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Augmenting foundational scaffolding principles by examining the workings of fixed and adaptive scaffolds

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Abstract
This study aimed to add greater particularity to existing principles of scaffolding by investigating the implementation of fixed and adaptive scaffolds in a design-based learning (DBL) environment. Data from observations through video recordings, students' worksheets and student interviews were collected and analysed. The analysis of data is presented in three vignettes. The vignette describes the workings of fixed scaffolds (FS) and adaptive scaffolds (AS), and how they worked or did not work independently as well as together. The analyses provided the foundation to augment the scaffolding principles suggested by Puntambekar and Kolodner (2005). Specific augmentations include breaking down broad goals into narrower and more focused ones; analysing multiple sources for timely diagnosis; complementing verbal interactions (AS) with illustrations or worksheets (FS); and introducing individual, groups and whole class discussions at a strategic time. It is such kinds of specificity, structure and directness that should be added to the SP. Practical and conceptual implications are discussed to inform fundamental scaffolding principles.

Keywords: Scaffolding principles, fixed scaffolds, adaptive scaffolds, knowledge integration, design-based learning

Introduction

In its original conceptualisation, scaffolding is used to explain the interaction between a tutor and a child that assists the child in solving a problem and accomplishing a more complex task that may be unachievable without any assistance (Wood, Bruner, & Ross, 1976) [46]. In this study, scaffolding is defined as a temporary structure or mediated action, guided by an assessment of a learner's needs to help the learner analyse a task and understand the procedures to accomplish it (Pea, 2004; Puntambekar & Kolodner, 2005; Stone, 1998) [27, 28, 36]. Fixed and adaptive scaffolds (Azevedo, Cromley, Winters, Moos, & Greene, 2005) [1, 26], or hard and soft scaffolds (Saye & Brush, 2002) [31] can be used to help students perform complex problem-solving tasks (Reiser & Tabak, 2014) [30]. Fixed scaffolds are static support planned prior to the implementation of lessons (Azevedo *et al*., 2005; Saye & Brush, 2002) [1, 31]. For example, prompts are used to support students' cognitive and metacognitive processes during knowledge construction (Davis & Linn, 2000; Ge, Planas, & Er, 2010) [7, 12]. Adaptive scaffolds are more dynamic and situational where teachers conduct ongoing diagnoses on students' emerging performances and provide adequate support till they can take responsibility for their own learning (Azevedo *et al*., 2005; Saye & Brush, 2002) [1, 31].

A synthesis of previous studies (Oppl, 2016; Puntambekar & Hübscher, 2005; Puntambekar & Kolodner, 2005; Smit, Eerde, & Bakker, 2013; Stone, 1998; Taber, 2018; Van de Pol, Volman, & Beishuizen, 2010) [25, 27, 28, 35, 36, 39, 45] found that the foundational scaffolding principles are: (a) establishing shared understanding of common goal; (b) ongoing diagnosis; (c) providing dynamic and calibrated support; (d) utilizing dialogic interactions as a primary means to make scaffolding decisions; and, (e) fading or transferring of responsibility. These foundational principles have not been adequately taken into consideration when teachers design and implement scaffolding (Puntambekar and Hübscher, 2005) [27]. In practice, these foundational principles should provide a basis for guiding the design and implementation of scaffolding in an inquiry learning environment (Puntambekar & Hübscher, 2005) [27]. Yet, these scaffolding principles lack the kind of particularity and precision that can actively inform practice (Van de Pol *et al*., 2010) [45]. For instance, scaffolding practices based on the principle of using dialogic interactions have an assumed fluidity that is shaped by what emerges in the learning context. In this fluid but progressing learning context, the visage of the dialogues should become more and more defined if not more circumstantiated in nature. These principles — if developed over time with more research such as this one, from different perspectives and using different methods — can develop into essential principles used by teachers, instructional designers and researchers of instructional design (Pea, 2004; Taber, 2018; Van de Pol *et al*., 2010) [26, 39, 45].

This article reports the first cycle of a design-based research (DBR) conducted in a design-based learning (DBL) context that included fixed (i.e., guided questions in the worksheets) and adaptive scaffolds (i.e., facilitator's scaffolding practices, primarily questioning and prompting) that matured in tandem with the aforementioned scaffolding principles. These fixed and soft scaffolds were to add more particularity to these scaffolding principles, making the complex DBL tasks more manageable, achievable and productive for students to learn how to integrate knowledge. The main research questions guiding this study were: a) How do scaffolding principles inform the design and implementation of fixed and adaptive scaffolding? b) How does the implementation of fixed and adaptive scaffolding, in turn, inform the development of more apposite scaffolding principles?

Literature Review and Conceptual Framing

This section will review the existing literature in relation to the framing of the study as illustrated in Figure 1. The key dimensions include foundational scaffolding principles, fixed scaffolds (FS), adaptive scaffolds (AS), the interaction between principle and practice in an inquiry-based learning environment modelled after design-based learning (DBL) and knowledge integration (KI). The acronyms in parentheses will be used in the article for brevity purposes.

