Technology is ubiquitous in the modern world; to harness its educational potential in the quest to introduce environments that are flexible and differentiate for individual student learning needs, the strategic use of the complex array of tools is required. Engagement with this challenge has the potential to lead to the provision of interfaces that allow students to access these resources and become independent learners. It is therefore important to identify and evaluate the features of such interfaces to calibrate and respond to individual student needs. In this context, the quality of differentiated support for learning, referred to as scaffolding, is established as paramount to the design and structure of online environments. In this study, the instructional design referred to as predict, observe, explain and evaluate (POEE), informed by constructivist theories of learning, to implement multiple scaffolding strategies is described. The POEE scaffolding strategy was applied in the creation of two inquiry learning modules. Student engagement with these inquiry modules in a self-directed online environment was explored to identify critical elements of the scaffolding. The findings of this study, based on students' interactions and engagement with the learning modules, enabled the conceptualisation of a multimodal scaffolding strategy for self-directed inquiry. We propose that the recommendations from the implementation of these scaffolded learning modules can represent exemplars illustrative of an enriched instructional design paradigm to support students' independent study in blended environments.

1. Introduction

In science education, many students hold strong personal views, based on their prior knowledge and experience; the elicitation of these ideas are central to a pedagogy informed by constructivism (Driver & Scott, 1996). When students are encouraged to engage in the process of eliciting their ideas, they receive an opportunity to articulate and clarify their views and reflect critically on them (Kearney, 2002). Therefore, this process was adopted to contribute to dynamically facilitating the change process of their science conceptions. Previous research studies have identified that the predict, observe and explain (POE) scaffolding strategy, promoted by White and Gunstone (1992), is a powerful pedagogical strategy underpinning constructivist environments. This strategy has potential to offer learners an indirect instructional intervention as the means to facilitate their construction of their own knowledge (Treagust, Mthembu, & Chandrasegaran, 2014).

Scaffolding was first introduced and described by Wood, Bruner, and Ross (1976) as the learning support that a more knowledgeable other (MKO), either a teacher or peer, provides to the learner in a learning context to enable them to complete tasks beyond

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their initial capacity. This concept of scaffolding was based on the notion of the zone of proximal development (ZPD) which Vygotsky (1978) defined as the gap between what a learner accomplishes independently and what can be accomplished with the assistance of a more capable other. This process of supporting the learner through the ZPD is identified as scaffolding which can be manifested as a teacher's measured and appropriate intervention through verbal prompts, the provision of carefully selected materials, the opportunity to interact with peers or even a well-chosen computer program (Pritchard & Woollard, 2010).

While the POE strategy has been considered a successful pedagogical model in a traditional environment, its integration in online environments to supplement and/or enhance traditional teaching still often presents a formidable challenge for educators. A number of studies have attempted to integrate the POE strategy in multimedia environments to promote students' scientific inquiry. For example, studies have been conducted demonstrating how the POE strategy can promote conceptual understanding (Rakkapao, Pengpan, Srikeaw, & Prasitpong, 2014; Sesen, 2013), concept maps (Yaman & Ayas, 2015) and scientific knowledge construction (Hsu, Tsai, & Liang, 2011) during the inquiry process. Bumbacher, Salehi, Wieman, and Blikstein (2017) used POE to investigate student's productive inquiry in both physical and virtual environments to understand how these environments and their affordances impacted on conceptual understanding (this study did not focus on student's self-regulatory processes or how these affect their inquiry learning). Brenner et al. (2017) investigated how the frequency and level of assistance provided to students interacted with their prior knowledge to affect learning in the web-based science inquiry-learning environment. They considered productive moves, clicks, total tries, elapsed time etc. to determine the level of assistance that students need. These recent studies contribute to understanding the potential benefits of integrating POE model into the multimedia environment. Nonetheless, evidenced methods for successful implementation and comprehensive use of associated technologies has proven to be a continuous challenge in areas such as science education. The incorporation of inquiry learning into the context of online environments accentuates this challenge. This is because inquiry learning requires an environment through which students are exposed to the scientific way of thinking enabling them to apply scientific processes such as stating hypotheses, engaging in experimentation, creating models, and evaluating the effects of interventions (van Joolingen, De Jong, & Dimitrakopoulou, 2007).

Besides the POE strategy, several other studies attempt to develop and formulate strategies to create effective learning environments and attempt to enhance students' understanding of inquiry processes using online, web-based or virtual environments. For example, strategic forms of instructional scaffolding were recognised as important in supporting students' self-regulation and learning in an online environment (Lawrie et al., 2016). Other examples include applications of the community of inquiry (CoI) framework in online and MOOC contexts (Kilis & Yildirim, 2018; Kovanović et al., 2018), experiment-based inquiry through a scaffolded concept mapping tool within an immersive virtual environment (Metcalf et al., 2018), and mobile inquiry-based learning (Suárez, Specht, Prinsen, Kalz, & Ternier, 2018).

In recent years, the popular CoI framework proposed by Garrison, Anderson, and Archer (1999) has enhanced online education through collaborative knowledge construction. In the CoI framework, Garrison et al. (1999) propose that a worthwhile educational experience requires two key participants: teachers and students; and assumes that learning occurs within the community through multiple forms of "presence", such as teaching, social, and cognitive presence. The CoI framework is rooted predominantly in social constructivism in which interaction between the participants is a requirement. It requires the students as the active participants who collaboratively engage in purposeful critical discourse and reflection to construct personal learning and confirm mutual understanding (Garrison & Akyol, 2013). A student's individual cognitive constructivism and self-regulatory learning process is not the key focus in the CoI model, as it distinctively advocates the multiple presence of the participants and interactions between them.

Another core learning framework proposed by Moore (1989) outlines the notion of interaction between the participants in online and distance learning environment. Moore (1989) defined three key interactions in online settings: student-content, student-teacher and student-student interaction. Moore's classification remains the most widely accepted framework for other studies that basically focus on the interrelationships between these three types of interaction (Xiao, 2017). Among them, Anderson's (2003) equivalency theorem is of particular importance to the current study.

Anderson's interaction equivalency model, that argues that "Deep and meaningful formal learning is supported as long as one of the three forms of interaction (student–teacher; student-student; student-content) is at a high level. The other two may be offered at minimal levels, or even eliminated, without degrading the educational experience" (Anderson, 2003, p. 4). Anderson (2003) further argues that the cognitive presence or interaction between students and content has long been recognised as a critical component of both on-campus and distance education. Yet, much of the research have been dedicated to reciprocal interpersonal interaction, that is, student-student and student-teacher interaction. There is far less research study in learner–content interaction despite its fundamental and critical role in ensuring the effectiveness of the online learning experience (Xiao, 2017). Student-content interaction can stimulate an environment where students can commit more to independent and self-regulated learning than the student-student or student-teacher interaction. While significant insights are available into the development of curricula where the teacher and/or peer support is indispensable in the learning process, there are few studies that explore how students might learn independently in an inquiry-based learning context in the absence of teacher-student and student-student interaction.

Recently, the role of independent learning and self-regulation in online environments has received substantial attention (Kilis & Yildirim, 2018; Lin & Tsai, 2016). Since students working in an online learning environment need to have acquired a degree of independence for successful learning, the ability of learners to engage in self-regulation is an important factor to consider (Wang, Shannon, & Ross, 2013). Self-regulated learning is an integrated learning process guided by a set of motivational beliefs, behaviours, and metacognitive activities that are planned and adapted to support the pursuit of personal goals (Schunk & Zimmerman, 2012). Research shows that students' self-regulated learning can be significantly impacted by three key constructs: prior domain knowledge, self-efficacy, and the use of learning strategies (Diseth, 2011; Sun, Xie, & Anderman, 2018).

