CLASS challenging tasks

Using cognitive load theory to inform the design of challenging mathematical tasks


James Russo
Wilandra Rise Primary School, Vic.
<mr.james.russo@gmail.com>

Sarah Hopkins
Monash University, Vic.
<S.Hopkins@monash.edu>

This paper outlines a seven step process for developing problem-solving tasks informed by cognitive load theory. Through an example of a task developed for Year 2 students, we show how this approach can be used to produce challenging mathematical tasks that aim to optimise cognitive load for each student.

Overview

In this article, we consider how cognitive load theory can directly inform problem-based task design through outlining a seven-step process for developing challenging mathematical tasks. We term this process the Cognitive Load Approach to Shaping and Structuring Challenging Tasks (CLASS Challenging Tasks). To demonstrate the practical utility of our framework, we show how it was used to develop a task exploring exponential growth with Year 2 students.

Context

Calls to reform mathematics education in countries such as Australia and the United States aim to increase the amount of time students spend engaged in deep problem solving and discussion through utilising more cognitively demanding tasks (Hollingsworth, Holden, & McCrae, 2003; Stein, Engle, Smith, & Hughes, 2008). Reform-oriented teaching approaches have frequently employed problem-based approaches to learning, with the teacher launching a mathematical investigation to begin the lesson, students exploring the problem and the class then discussing various ways in which the problem might be solved (Stein et al., 2008).

Although there is some evidence suggesting that higher-order mathematical goals, such as the ability to reason and think critically, are more likely to be realised when students are given an opportunity to explore concepts prior to direct instruction (Marshall & Horton, 2011), this emphasis on problem-based learning in mathematics is not without its critics. In particular, some cognitive load theorists have argued that launching a lesson with a cognitively demanding activity, which is not explicitly linked to teacher instruction and prior learning, is problematic (Sweller, Kirschner, & Clark, 2007). The central argument is that our working memory is limited in capacity when required to solve an unfamiliar problem (Kirschner, Sweller & Clark, 2006).

We take the view that cognitive load theory and problem-based approaches to learning are not incompatible, but rather the former can directly aid the development of the latter. Specifically, a seven-step process for developing a particular type of problem -based approach sensitive to the issue of cognitive load is outlined. This approach is referred to as the Cognitive Load Approach to Shaping and Structuring Challenging Tasks (CLASS Challenging Tasks).

The potential for challenging tasks to optimise cognitive load has been explored previously (Russo, 2015). The current paper takes this a step further through considering how cognitive load theory can directly shape task design. To demonstrate its practical utility, we illustrate this process through providing a sample of a task developed for Year 2 students. However, before we discuss our approach, there is a need to briefly describe cognitive load theory and introduce some key terminology.

What is cognitive load theory?

Cognitive load theory is premised on the well-established idea that our working memory has limited capacity to process novel information from the environment. It can, however, access extremely large amounts of previously processed and organised information from long-term memory (Baddley, 1992). Cognitive load theory essentially explores the instructional consequences of our limited working memory capacity (Sweller, van Merrienbier, & Paas, 1998). It can be used to explain how task design can influence the cognitive load experienced by learners.

Cognitive load refers to the number of interacting elements which need to be processed simultaneously in working memory. There are three types of cognitive load relevant to instruction: intrinsic cognitive load, germane cognitive load and extraneous cognitive load (Sweller, 2010).

Intrinsic cognitive load is determined by the extent to which the various elements inherent in a particular learning task interact (Sweller, 2010). In instructional terms, this can be thought of as task complexity. Intrinsic cognitive load is also determined by the extent of the learner's expertise with similar tasks and the level of outside support provided to tackle the task (Schnotz & Kurschner, 2007).

By contrast, extraneous cognitive load effectively reflects wasted cognitive load generated by poor instructional design. Importantly, the cognitive mechanism for generating extraneous cognitive load appears to be identical to the mechanism for generating intrinsic cognitive load; both are driven by element interactivity (Sweller, 2010). How then are we expected to distinguish between intrinsic and extraneous cognitive load? It is suggested that if element interactivity can be reduced without changing what is learned, the load must be extraneous. Conversely, if element interactivity can only be reduced through changing what is learned, the load must be intrinsic (Beckmann, 2010; Sweller, 2010). Sweller concludes that "the same information may impose an intrinsic or an extraneous cognitive load depending on what needs to be learned" (p. 125).