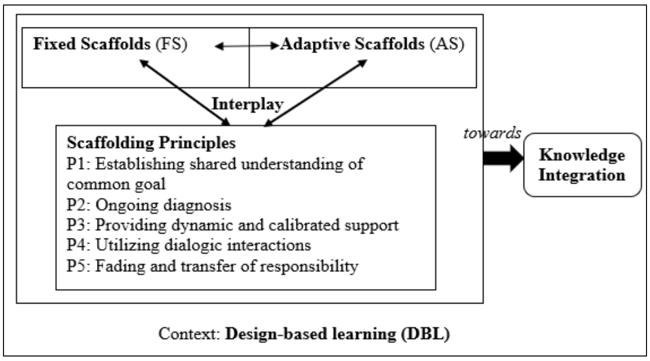

Fig 1: Conceptual framing: Analyzing the interplay between foundational scaffolding principles and the implementation of fixed and adaptive scaffoldings in a design-based learning environment

Scaffolding Principles

There are at least five fundamental principles of scaffolding: common goal; ongoing diagnosis; dynamic and adaptive support; dialogues and interactions; and, fading or transfer of responsibility (Oppl, 2016; Puntambekar & Hübscher, 2005; Puntambekar & Kolodner, 2005; Smit *et al*., 2013) [25, 27, 28, 35]. Several terms are used by these researchers — including features, characteristics, and elements — but this study will use the term "principle" to convey the development of rules of thumb that can be used as a guide for making scaffolding decisions across different inquiry learning contexts.

The first principle (P1) is establishing a shared understanding of a common goal. The common goal is attained when teachers and students develop a sense of shared ownership of a task (Puntambekar & Hübscher, 2005) [27]. While the main goals are largely shaped by curriculum requirements, the subgoals may shift as they are negotiated by the actors engaged in the inquiry learning contexts. FS and AS need to share these common goals (Tabak, 2004) [37].

The second principle (P2) involves carrying out ongoing diagnosis, specifically to identify learning gaps that prevent learners from making progress in the inquiry learning process (Puntambekar & Hübscher, 2005; Smit *et al*., 2013; Van de Pol *et al*., 2010) [27, 35, 45]. Some have referred to this ongoing diagnosis as "dynamic assessment" (Pea, 2004) [26] or "formative assessment" (Shepard, 2005) [33]. Diagnosis on students' needs helps teachers make scaffolding decisions on how to choose and adapt FS and AS to help students achieve intended learning goals (Reiser, 2004) [29]; and when to fade or enhance scaffolding (McNeill, Lizotte, Krajcik, & Marx, 2006) [24].

The third principle (P3) is utilizing dynamic and calibrated support. Based on the findings from ongoing diagnosis, teachers constantly refine and adjust scaffolding to support student learning (Puntambekar & Hübscher, 2005; Smit *et al*., 2013; Stone, 1998; Van de Pol *et al*., 2010) [27, 35, 36, 45]. Wood *et al*. (1976) [46] used the term "contingency" to describe a teacher's adaptive role in scaffolding. Scaffolder's dynamic and calibrated support or contingency must be based on a diagnosis of the learner's state of understanding (or misunderstandings), and that the learner made progress with the facilitator's situated help, and that the learner is able to eventually perform the task independently (Van de Pol *et al*., 2010) [46].

The fourth principle (P4) is utilizing dialogues and interactions to give students the opportunities to articulate their ideas and make their thinking visible to teachers and peers (Puntambekar & Kolodner, 2005; Smit *et al*., 2013; Tabak & Reiser, 1997; Van de Pol *et al*., 2010) [28, 35, 38, 45]. In principle, active participation from students is needed during scaffolded instructions to enable teachers to see, diagnose and monitor students' understanding; as well as to encourage knowledge building among students when they share, confront and negotiate ideas to achieve intersubjectivity (Puntambekar & Kolodner, 2005; Van de Pol *et al*., 2010) [28, 45]. While scaffolding is fundamentally dialogic and interactive in nature (Bae, Glazewski, Brush, & Kwon, 2021; Puntambekar & Kolodner, 2005) [2, 28], greater clarity is needed on how scaffolders can address the tension between open-ended dialogicality and more directed interactions.

The fifth principle (P5) is fading and transferring responsibility. In principle, scaffolding is gradually faded once students have developed the ability to complete the learning tasks independently (Pea, 2004; Puntambekar & Hübscher, 2005; Wood *et al*., 1976) [26, 27, 46]. There is a transfer of responsibility from teachers to students so that the students can take control of their own learning (Puntambekar & Kolodner, 2005; Taber, 2018) [28, 39]. Students will also be able to transfer the skills they have mastered to solve similar tasks once the scaffold is faded (Wood *et al*., 1976) [46].

Oppl (2016) [25] conducted a study on AS (i.e., modelling) in light of two scaffolding principles: contingency (P3) as well as fading and transfer of responsibility (P5). His study investigated how these two principles could be implemented in a vocational training programme to help students articulate ideas in a collaborative learning environment. This study demonstrated that timely, tailored support and gradual fading, helped students construct their collaborative mental models. However, this study did not demonstrate clearly how these principles were implemented in the AS design and implementation, and vice versa. There are, however, studies that have investigated specific FS or AS in light of a particular scaffolding principle. For instance, Belland, Glazewski, and Richardson (2008) [3] demonstrated that a shared understanding of focused learning goals (P1) within an inquiry learning context is essential. Without the necessary FS and AS, students' cognitive capacity to focus on the primary learning tasks may be distracted (Belland *et al*., 2008) [3]. Another study by van de Pol and Elbers (2013) [44] suggests that when AS is used for diagnosing (P2) students' actual understanding, the decisions lead to a more targeted calibrated support (P3) which improves student learning. Other studies have found that gradually faded (P5)

FS and AS prompts helped students develop conceptual understanding and reasoning skills (Fang, Hsu, & Hsu, 2016; McNeill *et al*., 2006) [11, 24]. Dialogic and interactive AS could help foster independent learning among students (Bae *et al*., 2021) [2].