Prior domain knowledge refers to the knowledge, skills or ability that students bring to the learning process (Jonassen &

Grabowski, 2012). Research has revealed a significant relationship between prior knowledge and self-efficacy (Ferla, Valcke, & Cai, 2009), and the use of learning strategies (Taub, Azevedo, Bouchet, & Khosravifar, 2014). The very nature of the online environment encourages these key constructs of self-regulated learning and lays the foundation of students' inquiry skills. Inquiry skills have been shown to relate to the ownership of their learning and self-regulated inquiry skills (Fang & Hsu, 2017; Raes & Schellens, 2016). However, in practice, it is difficult for students to achieve these key attributes of learning without direct, synchronous teacher support since students need to make decisions about the many facets of learning. These facets include: what to learn; how to learn it; how much time is needed to spend on learning; how to access and use instructional materials; and then to determine whether they understand the material or not (Azevedo, 2005). It is not surprising then that the potential of online environments to consistently facilitate inquiry learning may be weakened through students' inability to self-regulate critical aspects of their learning (Jacobson, 2008). Therefore, the fundamental research question that this study addresses is what nature of scaffolding facilitates students' independent learning, and can mitigate the needs of immediate teacher support, in the online inquiry context?

1.1. Design principles and scaffolding methodology

While there is continual progress in understanding what forms of scaffolding support student learning through self-regulated online inquiry-based modules, there is still a need to further explore how students respond to this scaffolding. In particular, while challenges and constraints are recognised (Fang & Hsu, 2017; Kim, Hannafin, & Bryan, 2007), few recommendations have been published for instructional design of scaffolding that supports online, self-regulated science inquiry in the absence of direct teacher or peer interactions. Therefore, this study attempts to address this situation and provides an evidenced exemplar of the design and implementation an inquiry-based learning module in an online environment making the scaffolding explicit. In this study, scaffolding is conceptualised as an interaction between the students and sophisticated digital tools and learning content. As such, the scaffolding strategy, which implies interactions between a 'more knowledgeable other' and an apprentice, has been mimicked through the adoption of technology to support students' engagement and learning (Sharma & Hannafin, 2007).

One approach to exploring the role of scaffolding in supporting a student's self-regulation in an online environment, and how it impacts on their learning and engagement during the inquiry process, is the development of learning modules. An online inquiry module typically involves a sequence of multimodal tasks that are interconnected using strategically placed questions, prompts or feedback that support student progression. The current study adopted POE as the foundation for a revised pedagogical strategy that is applicable in self-regulated online environments to create online learning modules. This study introduces the novel element of the evaluate (E) phase into the original POE strategy hence it is designated in this study as *predict, observe, explain and evaluate* (POEE). As students construct their knowledge through interactions with the online learning contents, it is important that they evaluate the quality of their gained knowledge (Lee & Hannafin, 2016). The intention of introducing the evaluate phase was to provide immediate synchronous feedback enabling students with the opportunity to independently evaluate their understanding in a self-regulated online environment. This substitutes the affordance of traditional POE environments in which students typically receive immediate feedback due to their interaction with their teacher or peers. The following schematic diagram (Fig. 1) illustrates the revised POEE strategy.

The anticipated workflow that students will apply during these POEE activities is summarized in Table 1 based on current understanding of student engagement and learning informed by literature.

POEE works as the umbrella framework (macro-scripted scaffolding) to assemble and structure the learning activities. In structuring and integrating learning activities into the learning modules, the POEE strategy borrows the same concepts of macro and micro level scaffolding strategy (Hammond & Gibbons, 2005; Jumaat & Tasir, 2014; Pan et al., 2012). In a recent study, Pierre, Luis, and Jennifer (2018) applied orchestration through micro- and macro-scripted scaffolding strategies; micro-scripted scaffolding is internal to a specific activity between the learners whereas macro-scripts concern the transitions between activities (often including individual activities, team activities, and class-wide activities). Classroom orchestration refers to the real-time management of multi-layered activities in a multi-constraints context in a physical classroom (Dillenbourg, 2013). More specifically this approach involves careful arrangement of a technology-equipped classroom environment or activities to achieve a desired learning effect or outcome (Chan, 2013). The adopters of this novel strategy have found it innovative in the provision of tools or design principles to support teachers and students by optimizing the classroom constraints (Dimitriadis, Prieto, & Asensio-Pérez, 2013). A limitation of this approach is that teacher intervention is the key string in the orchestration of learning in classroom environment. Since this approach

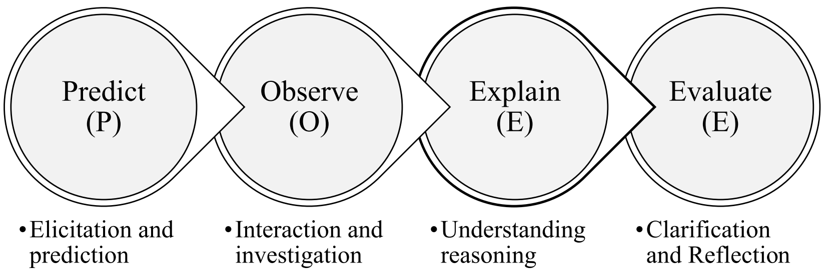


Fig. 1. The schematic representation of the flow of student activities guided by POEE strategy.

Table 1
POEE stages and anticipated students' workflow.

POEE	Anticipated students' workflow	Key constructs of self -regulation
Predict	Students predict the possible answer. The challenge the student faces in this phase will elicit and conceptualise their thinking in a specific direction. Gunstone (1995) recommends that students write their predictions with reasons to increase their level of commitment to the learning activity. This process encourages the formation of links between new and old concepts.	Prior domain knowledge
Observe	Students interact with the activities and contrast the observed outcome with their prediction. Self-regulation can take place during the exploration which brings more self-exploration of the given concepts and initiates a meaningful cognitive process and knowledge construction.	Self- efficacy and learning strategies
Explain	Students justify individual ideas with reasoning. This conceptually scaffolds a student's cognitive processing of the given concepts to help the process of learning. At the same time, it can support reconstructions and reformulations of thoughts and function as metacognitive scaffolding.	Self- efficacy and learning strategies
Evaluate	Students receive synchronous feedback which, as a result, supports their clarification and evaluation of their understanding. This evaluation helps the student to participate in meaningful knowledge construction (Lee & Hannafin, 2016) and facilitates competencies and understanding of the given problem (Hyland, 2000).	Self- efficacy and learning strategies

offers an instructional affordance, the same macro-micro concepts formula has been applied in the current study through provision of a carefully tailored technology-supported scaffolding that can act as a “surrogate” for teacher support and face-to-face guidance. It is recognised that orchestration often involves transitions and interactions between different levels (individual, team, classroom, teachers), whereas in the current study, the POEE strategy only enables interrogation of the effect of scaffolding in a single level (one student in an online environment) between individual activities.

An example of the POEE activity applied in the *Heat* module demonstrates how micro-scripted scaffolding was applied in each POEE phase in Table 2.

Table 2 illustrates that a range of different scaffolding tools are integrated at the micro-scripted level. For example, in the *Predict* phase, the notion of cognitive disequilibrium (Piaget, 1985) is used as the key concept to prompt students' initial ideas, to motivate them to engage in conceptual inquiry and, through this process, to embark on investigations (White & Gunstone, 1992). Provoking cognitive conflict can lead to effective learning by prompting learners to articulate and explore ideas and theories that they hold about a concept (Treagust et al., 2014). Elicitation of this prior domain knowledge is an important construct of self-regulated learning. Therefore, cognitive conflict is the state that propels students to modify some of their existing understandings about a known topic in accord with their new-found reality (Ronda, 2012). The *Predict* phase leads students to engage, so a meaningful cognitive process can be transacted during the *Observation* phase (Taber, 1999).