One possible interpretation of Sweller's conclusion is that distinguishing between extraneous and intrinsic cognitive load requires consideration be given to the learning objectives specified for a particular task. Specifically, does the element of the task under consideration connect to a specific learning objective? If the answer is yes, this element can be considered part of the intrinsic cognitive load of the task. If the answer is no, it is extraneous cognitive load.

The final aspect of cognitive load theory that needs to be considered is germane cognitive load. Within cognitive load theory, germane cognitive load refers to the "working memory resources that the learner devotes to dealing with the intrinsic cognitive load associated with the information". (Sweller, 2010, p. 126). Consequently, germane cognitive load can be considered to be the actual cognitive load the individual is able to dedicate to the material that needs to be learnt.

There is substantial empirical evidence to support cognitive load theory (e.g., Bokosmaty, Sweller & Kalyuga, 2015; Leppink, Paas, van Gog, van Der Vleuten & Van Merrienboer, 2014). Moreover, the theory has clear implications for instruction. It implies that teachers should develop instructional tasks which minimise extraneous cognitive load, maximise germane cognitive load and optimise intrinsic cognitive load.

CLASS Challenging Tasks is a process that endeavours to develop instructional tasks which do exactly this. Each of the seven steps involved in the development of a task are outlined below. Under each step, a task developed for Year 2 students (ages seven and eight years old) in an Australian classroom serves as a running example to further illustrate the process.

CLASS Challenging Tasks

Step 1: Identify your primary learning objective

This step involves the teacher being very clear about specifying exactly what he or she intends for a student to achieve within a particular lesson or series of lessons. It should be a highly valued objective, stated in explicit, student-centred language. This is a critical step in the process, as all subsequent aspects of the lesson are tied back to this primary objective.

In order to reinforce the focus on the most relevant aspect of the lesson, and therefore to maximise germane cognitive load, the primary learning objective should also be included as a summary statement (see Step 7).

Example of task for Year 2 students

Primary learning objective: To understand that doubling is a rule that makes collections (and number patterns) grow very quickly.

Step 2: Develop a problem-solving task

The second step involves the teacher developing (or sourcing) a problem-solving task that seems useful for meeting this primary learning objective. This problem-solving task should be engaging for students, have multiple solution pathways, involve multiple mathematical steps and take considerable time to solve. Such criteria for Challenging Tasks have been specified elsewhere by Peter Sullivan and colleagues, as part of their work on the *Encouraging Persistence, Maintaining Challenge* project (e.g., Sullivan & Mornane, 2013; Sullivan et al., 2015).

Example of task with Year 2 students

Problem solving task: Kai and Amaya loved donuts, so their mum decided to plant a donut tree. The tree was magical. Every day, the number of donut on the tree doubled. Kai was having his birthday party on Friday, so the family decided to not pick any of the donuts off the tree until then. On Monday, there were 3 donuts on the tree. Your job is to work out how many donuts there were on the tree by Friday.

Step 3: Ascertain potential secondary learning objectives

This step involves identifying additional potential learning objectives which appear to be embedded in the task as it is currently structured. Teachers should ask themselves the question: "What other skills and knowledge am I assuming that students either have, or will develop, through engaging in this task as it is currently presented?"

Example of task with Year 2 students:

Potential secondary learning objectives that may be embedded within the Doubling Donut problem include:

- identifying appropriate ways of mathematically representing worded problems;
- solving number pattern problems using only abstract representations (i.e., using numerals);
- independently initiate a number pattern through following a written instruction;
- exploring patterns involving numbers greater than 20 using abstract or quasi-abstract (i.e., pictorial) representations; and
- making connections between the problem and doubles patterns.

Step 4: Sort secondary learning objectives into intrinsic cognitive load (relevant) and extraneous cognitive load (less relevant)

It should be apparent from viewing these potential secondary learning objectives that some connect to, and build on, the primary learning objective, whilst others could actually detract from it. We suggest that one implication of cognitive load theory is that it is not prudent to expect students to simultaneously develop skills and capacities which do not share obvious synergies. Consequently, the next step involves sorting these potential secondary learning objectives into those which appear highly relevant (i.e., those we have determined should be part of the intrinsic cognitive load of the task) and those which are less relevant (i.e., those we have determined are part of the extraneous cognitive load).