Scaffolding Designed-based Learning (DBL) and Knowledge Integration

Design-based Learning (DBL) is a special form of project-based learning (PBL) (Lin, Wu, Hsu, & Williams, 2021; Silk, Schunn, & Cary, 2009; Tati, Firman, & Riandi, 2017) [20, 34, 41]. DBL focuses on integrating knowledge from different disciplines to solve ill-structured, real-life issues through an iterative cycle of the engineering design process (English, 2016; Go´mez Puente, van Eijck, & Jochems, 2013; Lin *et al*., 2021) [9, 15, 20]. Design processes involve identifying design problems, creating, testing, evaluating and redesigning a design solution (English & King, 2015; Go´mez Puente *et al*., 2013; Lin *et al*., 2021) [10, 15, 20]. Making connections between design activities, concrete artefacts and relevant conceptual knowledge is crucial in DBL (English & King, 2015; Silk *et al*., 2009) [10, 34]. While DBL has been shown to be effective in enhancing students' content knowledge and scientific reasoning (English & King, 2015; Puntambekar & Kolodner, 2005; Silk *et al*., 2009) [10, 28, 34], seeing the connections and consciously joining the connections between a task can be a significant challenge for students (Berland, Steingut, & Ko, 2014; English & King, 2015) [4, 10]. Students also tend to treat DBL tasks as craft activities, paying less attention to the concepts underlying their designed artefacts (Puntambekar & Kolodner, 2005) [28]. For example, students could suggest multiple solutions for designing and refining their designs, but they did not associate their designs with disciplinary knowledge (Berland *et al*., 2014) [4].

DBL can only become a productive context for student learning if appropriate scaffolds are provided to them (Go´mez Puente *et al*., 2013; Hmelo, Holton, & Kolodner, 2000; Puntambekar & Kolodner, 2005) [15, 17, 28]. For instance, FS such as worksheets maximises full affordances of DBL by guiding students to construct scientific knowledge, see connections between design stages and articulate scientific reasoning (Go´mez Puente *et al*., 2013; Puntambekar & Kolodner, 2005) [15, 28]. Several AS were found to be effective in enhancing students' knowledge and systematic thinking when they design an artefact. These strategies include introducing scientific terminology; conducting reflective discussions; planning self-directed and problem-solving tasks; asking questions, structuring activities; providing dynamic and timely feedback; and connecting new design task to students' prior knowledge (Go´mez Puente *et al*., 2013; Hmelo *et al*., 2000; Puntambekar & Kolodner, 2005) [15, 17, 28].

DBL is a promising pedagogy to help students integrate knowledge from different disciplines (English & King, 2015; Lin *et al*., 2021; Tati *et al*., 2017) [10, 20, 41]. KI is a process that involves students eliciting ideas to acknowledge their knowledge gaps, add on ideas to existing knowledge, distinguish ideas to identify the most appropriate solutions and seek evidence to support valid connections between ideas (Chiu & Linn, 2011; Davis & Linn, 2000; Schwendimann & Linn, 2016) [6, 7, 32]. The main aim of scaffolding KI is to help students integrate their prior and new knowledge, and subsequently, to enhance their mental models of scientific concepts (Chiu & Linn, 2011; Davis & Linn, 2000) [6, 7]. Various types of FS including question prompts have been found to be effective in supporting students to integrate knowledge (Davis & Linn, 2000) [7]. For example, self-monitoring prompts help students reflect on their learning while activity prompts focus students' attention on specific aspects of their task (Davis & Linn, 2000) [7]. KI prompts help learners compare ideas, seek evidence, transfer ideas and construct valid relationships between concepts (Chen & Bradshaw, 2007) [5]. Research has shown that FS and AS can be used concurrently to support KI. For instance, in Gerard and Linn's (2016) [13] study, the teachers used the information gathered from timely diagnosis (SP) to provide AS (i.e., asking questions) and FS (i.e., glossary lists) to help students integrate knowledge.

Design Framework

A real-life design task (English & King, 2015) [10] drove the DBL challenge. In this study, we designed a real-life design task to cultivate student understanding of KI. The students were required to design a water filter which could provide clean water to villagers by integrating knowledge from science, technology, engineering, arts and mathematics (STEAM). Specifically, the water filter must fulfil five inter-connected criteria: filtering speed; amount of filtering materials; clarity of filtrate; cost; and usability and attractiveness. In fulfilling these criteria, the students would learn about water crisis, concept of filtration, physical and cost attributes of filtration materials, application of basic arithmetic operations (length, mass, time, volume) and how to integrate these elements to fulfil the design requirements and design process. Based on the literature on DBL (English & King, 2015; Lin *et al*., 2021; Puntambekar & Kolodner, 2005) [10, 20, 28], we articulated a simplified DBL cycle that consisted of six major stages: problem identification; problem exploration; solution development; initial design evaluation; solution redesign; and decision making.

We designed the FS (mainly in the form of guided questions in the worksheets) and AS (mainly in the form of oral questions and discussion as well as explanations as the need arises) based on the five scaffolding principles. The FS and AS helped students analyse the issue, gather valid information, generate solutions, evaluate and reflect on the solutions using knowledge from the STEAM subjects at each DBL stage as shown in Table 1.