The *Observation* phase allows for the clarification of any discrepancies between the predictions and observations. If observations conflict with an earlier prediction, the reconstruction of initial thoughts is likely to reconcile the discrepancy in the process of promoting conceptual understanding (Tao & Gunstone, 1999). In the *Explain* phase, students receive the opportunity to explain their understanding of particular concepts. Students were required to justify their own individual ideas, understandings and justifications through their written explanations. As students do not receive any teacher support, synchronous feedback has been provided in the *Evaluate (E)* phase to minimize potential confusions and discrepancies in students' understanding. In the *Evaluate* phase, the provision of synchronous feedback is considered to be a key element, which facilitates students in evaluating their understanding (Zumbach, Hillers, & Reimann, 2004). This approach of providing synchronous feedback in an online environment is pivotal for learning (Leibold & Schwarz, 2015). Because the feedback is embedded in the student learning space, where all learning materials and resources are available, the usefulness of feedback is maximised (Hatziapostolou & Paraskakis, 2010). Students were provided hints and useful information and some detailed feedback on particular concepts which are found useful to correct and clarify the concepts (Keiding & Qvortrup, 2014).

Three micro-scripted scaffolding supports such as multiple external representation, inquiry questions and instructional guidance have been embedded within the learning modules. Table 3 illustrates how students received these supports in different phases of the POEE strategy.

Multiple external representations were used as scaffolding tools in this study since they present concepts in multiple modes therefore have potential to be combined to support students' development of representational competencies (Barrett, Stull, Hsu, & Hegarty, 2015). An example of how the different representational levels such as macroscopic, sub-microscopic and symbolic levels (Gilbert, 2008; Johnstone, 1993) have been combined is provided for the concept of thermal expansion from the *Heat* module (Fig. 2). Thermal expansion is an abstract science concept and requires molecular level representations of the phenomena to help students to understand the process. The following figure combines three representational levels of this concept.

These representational levels were applied in the online learning modules to facilitate students' understanding of abstract science concepts and phenomena (see Table 3). The representations were delivered through multiple modalities including static graphics, photos or diagrams, dynamic animations and simulations, videos and textual forms (information, questions, instructions, hints, highlighted words etc.). Embedded macro-level interactive functions in video-based learning environments have been shown to support students' self-regulation and learning outcomes (Delen, Liew, & Willson, 2014). While videos represent a useful dual mode of representation (audio and visual) students may engage passively with them, hence the current study also adopts interactive dynamic simulations as part of the design of modules aiming to engage students in active and independent exploration of concepts.

Instructional guidance (Belland, 2014) was used in the online self-directed modules, a process which potentially acted as a

Table 2
Example of a POEE activity, extracted from Heat module.

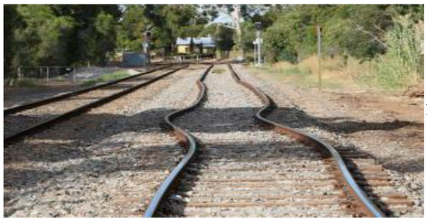
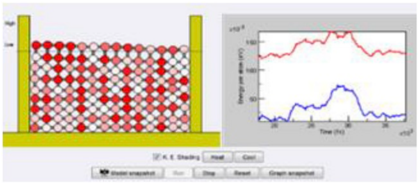
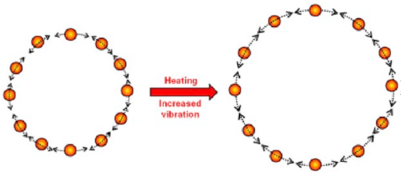
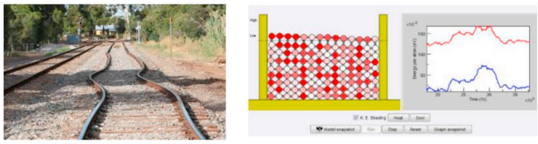
POEE Task	Multimodal Representations	Scaffolding tools
Predict (P) When you heat a substance, the rise in temperature is not the only thing that occurs on the atomic scale. There are other important changes that can arise from the transfer of heat energy. Think about the following question and explain your understanding in the text box. *Railway lines can buckle in very hot weather. Explain how this might occur in molecular terms.*	 Buckled rail lines: a macroscopic representation of a real-world context (Source: Science Blog, 2009)	Inquiry questions, multiple external representations
Observe (O) The following simulation shows that a solid responds to heat input by increasing its volume due to increased atomic vibrations. This is thermal expansion. *Click here* to go to the Molecular Workbench simulation entitled: *Heat and Temperature: An energy view of heating* (extract from page 8). Once you finish the activity, return to this page and do the following concept check activity.	 Simulation: Molecules vibrating in a solid: a molecular level representation (Source: Molecular Workbench)	Multiple external representations. Instructional guidance is minimal
Explain (E) The iron plate pictured here has a hole cut in its centre. What will happen to the hole when the plate is heated? Explain in molecular terms with reasoning.	 Hole in iron plate: a macroscopic representation of a real object (Lawrie, 2014)	Inquiry questions, multiple external representations
Evaluate (E) Students received synchronous feedback Feedback 1: First of all, we need to recognise what is occurring on a molecular, when the iron is heated. *The iron atoms vibrate more due to the increase in heat energy and each atom takes up more space. Consequently, on average each atom is further apart from its neighbors. This results in "thermal expansion" in the material being heated.* Here, the iron plate will expand. It is relatively simple to rationalize that the circumference of the outside of the plate has expanded, but this is not as simple when we consider the inner hole. Imagine the atoms that line the edge of the inner hole (effectively a circle of atoms – see the diagram below). If the distance between them increases, then the circle becomes bigger. In effect, the hole increases in size. Feedback 2: Watch the video to see a classic demonstration of this concept using a brass ball and ring.	 Feedback 1 Thermal expansion: a molecular level representation (Lawrie, 2014) Feedback 2  Video demonstration of expanding inner hole of the iron plate: a macroscopic representation. (Source: YouTube)	Feedback provision, multiple external representations

Table 3
Scaffolding supports provided across the different phases of POEE.

Scaffolding Phase	Scaffolding tools used	Scaffolding supports
Predict (P)	Inquiry questions, multiple external representations	Provide cognitive direction in the learning process and elicit higher order thinking
Observe (O)	Multiple external representations: instructional guidance, inquiry questions	Build in affordances to provide cognitive and intuitive direction in the learning process - Elicit higher order thinking - Promote self-regulation - Provide instructional direction - Offer familiarization of task - Provide directions to use and utilise the resources
Explain (E)	Multiple external representations, inquiry questions	Ask students to demonstrate their level of understanding in the given problem situation based on their prior experience and interaction in the *Observe* phase.
Evaluate (E)	Multiple external representations, synchronous feedback	Provide the evaluative or corrective information about student responses.



The simulation model shows that a solid responds to heat input by increasing its volume due to increased atomic vibrations. This is thermal expansion. The buckled rail lines are example.

(a) **(b)** **(c)**

Fig. 2. Examples of three different representational levels taken from the *Heat* module. (a) Static image: Macroscopic representation of the observable thermal expansion of iron train tracks. (b) Simulation: Sub-microscopic representation of metal atoms vibrating and a graph of kinetic energy as a function of time. (c) Textual information (symbolic representation).