Example of task with Year 2 students

Table 1. Doubling Donuts Challenge: Sorting the learning objectives

Relevant secondary learning objectives (Intrinsic cognitive load)	Less relevant secondary learning objectives (Extraneous cognitive load)
To explore patterns involving numbers greater than 20 using abstract or quasi-abstract (i.e., pictorial) representations.	To identify appropriate ways of mathematically representing worded problems.
To make connections between the problem and doubles patterns.	To solve number pattern problems using only abstract representations (i.e., using numerals).
	To independently initiate a number pattern through following a written instruction.

The three least relevant potential learning objectives, which were determined to be outside the scope of this lesson, can be viewed as generating potential extraneous cognitive load. It is critical to note that there is nothing inherently wrong with these learning objectives. Indeed, in a different context, these could have been deemed to be highly relevant. For instance, if the focus of the lesson was on students solving worded problems, clearly finding appropriate ways of representing worded problems would have been a highly relevant learning objective—and identified as a source of intrinsic cognitive load, rather than an extraneous source. The classification all depends on what the teacher is hoping to achieve through their teaching.

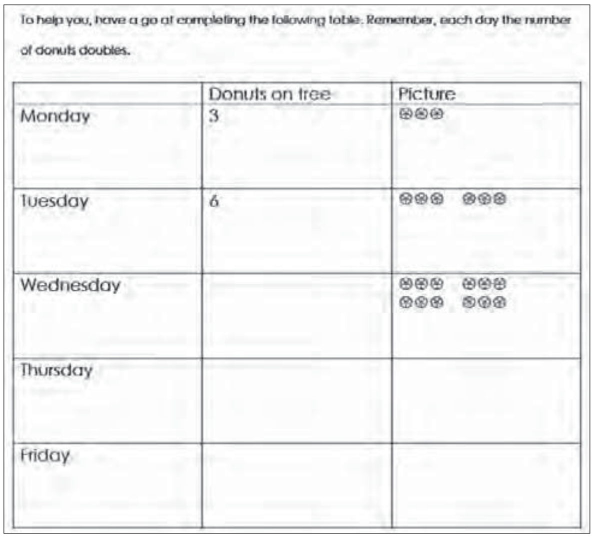
Step 5: Redesign the task to remove extraneous cognitive load

Step 5 involves removing the extraneous cognitive load through redesigning the task. Essentially, it involves acknowledging that certain potential learning objectives embedded in the initial problem-solving task were out of scope, and that it is advantageous to redesign the task to take the focus off these less relevant elements.

Example of task with Year 2 students

Students are given this additional information following on from the problem-solving task.

Students are provided with a table to help them represent the problem mathematically, which also includes a pictorial representation of the problem. Furthermore, the pattern has been initiated for students, (i.e., students are not expected to generate it themselves). This redesign of the task is intended to remove the three sources of extraneous cognitive load previously identified.



To help you, have a go at completing the following table. Remember, each day the number of donuts doubles.

	Donuts on tree	Picture
Monday	3	
Tuesday	6	
Wednesday		
Thursday		
Friday		

Figure 1. Doubling Donuts challenging task.

Step 6: Develop prompts to optimise intrinsic cognitive load

Although we have now removed obvious sources of extraneous cognitive load, the task as currently presented is likely to be too easy for some students, and too challenging for other students. To address this issue, enabling and extending prompts are used (Sullivan et al., 2014). Such prompts are developed prior to the delivery of the lesson as part of the task design process.

Enabling prompts are designed to reduce the level of challenge through: simplifying the problem, changing how the problem is represented, helping the student connect the problem to prior learning and/or removing a step in the problem (Sullivan, Mousley, & Zeven-bergen, 2006). Extending prompts expose students to an additional task that is more challenging. Generally, this extending prompt, although more challenging, requires students to engage with similar mathematical reasoning, conceptualisations and representations as the main task (Sullivan et al., 2014). A brief rationale for the development of prompts is included below.