Table 1: Samples of FS and AS in relation to DBL stages

DBL stages	Examples of FS and AS
1. Problem identification ▪ analyze design issue ▪ define design task ▪ ask questions relevant to the design problem.	Teacher facilitates group and whole class discussion *FS: Worksheet A Explain the design task. ▪ What do you need to design? ▪ What are the design criteria? *AS: Facilitator asks prompting questions during whole class discussion

	▪ "What is the meaning of design criteria?" ▪ "Which design criterion do you wish to redefine?"
2. Problem exploration ▪ explore features of filtering materials ▪ discuss experimental results	Teacher facilitates group and whole class discussion *FS: Worksheet B (record data in a table) AS: Instruction and prompting questions e.g., "Record the time taken for 150ml of water to pass through the stone. What did you notice?"
3. Solution development ▪ design water filter: individual, followed by group ▪ conduct experiment to test design	Teacher facilitates group and whole class discussion FS: Worksheet C Choose five filtering materials to construct your water filter. Explain your choice. ▪ How does it help to fulfil the design criteria? AS: Instructing and prompting questions e.g., "Compare your design with your group members. What are the differences between your designs?"
4. Initial solution evaluation ▪ identify strengths of design ▪ identify weaknesses of design	Teacher facilitates group and whole class discussion FS: Worksheet D Explain the strengths of your design. ▪ Which criteria has it met? ▪ What is the evidence? AS: Facilitator defines terms during whole class discussions e.g., "Evidence is the data you have collected from the experiment. What evidence do you have?"
5. Solution redesign ▪ redesigned solution ▪ conduct experiment to test redesigned solution	Teacher facilitates group and whole class discussion FS: Worksheet E Explain how you can improve your initial design solution. ▪ Which design criteria is not met? AS: Facilitator asks reflective questions during group discussion e.g. "What have you learned from the initial design?"
6.Decision making ▪ compare two solutions ▪ make design decision	Teacher facilitates group and whole class discussion FS: Worksheet F Discuss which design (initial or redesigned water filter) solves the design problem better. AS: Facilitator asks prompting questions during group discussions e.g. "You have chosen the redesigned water filter. Can you give specific reasons to support your choice?"

Methodology

Research Design

We investigated how FS and AS added particularity to the scaffolding principles using design-based research (DBR). DBR attempts to solve complex educational problems through an iterative development of research-based solutions situated in real-life settings (Design-Based Research Collective, 2003) [8]. In this regard, the DBR approach is a systemic means to describe and interrogate the interaction between the foundational scaffolding principles with FS and AS in a DBL classroom. This DBR study went through two cycles. Each cycle consisted of three phases: problem analysis; solution design and development; and iterative implementation, evaluation, and refinement (McKenney & Reeves, 2012) [22]. This article only reports the first cycle of our DBR research.

During the phase of problem analysis, we referred to the existing literature to identify the scaffolding principles and the design features of FS and AS which could facilitate knowledge integration in an inquiry learning environment. Concurrent interviews with five teachers reaffirmed the challenges that students faced with knowledge integration and provided greater clarity for the design of AS and FS. During the solution design and development phase, we designed the design task, FS and AS in conjunction with the five scaffolding principles. The first DBR cycle allowed us to understand how the five scaffolding principles guided the initial design of FS and AS to help students integrate knowledge as well as the challenges faced by the students in this process. The data was analysed for the purpose of improving the scaffolding design as well as adding granularity to the existing design principles, for the second DBR cycle.

This research involved 27 Year 7 students from a public school in Malaysia. Malay language was the primary medium of instruction. There were 16 separate 1-hour lessons over the period of four weeks. The students were randomly divided into nine groups of three students. The first author, who also played the role of the facilitator, has 10 years of experience in teaching science at the secondary level.

Data Collection and Analysis

We collected four types of data, namely: video recordings of all lessons, students' responses to the guided questions in the worksheet (FS), student interviews and researcher notes. The researcher translated the data from Malay language to English. The transcribed classroom recordings were coded using a constant comparison method. As Glaser (1965) [14] stressed that "while coding an incident for a category, compare it with the previous incidents coded in the same category" (p. 439), the researchers regularly checked and compared the codes across the six major design stages and across the nine student groups as new codes emerged. The data was coded by three coders. The first and the second author were two of the coders. The third coder is an academic at a US-based university with no direct involvement with this study other than being a coder and peer debriefer.

The students' progression in knowledge integration (KI) was assessed using an adapted KI scoring scheme (Lee & Liu, 2010; Liu, Lee, Hofstetter, & Linn, 2008; Schwendimann & Linn, 2016) [19, 21, 32]. This scheme examined the diversity and coherence between concepts or evidence in explaining the design solutions. The students' responses to FS were assessed as six progressively more sophisticated levels of explanation as shown in Table 2.

Table 2: Knowledge integration (KI) scoring scheme

KI level	Score	Description	Examples
No response	0	Students do not provide any response	
Off task	1	Students do not elicit relevant ideas/ do not use relevant theory or empirical evidence to connect ideas	500 ml plastic bottle, pen, scissors, plastic measuring cup, retort stand
No link (Intra subject knowledge)	2	Students elicit and connect normative ideas from a single subject/ use relevant theory or empirical evidence from a single subject to connect ideas.	To design a water filter to help villagers filter dirty water
Partial link (One link without justification)	3	Students make a connection between normative ideas from two subjects WITHOUT using relevant theory or empirical evidence to make a connection between two subjects.	To design an environmental-friendly water filter. This filter can supply clean water to villagers who face a clean water shortage issue. It needs to be able to filter 150ml of water within two minutes.
Full link (One full link with justification)	4	Students make a connection between normative ideas from two subjects AND use relevant theory or empirical evidence to make a connection between two subjects	We need to design a water filter. This aims to filter dirty water for villagers facing clean water issues. The design criteria include attractiveness, cost-saving and produce clean water.
Complex link (At least two full links with justifications)	5	Students make two/ more connections between normative ideas from at least two subjects AND use relevant theory or empirical evidence to make two/ more connections between at least two subjects.	To design an environmental- friendly water filter. The aim is to help villagers staying in remote areas to get clean water. It needs to fulfil four criteria: cost-saving; produce clean water; attractive; and filter 150ml of water in two minutes.

The students' responses were scored by two coders - The first author and a high school teacher who has vast experience in marking Malaysian high-school standardized exams. The teacher merely served as a coder and peer debriefer.