Table 4
The nature of instructional support and the relevant representational components.

Instructional guidance	Representational components	Functions	Intended outcomes
Strongly guided	Graphical and symbolic representations: simulations, videos, textual instructions, questions, highlighted words	<u>Guided learning.</u> Students receive detailed scientific instruction of actions that will help them to understand the concepts in the simulation environment. Students have the freedom to inquire into different concepts independently.	Students construct knowledge and learn concepts by following the guided instructions. However, even with explicit instruction, a student might choose to explore the simulations further in a self-directed way to inquire into the unknown.
Moderately guided	Graphical and symbolic Representations: simulations, videos, check concept buttons, hints, questions	<u>Exploratory learning with moderate guidance.</u> With moderate instruction, students are placed in inquiry learning contexts and asked to explore and understand the concepts.	Students gain initial support from the instructions and explore the simulations. They come to understand the concepts through their independent explorations receiving moderate guidance.
Open ended (or, minimally guided)	Graphical representation: simulation models and videos	<u>Pure Exploratory learning.</u> This creates exploratory learning environments, based on the foundation of constructivist and inquiry-based premises. Students might obtain support and guidance from the built-in affordances in the environment	Students construct their own understanding and learn the concepts through self-exploration.

"surrogate" facilitator in the absence of a teacher or peers. Therefore, under the *Observe* phase of the POEE scaffolding strategy, all interactive simulation tasks were scaffolded by providing either strong, moderate or minimal (for example open exploration) guidance. Examples of the forms of instructional guidance and the relevant representational components are provided in Table 4.

Five types of questions were used as scaffolding: cognitive conflict questions; question prompts; concept check questions; confidence check questions; and multiple-choice questions. Collectively they are referred to as *inquiry questions* drawing attention to the common nature of the questions that elicits students' thinking about a topic and they facilitate inquiry relating to the scientific concepts addressed by these questions. Questions and prompts were embedded at strategic points in the modules to support student inquiry (Chin, 2007; Kawalkar & Vijapurkar, 2013). Table 5 illustrates the examples of the separate functions of these questions:

Table 5
Examples of inquiry questions.

Inquiry Questions	Example questions	Functions	Scaffolding phase
Cognitive conflict questions	On a cold day, when you grab a metal box with your bare hand it feels very cold. When you hold a second box, which is made of plastic it does not feel cold. Explain why the metal box feels colder than the plastic box. (Module: Heat)	Elicit what the students know, encourage them to elaborate on their thinking, and help them to resolve the problems	Predict (P)
Question prompts	Reflective: Can you relate what you see in the simulation why water is most dense than oil? (Module: Phase Change). Elaborative: Carefully compare each conductor and analyse all your readings. Which conductors allows the solids to reach equilibrium fastest? (Module: Heat). Procedural: In the following simulation, use different substances and observe which type of molecule clumps together most tightly? (Module: Phase change).	Encourage students to explore the concepts, look for evidence in the learning modules, guide them to inquire into meaningful and productive exploration	Observe (O)
Concept check questions	Explain why water is often liquid, but oxygen (O_2) is always a gas at room temperature. (Module: Phase change)	Facilitate students in explaining what they have understood, help them to evaluate and reconstruct their knowledge	Explain (E)
Confidence check questions	How confident are you about your answer? 4: Very high, 3: High, 2: Low, 1: Very low.	Reflect on what they have understood and explain, help them to refine and modify their understanding and scientific reasoning	Explain (E)
Multiple choice questions	Q. Why is the water vapour less dense than the liquid water? A. Because the molecules in water vapour have more energy and no longer stick together. B. When heated, water vapour molecules weigh less than liquid water molecules. C. Because molecules of water vapour release energy and becomes lighter. D. Water vapour is gas, so it is lighter than water.	Serve the same purpose as concept check questions, e.g., facilitate students to explain what they have understood, help them to evaluate and reconstruct their knowledge by encouraging them to revisit the simulation models	Explain (E)

2. Methodology

This research study involves a bias towards qualitative data collection however the inclusion of some quantitative data to strengthen findings makes this study a qualitative dominant status mixed-methods approach (Leech & Onwuegbuzie, 2009). Data was collected from multiple sources including observations of student activity, video recording, written responses and stimulated recall interviews. This multi-method approach of qualitative data collection forms the basis of triangulation to corroborate or converge the results from these alternative approaches and systematically reduce potential bias inherent in any one method of data collection (Creswell, 1999). Researchers are able to probe further into a dataset to understand its meaning and to use one data set to verify findings stemming from the other data set (Onwuegbuzie & Teddlie, 2003). The data collected from multiple sources ensure the rich description of the context and convergence of information confirms the trustworthiness and reliability of the data (Borrego, Douglas, & Amelink, 2009). A subset of this data is reported here for brevity however the extended study is available (Mamun, 2018).

2.1. Content delivery

Two learning modules were designed around the important science concepts of *Phase change* and *Heat* that also aligned with concepts taught in a first-year chemistry curriculum. A web-based platform was used to support delivery of the modules. The researchers designed and developed the learning modules through adoption of the free, open-source content management system WordPress. This system provides a range of customisation opportunities for embedding the learning content. Although embedding the Java applet (particularly to support the simulations) was critical, the HTML 5 options for some of the simulations made it easier to integrate them within the learning modules.

Learning modules were not integrated into the formal curriculum during the study; rather they were offered as separate activities alongside the formal, face-to-face teaching and hence were not formally linked to the students' assessment process. However, the topics of the learning modules were based on those that were formally part of high school and first year chemistry curricula hence perceived to be beneficial to students who participated in the study. The extent of students’ participation was voluntary.

Students were allowed to explore resources and find information and/or solutions independently from the material provided, thus allowing them to explore topics that they found interesting further. However, scaffolding in the form of question prompts, hints and instructional guidance were provided within the learning modules to facilitate student interaction with the modules and keep them on track towards the anticipated learning.

2.2. Participants and sampling technique

This study is dependent upon a relatively small sample size of 30 students. The strength of a small sample is that it enables researchers to obtain detailed, in-depth data about the key ideas, and provides the opportunity to secure detailed experiential accounts in relation to the phenomenon under study (Creswell & Clark, 2007; Ryan, Coughlan, & Cronin, 2009). The context of the study was a single, large Australian tertiary institution. A convenience sampling technique was utilized in this study to recruit participants from a cohort of first year chemistry students. An invitation to participate was distributed to all enrolled students through the learning management system and only those who expressed interest in participating in the study were recruited. First-year science students were invited to participate because students in this context often reveal problems in understanding abstract science concepts at the beginning of their tertiary education (Markow & Lonning, 1998). The processes of data collection and storage used in this study have been approved through the institutional ethics committee and participation required students to opt in based on informed consent.

The participants were filtered into two groups based on their self-reported prior knowledge of chemistry. This study avoids pre-testing the students because of potential testing threats that may change participants' behaviour during the actual study due to information they may gain from a pre-test. Researchers can control testing threat by using a control group; however, the nature of this study does not demand any control group. Therefore, grouping students based on their prior chemistry experience was appropriate.

2.3. Data collection

Each individual student was invited to engage with one learning module (either *Phase change* or *Heat*), which they accessed on a pre-formatted computer interface in a study room where only the student was present. Participants were required to commit to a learning module for about 50 min. Prior to their commencement of activities, students were briefly introduced to the module by the researcher who oriented them in the simulations and how to navigate the online settings. They were then left to work independently on the module. However, their on-screen activities were monitored by the researcher from a remote location (nearby separate room) with the assistance of Virtual Networking Computing (VNC) software. While students were interacting with the online website content, their computer screen activity was monitored and recorded by Echo360 screen capture software to capture how the participants' interacted with activities. Drawing upon the students' experiences, the study used the stimulated recall interview after they had completed their online activities as the key tool for data collection (O'Brien, 1993). Collecting the data involved several phases: video recording of students' onscreen activity, observational notes, students' written responses entered online to different inquiry questions embedded in the learning modules and finally a stimulus recall interview. The combination of the first two phases, video recording and recording of observational notes, provided the groundwork for the questions in the stimulated recall interview.