According to cognitive load theory, to maximise learning, intrinsic cognitive load needs to be at an appropriate level as determined by the interaction between the complexity of the problem and the expertise of the learner (Sweller, 2010). If intrinsic cognitive load is too high, students will have insufficient germane cognitive load to devote to the task and learning will not occur. However, if intrinsic cognitive load is too low, learning is also undermined. Not only is cognitive capacity underutilised, but more expert learners may choose to disengage and 'tune out' if the level of challenge is inadequate (Schnotz & Kurschner, 2007).

Enabling and extending prompts are accessed by students when required during the lesson. Through introducing enabling prompts and extending prompts on a 'just in time' basis, the level of intrinsic cognitive load (i.e., learner-specific complexity) can be optimised for a given learner. In the first instance, accessing sequenced enabling prompts can reduce the amount of interactivity amongst the elements of the task until the task is at an appropriate level of challenge for a given learner's expertise. Although this process necessarily alters the presentation and/or nature of the learning task, and therefore impacts on the learning objectives, the enabling prompts need to be designed in such a manner that does not undermine the primary learning objective. Likewise, the extending prompt should continue to build on the primary learning objective, rather than require students to demonstrate qualitatively different skills and capacities.

Although students who have accessed prompts are in reality working on slightly different problems, critically they have a similar experience in having worked on the same challenging task. This enables them to actively participate in the discussion component of the lesson, and reflect on the key mathematical concepts explored.

Example of task with Year 2 students

In our example, the first enabling prompt (Enabling Prompt A) offers a simpler problem for students. Instead of there being three donuts on the tree on Monday, there is only one donut. This means that on Friday, there will only be sixteen donuts on the tree. Consequently, accessing this prompt effectively suspends the secondary learning objective: To explore patterns involving numbers greater than 20 using abstract or quasi-abstract (i.e., pictorial representations).

Although the exploration of large numbers is relevant to our primary learning objective, using numbers larger than twenty may prohibit some students from making progress with the task. Consequently, this prompt is designed for students to explore the power of doubles patterns using smaller, more familiar numbers.

The second enabling prompt (Enabling Prompt B) provides students with access to artefacts used in the classroom presented in relation to doubles patterns. Specifically, students are shown pictures of subitising and doubling cards used during previous instruction to attempt to connect prior understanding of doubles patterns to the current problem. Accessing this prompt effectively suspends the secondary learning objective: to make connections between the problem and doubles patterns.

To help you, have a go at completing the following table. Remember, each day the number of donuts doubles.

	Donuts on tree	Picture
Monday	1	
Tuesday	2	
Wednesday		
Thursday		
Friday		

Figure 2. Enabling Prompt A: An easier problem.

Again, connecting the concept of doubling to the current task was a desired learning objective, because this lesson is attempting to build on this previous understanding through exploring repeated doubling patterns. However, if students cannot bring to mind the concept of 'doubling', it is necessary to provide students with some prompt, otherwise they are unlikely to engage productively with the problem at all.

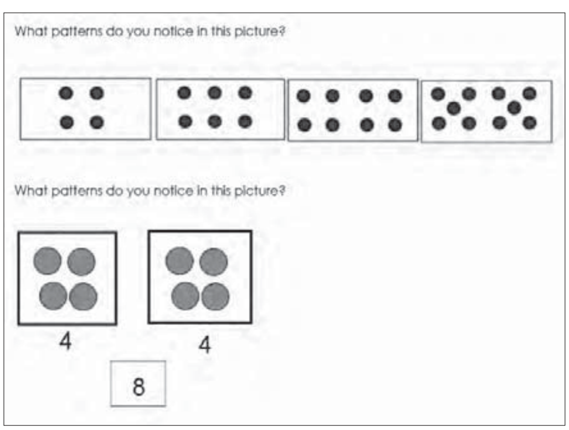


Figure 3. Enabling Prompt B: Previous material about doubles facts.

Finally, the extending prompt for this Challenging Task invites students to continue the double patterning by postponing the day of the party. Specifically, the prompt states:

> How many donuts would be on the tree if Kai decided to have the party on Saturday instead? How about if he had the party on Sunday? Can you keep the pattern going?

This prompt builds on our primary learning objective through emphasising the relevance of exploring large numbers in understanding exponential patterns. It effectively introduces an additional secondary learning objective: to explore patterns involving numbers greater than 100 using abstract or quasi-abstract (i.e., pictorial) representations.