A few strategies were used to strengthen the trustworthiness of this study. First, the researchers collected multiple data sources such as video recordings, students' worksheets, student interviews and self-reflection journals for data triangulation. Second, all transcribed data were coded by three coders as explained in the previous section. The three coders chose one response and coded the data separately. Then, the codes were reviewed and revised based on the consensus of the three coders. Once agreement was reached on the coding schemes, all responses were coded. Next, the coders discussed their coding results and explained their coding decisions until consensus was reached. Across the entire process, approximately 10% changes were made. The third strategy involved the documentation of data which allowed for an audit trail.

Research Findings

Three salient vignettes are used to describe two student groups that provided the most contrasting insights in light of the research questions. Group A—consisting of three girls, Aishah, Allie and Amy—was generally quiet but diligent in completing all the tasks on time. The group started off strong, and as a result did not receive much AS. They struggled with knowledge integration in the later stages of DBL. Group B consisted of three boys: Ben, Baki and Bruce. Because they fell back early in the DBL stages, they received more AS. The contrasting results provide some insights into the role of AS and FS in light of emerging granularity for the scaffolding principles. Figure 2 shows the KI scores achieved by Group A and Group B.

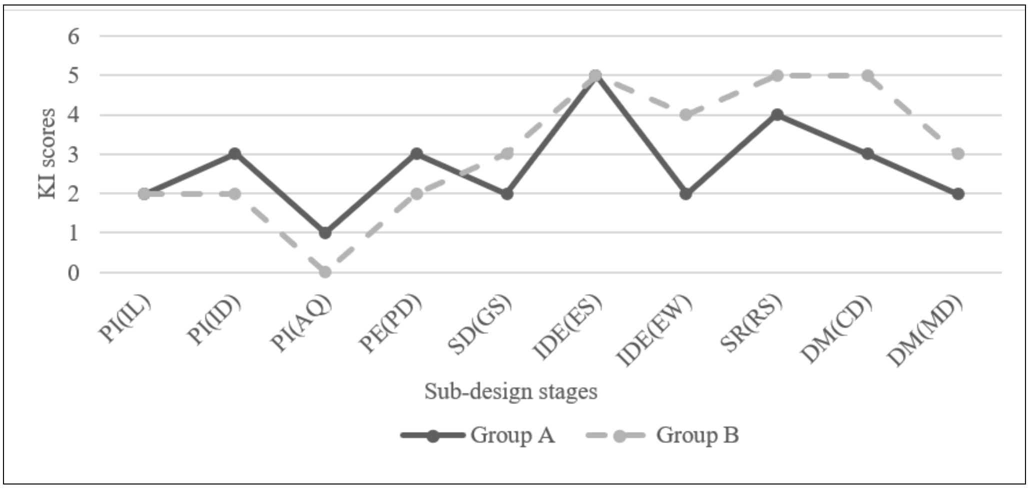

Fig 2: Group A and Group B's KI scores across six major design stages

Notes

PI(IL): Problem identification (identifying leaning issue); PI(ID): Problem identification (Identifying design solution): PI(AQ): Problem identification (Asking questions); PE(PD): Problem exploration (Predicting); (SD)GS: Solution development (Generating solution); IDE(ES): Initial design evaluation (Evaluating strengths); (IDE)EW: Initial design evaluation (Evaluating weakness); SR(RS): Solution redesign (Redesigning solution); (DM)CD: Decision making (Comparing design solution); (DM)MD: Decision making (Making design decision)

Vignette 1: Early emerging interaction of scaffolding principles and practice

The facilitator used P1 (common goal) and P2 (ongoing diagnosis) to develop the guided questions in Worksheet B – the primary fixed scaffolds (FS) tool used in the instructional process. At this stage, the FS was designed to help the students focus on the design process, synthesise or integrate from different knowledge bases and work towards P1. It also functioned as a tool to diagnose (P2) students' progress. In this context, P1 and P2 drove the design and usage of the guided questions in the worksheet (FS). The students' responses on the worksheet were used to guide the adaptive scaffolding (AS) decisions.

In this scenario that happened at the fourth DBL stage, the FS helped the students predict the effects of using different amounts of filtering materials on water clarity, cost and filtration speed. This was to ensure that the students know the relationship between different variables. Both student groups responded to FS independently without any AS. The responses from the workshe *et al* lowed the facilitator to diagnose (P2) the specific problems faced by the students. The facilitator found that five out of the nine student groups, including Group A and Group B, either made wrong predictions or could not explain their predictions precisely. For example, Group A scored three points (partial link) as they could make all predictions correctly. Group B scored two points (no link) as they wrongly predicted that the cost of constructing a filter would decrease. However, both groups did not provide any explanation for their predictions. The facilitator's scrutiny of the students' responses (P2) revealed two problems with FS. First, the ambiguous wordings in the FS caused confusion as the students might not know how comparisons should be made (i.e., against how many types of material). Second, both groups overlooked the explanation part due to the presentation of the FS.

In terms of the augmentations of the scaffolding principles, three key analyses emerged from these representative critical incidents: First, P1 could have informed the FS to be more structured and unambiguous. This would help students focus on the common goals of the tasks. Second, strategically timed AS must be planned based on common goals, perhaps expressed more explicitly in terms of milestones (P1) so that specific gaps and confusions could be identified proactively. Third, P3 must be provided before moving to the next phase of DBL. If learning gaps aren't addressed, the students would have proceeded without a clear understanding of the relationship between various variables.

Vignette 2: AS decisions augment P3 and P4

In this vignette, the students began to design their water filter at the solution development phase. The guided questions (FS) in Worksheet C were designed based on P1 (common goal), primarily to help the students evaluate and identify the underlying principles of making a water filter. The students must choose five filtering materials from nine materials made available by the facilitator.