Each participant was assigned a unique identifier and the module that they completed is designated as either 'H' for heat or 'P' for phase change when data is presented in the results section.

2.4. Data analysis

Thematic analysis, the most widely used qualitative analytic method in research, was applied to the qualitative data collected in this study. This study considered the model proposed by Braun and Clarke (2006) as a blueprint for the inductive approach to find patterns across the data sets. The data derived from the student activity, observational notes, interviews, students' written responses were examined and coded to cast light on the research questions. A theory driven approach to finding the patterns and themes related to the research questions was also applied where several constructs, relating to the students' activity, emerging from the literature were applied as key indicators while searching for the themes from the data. This approach enabled organization of the data for subsequent interpretation and several subthemes that would support this theory were identified.

3. Results

Findings from this study demonstrated that the POEE scaffolding strategy fulfilled the four conditions of a constructivist learning environment suggested by Baviskar, Hartle, and Whitney (2009). In their study, Baviskar et al. (2009) argued that the constructivist environment needed to establish four essential criteria that enabled the student to construct knowledge or build on their prior knowledge. These criteria are: a) the elicitation of a student's prior knowledge; b) provision of a context that creates cognitive dissonance in a student's mind; c) giving a student the opportunity to apply the new knowledge; and d) providing feedback and support for reflection and clarification during the learning process. Examples of evidence that was elicited that support the realisation of the four criteria are provided in Table 6 (a single students' case has been illustrated).

In the following sections, the combined data was analysed to consider how effective the scaffolding was in terms of each phase of the POEE strategy and student progress through the modules.

3.1. Predict phase

The predict phase revealed that inquiry questions, such as the cognitive conflict questions, had created a level of cognitive dissonance in students' minds about what they knew. In many cases, it was ascertained that several students were confused and uncertain about their original answers. There was evidence that they were left in a state of disequilibrium when their knowledge

Table 6
Example of evidence of a student behaviour in constructivist learning environment.

Tools used	Example of evidence: Student's responses	Researcher's Comment
Criteria 1: Elicitation of student's prior knowledge **Cognitive conflict question:** On a cold day, when you grab a metal box with your bare hand it feels very cold. When you hold a second box, which is made of plastic it does not feel cold. Explain why the metal box feels colder than the plastic box.	*The metal box feels colder as heat is transferred more quickly to the hand than the plastic box* [H207]. (excerpt from written response)	The student drew on his prior knowledge which was elicited through this question. That student addressed the issue that heat transfer is faster from metal to hand in comparison to plastic. This is clear evidence that the student has prior knowledge of this phenomenon and therefore he explained it based on his prior understanding.
	Criteria 2: Create cognitive dissonance *This concept is confusing a little bit. I actually did stuff like that and I just can't remember anymore, unfortunately. I don't know why, but I thought, I am kind of confused with the concept, and I am assuming that metal is a quicker conductor and it drags the heat away from your hands faster than the plastic as its a poor conductor.* [H207] (interview data)	When the student failed to produce a satisfactory answer, it created cognitive dissonance and eventually, the student realised the gap between his prior knowledge and the problem being presented. The cognitive dissonance created intrinsic motivation and led him to explore the concepts.
Concept check question, CnCQ8: In a popular lecture demonstration, a rod that is half wood and half metal is wrapped tightly with a sheet of paper. If held over a flame, the paper on one-half of the rod burns while the paper on the other half is unaffected. Which half of the rod has the burnt paper? Explain with reasoning. (CnCQ8 is a follow-up question to the previous CgCQ4 to understand how students apply their knowledge in a different situation.)	*Criteria 3: Applying the new knowledge* *The half of the rod that has the burnt paper is the wood as it is a poor conductor of thermal energy. Metal, on the other hand, is, therefore, heat is transferred quickly from the flame to the metal rod, causing the paper to catch on fire. [H207*]. (excerpt from written response)	After exploring and experiencing the simulation model, the student was asked to explain the problem in a new situation. The student tried to explain and apply his understanding to address the given problem.
Synchronous feedback on CnCQ8: Metal is a good thermal conductor. The paper loses its heat immediately to the metal, so it wasn't affected by the flame. The metal conducts the heat from the flames obtained by the paper. In wood, the paper will burn because wood is a poor conductor of heat.	*Criteria 4: Support reflection and evaluation* *I didn't realize that, and I haven't ever really thought about that. Once I read the explanation (feedback), I was clear. I kind of understand the concept from the reading.* [H207]. (interview data)	Once the student completed the written explanation, he received immediate feedback on the concept which helped him to reflect on his understanding. It gave him the opportunity to clarify and evaluate his current understanding.

Table 7
Student behaviour while responding the cognitive conflict questions.

Subthemes	Frequency [N = 30]	Data source
Create dissatisfaction (sometimes confusion) in understanding the concepts	14	Observation, video record and interview
Awareness about lack of knowledge and the inability to explain correctly	10	
Dissatisfaction or awareness causes to prompt investigation	19	

relating to the given problem was inadequate in providing a satisfactory explanation. Table 7 summarises student behaviour using data collected from an individual student's interactions (observations and video record) and interviews.

An example of a cognitive question that was used in this study is: ‘On a cold day, you grab a metal box with your bare hand. It feels very cold. You grab the second box, which is made of plastic and does not feel cold. Explain why the metal box feels colder than the plastic box’. During the post-activity interview students expressed their confusion and uncertainty about the answer that they had provided for this question:

> I was not too sure what caused the … like I know the metal can change shapes when it gets really hot. I just knew that molecules can move around the … but I am not sure actually. [H105]
>
> I know that metal is a quicker conductor, but yeah, I would actually be struggling with this because I could not think about it. … I knew that I experienced it before, but I was kind of getting frustrated about what happens there. [H207]

Based in these student reflections during the interview, the cognitive conflict questions appeared to have precipitated some confusion amongst students; further, this initial disorientation proved to be catalytic in prompting them into becoming more mindful of their inability to reconcile the concepts with their existing knowledge schema. Therefore, student reflection on their own thinking indicated that inclusion of the cognitive conflict questions had prompted an awareness of their own thinking. The following quotes demonstrate how cognitive conflict questions facilitated this self-awareness:

> I was trying to think ahead about what information was going to be like, to answer the questions right. I knew it (that the information I have) was not going to be exactly right. [H104]

> I had a vague idea of what the answer might be but before I even knew what answer I was going to put down, I knew I was not confident in that. [H105]

This was an important consequence of the cognitive conflict experienced (Bao, Kim, Raplinger, Han, & Koenig, 2013, pp. 1–51). This awareness appeared to prompt students to further investigate and explore the simulation-based activities to clarify and repair their lack of conceptual understanding. The uncertainty as well as self-awareness about their inability had a combined effect in prompting students to investigate the concepts. This was confirmed by a number of students in their interviews.

> I just did not quite know how to answer it. So, I thought just put down what I knew, and then just do the simulation model, like, see if I could learn from there. [H203]
>
> I knew it (that the information I have) was not going to be exactly right. So, it pushed me to engage (in the activity) to find the information for it. [H104]

In summary, the cognitive conflict questions allowed students to notice the discrepancy between their existing knowledge and the information provided in the problem, leading to a state of disequilibrium (Limón, 2001; Piaget, 1985; Ronda, 2012). At this stage, the scaffolding function appeared to have worked on two dimensions. First, it encouraged students to think about the given concept and second, the resulting confusion precipitated students to engage in a metacognitive process, which stimulated them to further investigate the concepts to adjust their understandings (Bao et al., 2013).

3.2. Observe phase

The *Observe* phase is a central scaffolding element of the POEE strategy. After being challenged through cognitive conflict questions in the predict phase, students were guided to make observations using the simulation-based or, on fewer occasions, video activities. Examples of how students followed an inquiry process regarding the concepts observed at the sub-microscopic level through external representations are provided below.

> I saw these atoms bouncing around. I can see the molecules in a hot area moving a lot faster, and I can see how that would mix … I could see how a hot substance will influence a cold substance to get equilibrium in temperature. [H101, ref: hSim1]
>
> I see the clash and the distinctions between two edges of the molecules on the way that was spinning and specifically colliding (to each other). I got a sense of the behaviour of molecular interactions, which I suspected, but I never actually seen before in my studies. [P207, ref: pSim1]

It was evident from the above comments that the students had observed and interacted with the dynamic nature of molecules and atoms and their subsequent behaviour resulting from their movement and structure. The sub-micro level representations of the concepts in the simulation activities during the inquiry process supported students in reconciling the state of disequilibrium that they had confronted earlier. It is known that during the inquiry process, students' visualization skills can be improved with dynamic representations (Chang & Linn, 2013; Ryoo & Linn, 2012) supporting students in their conceptual understanding of the topic under investigation. As each activity progressed, students experienced various types of visual and interactive activities. A form of learning progression had taken place through the growing perception of the structure and behaviour of molecules that facilitates the transition of students' understanding from the macro to the sub-micro level (Dickson, Thompson, & O'Toole, 2016; Gilbert & Justi, 2016). This learning progression afforded the students the opportunity to apply deeper cognitive processes.

Another key procedural scaffolding technique applied in this study was the various modes of written instructional guidance that were embedded to support students' interactions with the different activities. It appeared, based on students' responses in interviews, that a strongly guided activity was the most effective scaffolding technique to facilitate their engagement in the self-directed environment (Table 8).

Many students observed that they had found it difficult to independently explore and engage with the learning modules when these were framed as open-inquiry activities. For example:

> There are some parts requiring to do some activities but not enough instructions for me. So I am struggling there. [H204]
>
> The simulation was pretty hard to understand. Because I had to play around the things myself, and it will better if there was? somebody voicing over or explain to me. [P205]
>
> If there was nothing to tell me what to do, then I probably would have stumbled around for a bit. [H205]

The above insights align with current perspectives in literature where researchers argue that instructional guidance in inquiry learning is important (Clark, Kirschner, & Sweller, 2012; Kirschner, Sweller, & Clark, 2006; Luo, 2015). Specifically, the data from this study reveal that instructional support was found to be the key element in the scaffolding strategy to facilitate students' self-directed learning in the inquiry process. However, since several students preferred the opportunity to engage in minimally guided activities, it indicates the importance of flexible instructional guidance in online settings. This identified issue suggests that further research into the context of self-directed online learning is warranted.

3.3. Explain phase

In the *Explain* phase, two types of inquiry questions were used to probe students' understanding of the concepts that they had just investigated. Concept check questions were used as a scaffolding strategy to support student inquiry enabling self-testing to ascertain which concepts had been learned. Students were required to commit to writing down their understanding in a text box embedded in the web page and press the submit button once they had completed their explanation. This strategy allowed students to participate in

Table 8
Example of student comments in favour of the strongly guided activities.

Subthemes	Examples of students quotes	Findings
Strongly guided	I follow the instruction. I went up and down few times to check this. The non-polar molecules start kind of moving away a little bit more. They break their bonds and they start to make separating whereas the polar one just stays because they are all tightly packed. [P103]	Improves visual ability, supports meaningful exploration, helps to understand the polar-nonpolar bonds
	I think it's really important to have textual instructions. If something you don't understand, it is there in front of you and you can work way through it. [H101]	Supports meaningful exploration
	Instruction says that run the model for a while and observe the bar graph on the right. So, sort of just waiting to see if anything was going to happen. And, yeah, I did notice that the temperature was decreasing when the cover was removed as the molecules start evaporating. [P105]	Improves visual ability, supports meaningful exploration, helps to understand the evaporation process
	The instructions said, see how quickly the heat is conducted from the hot object to the cold object and like from knowing that from the instruction then you are going to do with the activity clearly. [H103]	Supports meaningful exploration

their learning process by explaining their acquired or intuitive knowledge, and any critical thinking that they may have employed in the process. To demonstrate how concept check questions facilitated students' cognitive engagement, the following examples were extracted from students' written entries (Table 9).

In the first item (Q4, Table 9) students were required to agree or disagree with the statement, this approach guided students to commit to an answer and justify it. A cognitive response was required to answer a question even when the respondent's ability and/or motivation was low (Tourangeau, Rips, & Rasinski, 2000). To respond, students need to comprehend the question, retrieve relevant information from their memory and integrate this information into a decision. The example in Table 9 revealed that students were committed to opting for an answer by showing disagreement with the statement. Thereafter, student P101 explained their reasoning by referring to the strong molecular bonds (intermolecular attractions). In contrast, P104 failed to mention any reasons for such behaviour. The data revealed that these students understood the concept that molecules are vibrating in solid states, which supports the hypothesis that these types of questions are useful in the self-directed online learning. Q9 (Table 9) also appeared to promote students' reasoning skills as students demonstrated sound conceptual understanding in their responses. The first student, H206 understood the problem and addressed the reasoning correctly. This confirms that Concept check questions, in the form of inquiry questions, helped students to think and gain conceptual understanding (Kawalkar & Vijapurkar, 2013). On the other hand, H107 misunderstood the concept of vacuum as he indicated that it contained a "layer of air". This is an example of where a student had developed alternative conceptions (sometimes misconceptions) during the learning process. The nature of these alternative conceptions and misconceptions should be explored further in future research into the nature of scaffolding in online inquiry environments.

Confidence check questions were included as metacognitive elements in the *Explain* phase by providing the students with an opportunity to reflect on what they had understood from the experience of thinking about given problems. This type of question

Table 9
Role of concept check questions in supporting students' cognitive engagement.

Concept check questions	Students' written response
Q4: 'Water molecules do not move in the solid (ice)' - Do you agree or disagree? Explain.	Disagree. The molecules within a solid state vibrate! They may not move freely like water, but they are still moving small amounts. [P104] This is incorrect, molecules in solids do move, however, they do not move as rapidly, nor do they spread like that of a gas due to their inability to move. This is due to the restriction they have due to the bonds with other water molecules. Their movement never stops. [P101]
Q9: A vacuum flask (Thermos flask) is a double-wall container with a vacuum between the two walls. How does the flask keep its contents hotter or cooler than the outside air?	Since a vacuum has no particles in it, it stops conduction by allowing the particles to collide, so if there are no particles to collide with, heat won't be transferred, and the temperature will remain constant. [H206] The effect of the air on the outside of the container is kept away from the contents by a layer of air being between it and the inside layer of material which is touching the liquid. [H107]

Table 10
Examples that support the subthemes in relation to Concept check questions.