The information derived from diagnosing (P2) the students' worksheets at the previous stage provided critical information to inform following AS decisions. This AS decision was also informed by P3 (calibrated support) to provide explicit instruction to address gaps in students' understanding. As a result, the facilitator took pre-emptive actions by modelling how the students should consider the underlying reasons for selecting their filtering materials. The following is one such example of how whole class interaction played out at the fifth design stage:

Facilitator: Let's say that I choose fine sand as one of my filtering materials. How much does it cost?

Student 1: RM 2.50 (per unit)

Facilitator: Sand can be quite expensive compared to other filtering materials. You may need to consider the amount of fine sand to reduce the cost. Any other reasons for choosing fine sand?

Student 2: The space between fine sand is narrow, so water becomes clearer.

Facilitator: How does the narrow space make water clearer?

Student 3: … the larger pieces of dirt can be filtered out… The larger dirt cannot pass through the narrow space.

Using fine sand as an example, the facilitator modelled how to better justify the selection of materials from the aspects of cost and water clarity. This AS move was largely informed by P2 and P3. It meant that the facilitator decided the type of calibrated support based on her diagnosis of the students' understanding.

Whole class scaffolding breaks down: Group A doesn't realize feedback is for them

Following the above whole class modelling, the students proceeded to answer the guided questions (FS) while the facilitator visited each group. The facilitator's diagnosis (P2) on the students' responses in the worksheet found that most of the groups, including students in Group A, provided written responses that lacked depth when asked why they chose a specific material (no link - 2 points). For instance, Group A wrote: "Stone. It can filter water quickly." and "Gravel. It is low-cost." In this process, the facilitator recognized two issues that signalled limited KI. First, the students only justified the selection of a filtering material based on a single, simplistic reason. Second, they did not support their responses with empirical data or valid reasons. This data again shows that students need FS that are more explicit, so that they will learn to justify the selection of the filtering materials from various aspects with valid reasons.

The facilitator tried to address these gaps again through another series of directed instruction and feedback at the whole class level. But this approach was largely ineffective. Most groups, including Group A, did not realise that the feedback given to the whole class was relevant to their group. Group A's written responses remained as superficial as before, without showing any progress. For instance, they wrote that "Cotton. It can absorb water" and "Marble. The cost is low."

The students struggled to discern from the whole-class discussion the key ideas most relevant to their own groups. These data suggest that P3 (calibrated support) needs to be applied in a way that is clearly directed to the group that needs it. The facilitator can provide whole class scaffolding whenever possible, especially when the majority of students share similar learning gaps. However, feedback in the form of whole class scaffolds can easily be overlooked by learners if it is not clearly directed to specific persons or groups, or specific issues. As such, facilitators should also provide explicit reference to the specific groups when necessary. The facilitator's actions in the next part of the vignette reinforce this notion while providing practical clues on how this can be carried out.

Directed feedback makes a difference for Group B: P3 and P4 refined

The facilitator's actions with Group B would provide a contrasting account to Group A. Here, P3 (calibrated support) and P4 (dialogues) interact with AS in a way that helps students make progress. From the on-the-spot diagnosis by the facilitator, Group B had similar superficial responses as Group A. With Group B, the facilitator provided support by asking questions to understand their current understanding. For example, she prompted the students to justify the selection of gravels using empirical data by asking "Can you give any evidence from the exploratory activity to support your argument (water filters through gravel more quickly)?" The students responded that the filtering time was 17.3 seconds and compared it with the longer filtering time of other materials. The facilitator further prompted them to consider the characteristics of gravels from different aspects, asking "Is there only one advantage for selecting gravel?"

This seemed to also help the students become explicitly aware of their own learning gaps. Ben, one of the Group B members, answered, "...It is cheap. It only costs RM 1 per (unit)." The facilitator summarized that "There are many reasons for choosing a filtering material such as what it filters, water clarity, filtering time and cost. Each reason needs to be supported with evidence or logical arguments." Finally, she asked the students to evaluate their responses in the worksheet based on her feedback.

After receiving the small-group scaffolds, they could justify the selection of fine sand (complex link - 5 points) as "It filters out big size substances as the spaces between the fine sand granules are narrow. Thus, the water becomes clearer. Its mass is low, making the water filter more portable." This data indicated that directed feedback was essential. Several students recognised it, with one of them saying during the interview, "Teacher checked our answers and told us our mistakes or what is lacking in our answers...we only explained about the filtering time, she commented that we should explain other aspects, such as cost etc…"

Comparing the analysis of Group B to that of Group A reinforced the aforementioned added granularity to P3–facilitator can provide whole class scaffolding but needs to ensure that groups are aware that certain feedbacks are more relevant to specific groups. Unlike Group A, Group B received this directed feedback and as a result exhibited higher degrees of KI. This also adds to P4–whole class dialogues may not be enough. The facilitator must help groups identify feedback most relevant to each respective group.

Vignette 3: Interactions between P2 and P5 facilitate learning

Vignette 3 took place towards the end of the DBL, at the decision-making stage. The guided questions in Worksheet F (FS) were designed based on P1 (common goal), primarily to get the students to compare their initial and redesigned water filter as well as to identify the water filter which best fulfilled the design criteria. The P1-based FS and the subsequent AS were designed to help students evaluate the strengths and weaknesses of their two design solutions.

The responses from the worksheet revealed gaps in students' understanding (P2). The facilitator realised at this point that the students needed AS so that they could better understand how to use the FS provided to explain their design. The AS decision was informed by P3 (calibrated support). The facilitator adopted an initiate-response-feedback (IRF) strategy to help the students compare their designs during a whole-class discussion. One of the examples is shown below:

Facilitator: You must compare your initial and redesigned water filter from these five aspects: filtration rate; water clarity; cost; aesthetic and usability elements as well as mass… Group 4, what is the filtration rate of your initial and redesigned water filter?