Findings	Students' quotes from interview
Aware about the inability to understand the reason	*I was not confident about the vacuum one. I choose Low confident. I know that there (in vacuum) is no heat transfer. They just remain the same temperature. But do not know the reason behind it.* [H104] *I have Low confidence. I did not really know the kinetic molecular theory. I was not too sure what that was.* [H105] *I want it like one in between (High and Low). I have the right idea, but I am sure I didn't have the right terminology or the right way of explaining it.* [P104]
Rethinking of the concepts, they learned	*When I put Low, definitely I want to learn more as well. If I put in High, then I want to sort of second guess myself and ask myself again, do I really think that I am good at it or something like that.* [P101]

followed each concept check question to engage students with what they had written and to ascertain their degree of confidence in their understanding of the concepts that they had learned. They were asked to rate their confidence level from 'very high' to 'very low' on a 4-point rating scale. This study does not focus on quantifying the percentage of students that selected the options of *High*, *Low* etc., but rather explores how the confidence check questions influenced students' thinking about their answers. The data revealed that once students encountered the confidence check questions, they became mindful of their explanation (evidence of metacognition). Examples of students' reflections in relation to confidence check questions are provided in Table 10.

It was demonstrated that when students encountered the confidence check questions (Table 10), they were prompted to reflect on their thinking and actions in term of whether they had responded correctly and at sufficient depth. In several cases, these questions improved the student's awareness and deeper thinking in the concepts that they had understood, and in the process helped them to rethink their initial understanding.

3.4. Evaluate phase

The introduction of the *Evaluate* phase represents the extension of the POE strategy proposed in this study as a potential approach to enhancing the scaffolding design in online environments through engagement of students with feedback to further facilitate reflection and evaluation of their understanding. Hattie and Timperley (2007) stated, in relation to students receiving high quality feedback, that three essential questions needed to be resolved by students in striving to achieve their learning goals: 'where am I going?', 'how am I going?' and 'where to next?'. van den Bergh, Ros, and Beijaard (2013) pointed out that the first question should address the intended learning goals. The synchronous feedback adopted in the current study essentially provided students with the goals for what they were about to learn in case students had deviated from the anticipated learning outcomes. Students' quotes confirm how feedback helped them refocus on the anticipated learning goals.

> If I did not get the feedback and if I did not know the answer, I would just carry on with not really understanding the concept. But because it gives you the opportunity to answer and then give feedback on it, yeah, I think that is really helpful. [P103]
> I did not understand until I read the feedback. I have not connected until I got the explanation. [H107]

van den Bergh et al. (2013) further pointed out that the last two questions raised by Hattie and Timperley (2007) should address what students need to know: how their current performance relates to the learning goals and what activities need to be undertaken to make progress. Synchronous feedback, as observed in this study, prompted students' awareness that their current performance (students' self-exploration and engagement with the activities) was on track (or not) thus enabling them to consider their understanding of the concept.

> There were a couple of questions in there that did give feedback, then it explained why I would get the question wrong and why I would have got it right. I found that particularly useful. [H101]

This eventually led students to encounter the third question of 'where to next' by referring them back to the activities for revisiting, re-exploring and re-evaluating their understanding. This has been a common pattern observed in student behaviour while interacting with the simulation activities. When students come across the hint buttons, or received a feedback after submitting their answer, they typically went back to the simulation activity to verify the concepts.

> When I got it wrong (received the feedback), I went up again (to the simulation). Then I cooled it down. OK, now I understand how the intermolecular bonds like just expand and contract. [H204]

It is clear that providing synchronous feedback potentially improves student engagement and learning in online settings, a finding that aligns with the research of Mount, Chambers, Weaver, and Priestnall (2009). In addition, when students realised their presumed understanding was incorrect based on the feedback, many were prompted to re-visit and re-explore the simulation model. This is an important step in the inquiry learning process.

While the *Evaluate* phase has proven critical to the cognitive development and metacognitive reflective process embedded in the core POEE scaffolding strategy, which acted as the "backbone" for the online modules, it is apparent that many students required more explicit content feedback, located earlier in the strategic process, such as inquiry questions, hints and instructional guidance used in this study. This aligns with the second question that Hattie and Timperley (2007) cite: 'how am I going?'. It seems that feedback at different stages of the modules has the ability to meet different psychological and educational purposes. Therefore, feedback is conceptualised as a many-faceted and a multi-dimensional strategy that is indispensable to students' achieving understanding of their current learning status. For example, the below examples (derived from interview data) share student' perceptions and illustrates how synchronous feedback contributed to helping the students evaluate their own understanding.

> I was recalling the previous knowledge, so I choose the charged particle one. The feedback that was given from the wrong answer I think really did clarify what was happening. [H108]
>
> I didn't realise that, and I haven't ever really thought about that, because in my mind the things obviously expand but, it's apparently not. Once I read the explanation, it was clear to me. [H207]

This data revealed that, in the self-directed online learning, synchronous feedback assisted students to evaluate, clarify, and confirm their learning. It also supported them through a structured learning progression so that they could proceed without direct supervision. Previous research also confirmed the importance of timely and frequent feedback that contributes to online learner performance (Goldsmith, 2014; Thiele, 2003).

It should be noted, a small number of students suggested that the feedback should be very concept specific as it was perceived that excessive information potentially created cognitive overload and thus detracted from their achievement of the desired learning outcomes. Therefore, it is essential that feedback be well-crafted and concept specific, qualities which not only help students to clarify their concepts but also to serve as an instructional tool in the learning process. It is possible that future development of modules needs to consider the nature and positioning of various forms of feedback in relation to the strategic stages.

4. Discussion

The rationale for the instructional design of two scaffolded online learning modules has been presented in this study; this design was informed by constructivist theory to promote students' inquiry learning. The POEE activities were designed to elicit students' initial ideas which were then used as the basis to lead students into probing their own understanding in a self-regulated way. Application of the POEE strategy in this context represents a new development in the use of this strategy in online environments within science education. The extension of the POE through the evaluate (E) phase represents a significant innovation and substantial evidence was found in this study to indicate this approach had been effective.

The results from this study have been delineated into the four key phases of scaffolding thereby conceptualizing POEE as a multimodal scaffolding strategy. The POEE strategy was implemented to support students' inquiry learning (Fig. 3).

Multimodal scaffolding is an approach that can provide support in multiple ways through combination of diverse tools in the learning environment. There is growing evidence that multiple scaffolding supports in a virtual environment can accelerate learning through inquiry practices (Li, Gobert, Dickler, & Moussavi, 2018; Puntambekar, 2015; Ustunel & Tokel, 2018). Earlier research has established that students require multiple forms of support through instructional materials, task sequencing, representations, prompts and timely interventions to learn science successfully (Puntambekar & Hubscher, 2005; Ustunel & Tokel, 2018). Nonetheless, there is evidence that despite the richness of these supports, scaffolding may not achieve its potential in the absence of direct teacher mediation and peer interaction (Palincsar, Fitzgerald, Marcum, & Sherwood, 2018). The current study does not challenge this idea directly since it did not compare student performance with and without teacher-mediated environments. However, instead this study designed and explored a new scaffolding strategy to understand how this novel approach facilitated students' science inquiry. This aimed to address the lack of published recommendations and evidence for how an individual student engages with, and enquires into,