Group 4: The filtration rate of the initial water filter is 0.33ml/s and for the redesigned filter... it is 0.94ml/s.

Facilitator: How about the cost?

Group 4: The redesigned water filter is cheaper.

Facilitator:...It is better if you can mention the cost of both filters. For instance, the initial filter costs RM70.45 while the redesigned filter costs RM63.45.

Following the whole class discussion, the students proceeded to answer the guided questions in the worksheet.

Groups lack depth again as interaction between P2, P5 and AS-FS breaks down

The facilitator visited each group as the students were evaluating their water filter. For a number of groups, including Group A, the facilitator left when she saw that the students were comparing their two versions of water filter designs with the support from the FS. Since on-site diagnosis (P2) did not take place in Group A, no AS decision was made to further support the students. The facilitator considered this as fading of AS for Group A.

Later, the facilitator's assessment of worksheet responses (P2) found that four groups including Group A provided written responses that, again, lacked depth (no link - 2 points). For instance, Group A wrote that "The filtration rate increased. It might be caused by the larger spaces which allow water to pass through more quickly." The facilitator recognized two issues that signalled limited KI. First, they did not provide evidence to differentiate the filtration rate of the two water filter designs. Second, they did not analyse the contributing factors for the changes in the filtration rate such as the type of filtering material.

This account, as with other critical incidents, suggests two key points. First, there seems to be a breakdown in the interplay between AS with P2 (diagnosis) and P5 (fading or transfer of responsibility) in Group A. Since the facilitator could not assess the students' worksheets on the spot, she overestimated the students' ability and overlooked their learning gaps. Premature fading and misdiagnosis of students' state of competency took place in Group A, which were detrimental to student learning.

Second, just like in Vignette 1, the students could have benefited from more structured support in the FS, particularly if the intent was to fade AS earlier. In this case, the FS did not provide enough structure for students to make a more in-depth comparison between the two versions of their water filters. The students could have benefited from more specific guided questions that are based on various aspects, with a recommendation to use empirical data.

Interaction between P5 with AS: Group B engages in higher level of KI

In three out of the nine groups, P5 (fading and transfer) interacted with AS in a way that helped students make progress. Unlike Group A, Group B received additional AS.

When the facilitator visited their group as they compared two versions of their water filter designs, they just looked confused. The facilitator asked if they needed help. Ben responded, "We are not sure how to answer part 'b' (i.e., what are the factors that might cause the differences in: filtration rate; water clarity; cost; aesthetic/usability elements; mass)."

The facilitator went on to provide additional AS after making a diagnostic decision (P2) based on the students' oral statements above.

Facilitator: In part 'A', you have explained that the filtration of the redesigned filter is faster. To answer part 'b', ask yourselves: 'What changes have you made to the redesigned filter?'

Baki: We changed some filtering materials and rearranged them.

Facilitator: So, do you think the difference is caused by the changes in the filtering materials? If yes, what materials have you changed?

Bruce, Baki and Ben proceeded to discuss the changes that may have led to the differing results between the first version and the second version of their filter, with occasional interjections and questions from the facilitator (P4). As they deepened their discussion on how the different materials and arrangements could impact the quality of the water filter, the facilitator asked if they were ready to answer the remaining questions on their own (P5). Bruce confidently responded: "I think we can." And they did, providing more nuanced explanations that integrated different knowledge areas that have emerged through the course of the DBL process (full link - 5 points). For instance, they wrote "The water collected from the redesigned filter is less clear than the initial design. This might be caused by the changes in the arrangement of the materials. In the second design, we put the fine sand at the bottom, replacing cotton. The redesigned filter has a lower mass of 175g. We reduced the unit of high mass material such as stone."

The working of AS added additional insights to P5. with AS added additional insights. P5 needs to be thought through based on the students' readiness and willingness to assume greater responsibility for their own learning. The learning responsibility should be transferred to students gradually, in a non-abrupt way, following continuous diagnosis and careful calibration of support.

Discussion

The purpose of this research was to add more granularity to the five existing scaffolding principles. The findings from this first cycle of DBR would be used to improve the design of scaffolding in the second cycle. Group A struggled in making connections between different knowledge bases due to the limited interaction between FS and AS with the five scaffolding principles. Group B saw greater ability in integrating knowledge with more extensive interaction between FS and AS with the principles, especially P2 (diagnosis), P3 (calibrated support) and P5 (fading and transfer of responsibility). The scaffolding principles were very useful to guide the design and implementation of AS and FS, but through the implementation, there was also a feedback loop that helped augment the scaffolding principles.

In studying the interactions between FS and AS, a more detailed set of scaffolding principles emerged. The first scaffolding principle is concerned with establishing a shared understanding of common goals (P1) to provide a focus to inform FS and AS decisions (McNeill & Krajcik, 2009; Tabak, 2004) [23, 37]. While establishing common goals helps students develop a sense of shared ownership of the task (Puntambekar & Kolodner, 2005) [28], this study found that establishing broad goals alone was insufficient. Goals need to be specific enough — i.e., broken down into milestones — to guide the design of FS and AS based on the nature of each DBL stage. The findings also revealed that proper sentence structure, clear presentation of FS and use of unambiguous wordings could minimise misinterpretation and confusion about the common goal. In the second DBR cycle, FS would be more structured and specific. Ambiguous FS would be rephrased to avoid misinterpretation. Some samples of initial and redesigned guided questions are shown in Table 3.

Table 3: Samples of initial and redesigned guided questions at problem identification stage

<table>
<tr><th>DBL stages</th><th>Initial guided questions (Cycle 1)</th><th colspan="3">Redesigned guided questions (Cycle 2)</th></tr>
<tr><td rowspan="6">Problem exploration</td><td rowspan="6">What will happen if you use two types of filtering materials to filter 150ml dirty water?

Explain your answers in (a) from the aspects of (i)filtration rate; (ii) water clarity; and (iii) cost.</td><td colspan="3">What will happen if you use two types of filtering materials to filter 150ml dirty water?</td></tr>
<tr><td>Aspects</td><td>Why may happen?</td><td>Why does this happen?</td></tr>
<tr><td>Filtering time</td><td></td><td></td></tr>
<tr><td>Water clarity</td><td></td><td></td></tr>
<tr><td>Cost</td><td></td><td></td></tr>
<tr><td>Mass</td><td></td><td></td></tr>
</table>

In terms of ongoing diagnosis (P2), the research findings suggest that multiple data sources — verbal interactions between teacher-student and students' written artefacts — are needed for triangulation purposes. Though students' writing can provide meaningful information about their logical thinking and decision-making, the facilitator cannot diagnose each student's progress from the workshe *et al*one. Thus, individual reflective journals would be added into the second cycle. Various resources not only help teachers determine students' current state of knowledge (Puntambekar & Kolodner, 2005; Van de Pol *et al*., 2010) [28], but also to understand other factors which may support or hamper students' progress.

Teachers should constantly calibrate scaffolding (P3) to address students' learning needs based on the ongoing diagnosis of their current state of knowledge (Puntambekar & Hübscher, 2005; Stone, 1998; Van de Pol *et al*., 2010) [27, 36]. This study suggests that P3 should be planned to close students' learning gaps before they move to the next stage of learning. Otherwise, students such as Group A may struggle to build more sophisticated knowledge in the next stage. Calibrated scaffolding such as feedback, questions and instructions have to be explicitly directed to the target students so that they are aware of what their learning gaps are and how to close these gaps. Directed instructions, explicit prompts and sample answers are particularly critical for students with a poor initial understanding of a task (Kirschner, Sweller, & Clark, 2006; van de Pol & Elbers, 2013) [18, 44]. Visual and/or written anchors may be needed to complement verbal instruction to help students see the most salient points. The second cycle would attempt to address both these augmentations in situ.

The fourth principle is using dialogues and interactions (P4) to make visible students' current state of learning, to enable knowledge sharing as well as to guide scaffolding decisions. It is important to introduce individual, group and whole class discussions at a strategic time so that teachers can assess students' knowledge, including their misconceptions (Puntambekar & Kolodner, 2005; Reiser, 2004; Reiser & Tabak, 2014; Tabak & Reiser, 1997; Taber, 2018) [28, 29, 30, 38, 39]. While individual students share and negotiate ideas during small group discussions, each student group can publicise their group ideas during whole class discussions (Puntambekar & Kolodner, 2005; Tabak & Reiser, 1997) [28, 38]. However, essential content emerging in whole class discussions may be lost to students who need it the most. Thus, whole class discussions need to have sufficient structure and specificity to support the target students. Dialogic interactions may involve asking higher cognitive questions (Tan, Tee, & Samuel, 2017) [40] and providing sufficient wait time so that students have more opportunities for thinking (Bae *et al*., 2021; Tan *et al*., 2017) [2, 40]. In the second cycle, whole class and small group discussions would be seamlessly integrated.

The fifth scaffolding principle is fading and transfer of responsibility (P5). Like previous studies (McNeill & Krajcik, 2009; McNeill *et al*., 2006) [23, 24], this study also found that P5 should only be done when the students have sufficient knowledge and confidence to take greater agency for their learning. Fading before students are ready to be independent is detrimental to student learning (McNeill *et al*., 2006) [24]. The length of scaffolding needs to be flexible, depending on the students' progressive development. Turn-taking and extended discussion time with the provision of examples are effective ways to transfer learning responsibility to students (Bae *et al*., 2021) [2]. In the second cycle, the AS and FS would be used in a way that addresses these requirements.

Conclusion

Scaffolding principles are essential to guide the design and implementation of AS and FS (Puntambekar & Hübscher, 2005; Puntambekar & Kolodner, 2005) [27, 28], but through the implementation, there is also a feedback loop that augments the scaffolding principles to support knowledge integration in an inquiry-based learning environment. This study suggests that scaffolding analyse should identify the goal of scaffolds (P1) and students' needs (P2), including the challenges they face in learning, as well as restructure tasks using calibrated support (P3), talks (P4) and timely fading (P5) to support knowledge integration, without losing the complexity of the design tasks.

Open and complex learning environments such as DBL need more rather than less guidance (Hmelo-Silver, Duncan, & Chinn, 2007; Kirschner *et al*., 2006; Reiser, 2004) [16, 18, 29]. More directed and structured instruction (Hmelo-Silver *et al*., 2007; Taber, 2018) [16, 39], work samples and structured worksheets (Kirschner *et al*., 2006) [18] can support student learning by reducing cognitive load. If a task involves too much information and students only receive general and non-directive support, they will have a hard time consolidating the information in a meaningful way (Smit *et al*., 2013) [35]. This issue reveals a tension between giving autonomy versus being more structured and more directed in the inquiry learning process. Perhaps the issue here is not more or less structure or guidance, but what is the appropriate amount and timing of scaffolding needed as determined by the condition of the learner in relation to the learning goals (Tobias & Duffy, 2009) [43]. Recent national studies found that Malaysian classrooms to be persistently monologic, significantly driven by the sociocultural and epistemic assumptions dominant within the public-school setting (Tan *et al*., 2017; Tee, Tan, & Symaco, 2018) [40, 42]. Clearly, there's much to be done to address the issues raised in the second cycle of this study.

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