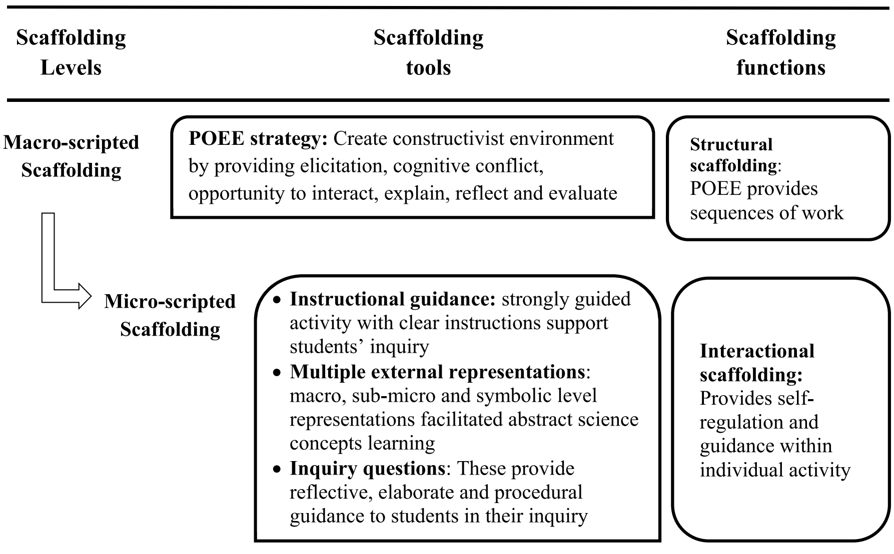


Fig. 3. Levels of the conceptualised multimodal scaffolding strategy (POEE) that was applied in online inquiry learning modules.

science concepts independently in online environment. Observation of students' progress and engagement with activities in response to this scaffolding strategy provided supporting evidence that the POEE scaffolding strategy had successfully underpinned the task sequence (macro-scripted). This study confirms that within the POEE model, as similarly reported in other studies, cognitive conflict strategies are effective enough to increase motivation among learners in order to establish a higher science balance and increase the student performance (Arguedas et al., 2018; Yang, 2010). Specifically, the provision of the opportunity for students to predict answers is a necessary part of the process for them to gain a conceptual understanding. It was also found that the provision of synchronous feedback as part of the POEE scaffolding strategy was an important element for successful outcomes in the self-directed online learning. Indeed, several findings of this study align with current thinking in published research, such as that students who received immediate feedback performed better on subsequent inquiry tasks (Li et al., 2018) and can develop effective self-regulation skills (Basu, Biswas, & Kinnebrew, 2017). Students require, however, a certain level of cognitive engagement to interpret the feedback and make the necessary accommodations to their conceptual understanding (Louwrens & Hartnett, 2015). Van der Kleij, Feskens, and Eggen (2015) in a review, argue that elaborate feedback can bring higher learning outcomes, especially for the higher order learning constructs. Thus, feedback, through which students receive immediate support, is found to be a key aspect of inquiry learning in the self-directed online environment.

The second tier of scaffolding tools (micro-scripted) embedded in the POEE strategy functioned as interactional scaffolding by incorporating question prompts, instructional guidance and multiple external representations. The findings support the notion that learning with prompts increases learners' interaction and self-regulation during the learning activity. This finding is aligned with other studies, particularly in the virtual environment where Müller and Seufert (2018) argued that learning with prompts may foster self-efficacy and therefore self-regulation across learning sessions. Instructional guidance regulated students' activities and supported students' inquiry, multiple external representations supported the construction of mental models and finally inquiry questions provoked reflective, elaborative and procedural guidance in the inquiry process. This conceptualisation of the scaffolding strategy was supported by the notion of structural and interactional scaffolding as proposed by (Hammond & Gibbons, 2005).

As an overarching strategy, the POEE environment promoted student interactions with the learning modules and the opportunity to engage cognitively, which are the key ingredients for successful learning reported by Rapp (2005). The second level of scaffolded support worked in concert to enhance students' engagement and provided an opportunity for them to inquire into the scientific phenomena in multiple ways. In short, the POEE strategy signifies a new development in the use of the original POE strategy to explore abstract science concepts in online inquiry-based settings.

4.1. Generalisability and limitations of this study

The POEE scaffolding strategy directly extends the well-characterised POE pedagogical design supporting the generalisability of findings from this study. It is proposed that this POEE strategy may be adopted as a scaffold for students' interactions when determining the quality of students' engagement in online learning modules. Since students enrolled in introductory science courses often possess similar prior learning experiences in tertiary contexts, it is proposed that the findings could be applied to a range of activities in STEM disciplines. However, it is also recognised that restricting this current study to the context of an introductory science course at a single university resulting in a small sample size may influence the generalisability of the findings. The multiple sources of qualitative data have led to valuable insights that can be used to inform the development of additional effective scaffolding strategies to be used in self-directed online modules that can be translated between same level programs of tertiary institutions. There are few studies that demonstrate generalisable outcomes (e.g., Karamustafaoğlu & Mamlok-Naaman, 2015; Şeşen & Mutlu, 2016) but sharing the outcomes for individual contexts will potentially inform instructional design through a combined weight of evidence. In addition, the application of this modified scaffolding strategy in the context of online self-directed environment is novel, therefore, it does need further testing to determine whether the findings will be generalisable to different levels of science programs.

This study assumes that the use of simulations will enhance student understanding of complex scientific phenomena irrespective of student experience with the technology. Some students may lack even basic computer skills necessary for learning in a computer-mediated environment; the achievement of this core skill was not tested in this study however no instances of poor engagement with activities were observed attributable to poor technological competency. While such students may be sparse in this digital age, these students may actually experience this impediment to their learning in the context of the learning environment adopted in this study. Further, students who experience various learning difficulties may also require specialized support to assist their learning, to enable access to these environments successfully. In addition, as the study reported, there may be some students who have developed a rigid method of monitoring their own understanding of a subject, and thus may not recognise or value feedback that is delivered through the web interface (Dedic, Rosenfield, Cooper, & Fuchs, 2001). Despite such inherent limitations, this research has potential to add to the understanding of how scaffolding strategies influence the instructional design of a self-directed online inquiry learning environment therefore may become increasingly generalisable once evidence in related studies is published. By linking pedagogical theory, constructivist environments, web-based instructional design, inquiry questions, and multiple external representations, educators may gain a better synthesis of a self-directed inquiry-based learning environment that can better facilitate student engagement and learning in online context.

The modules designed in this study are most suitable for application in either general chemistry or upper level high school chemistry contexts and may be used either as independent learning activities during class or as an off-campus activity as part of a blended learning environment. A limitation is that additional scaffolding or instruction might be required to support students who have low or absent prior chemistry knowledge, this aspect was explored as part of this study however will be reported separately due to brevity.

Since the elements of science and engineering disciplines are similar in nature, and engineering students are often required to integrate knowledge and practices from the sciences, the POEE framework might provide a foundation for problem-based learning scenarios in engineering discipline to investigate how it support students' independent learning.

5. Conclusion

This study provides a positive exemplar of how to implement an inquiry-based learning in an online environment while considering no immediate teacher or peer support. The findings suggest that the overarching POEE framework and effective use of the pedagogical tools such as multiple external representations, inquiry questions, and instructional guidance can potentially mitigate the need of immediate teacher and peer support in an online environment. However, recent research also warrants more attention as challenges increase when scaffolding is employed in the self-regulated learning environments without direct teacher support (Palincsar et al., 2018). Some researchers argue the effectiveness of combining multiple scaffolding tools since these tools had varying effects on students' understanding of a problem (Zydney, 2010). Therefore, Ustunel and Tokel (2018) suggest that technology-based scaffolds and their integration within a learning setting must be considered carefully by designers taking into consideration both goals and contexts. In line with this argument, this study recommends that there are need for studies in a larger scale and in other domains about the use of multimodal scaffolding, particularly the proposed POEE strategy in the self-directed online context without the personal, direct, synchronous guidance by a teacher or peer.

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Appendix A. Supplementary data

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