Step 7: Include a lesson summary to maximise germane cognitive load

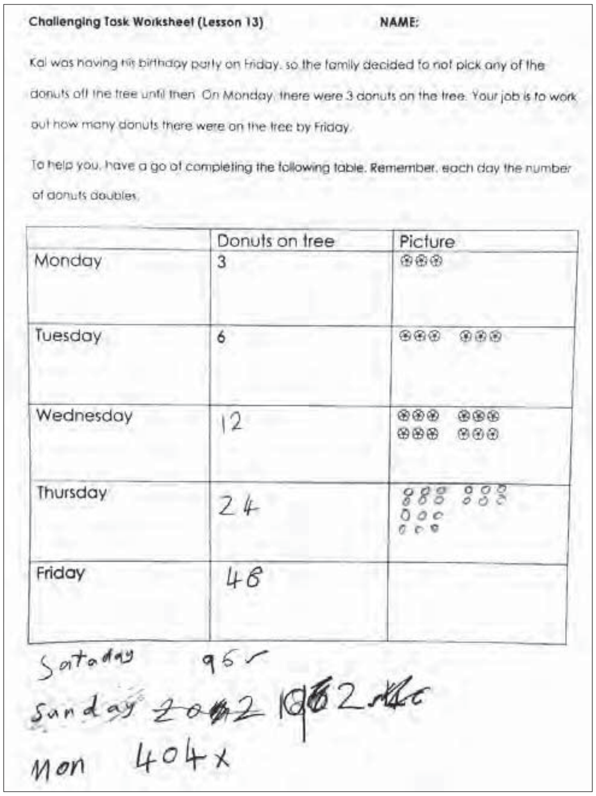
As part of the process, the teacher should aim to conclude the lesson by offering a two-minute summary to reinforce the primary learning objective. This focuses students' attention on the most relevant part of the lesson, and therefore helps to maximise germane cognitive load. The process of developing this summary is very straightforward. The primary learning objective should be restated to students by the teacher, with a sample of student work which effectively illustrates the primary learning objective presented alongside it. The summary is the only component of this seven-step process in which part of the process (i.e., the student work sample) is developed in the lesson, rather than prior to the lesson.

As an aside, it is worth noting that, in contrast to the primary learning objective, it is generally not desirable at any point in the lesson to share any secondary learning objectives with the students. This is mainly to ensure that students are not overloaded with less relevant information (extraneous cognitive load), enabling them to instead focus on the primary objective. In addition, the specific secondary learning objectives are dependent on the enabling and extending prompts a student accesses and therefore will be different for different students.

Example of task with Year 2 students

Lesson summary (restating the primary learning objective): to understand that doubling is a rule that makes collections (and number patterns) grow very quickly.

Alongside the lesson summary, a student attempt at the task which makes very clear the power of continuously doubling numbers can be presented (see Figure 4).


Challenging Task Worksheet (Lesson 13) NAME:

Kai was having his birthday party on Friday, so the family decided to not pick any of the donuts off the tree until then. On Monday, there were 3 donuts on the tree. Your job is to work out how many donuts there were on the tree by Friday.

To help you, have a go at completing the following table. Remember, each day the number of donuts doubles.

	Donuts on tree	Picture
Monday	3	⊛⊛⊛
Tuesday	6	⊛⊛⊛ ⊛⊛⊛
Wednesday	12	⊛⊛⊛ ⊛⊛⊛ ⊛⊛⊛ ⊛⊛⊛
Thursday	24	
Friday	48	

Saturday 96 ✓

Sunday 192 …

Mon 404 x

Figure 4. Sample of student work.

Summarising CLASS Challenging Tasks

This paper has outlined a seven step process for developing problem-solving tasks informed by cognitive load theory. This process has been labelled the Cognitive Load Approach to Shaping and Structuring Challenging Tasks (CLASS Challenging Tasks), and can be used to produce challenging mathematical tasks that aim to optimise cognitive load for a given student. These seven steps are summarised in the figure below (Figure 5).

We encourage teachers to work through the seven steps to develop their own challenging tasks, share the resultant tasks with their fellow educators, and provide feedback about the process. We believe CLASS Challenging Tasks is an illustration of how developments in mathematics education (e.g., Peter Sullivan and colleagues' notion of challenging tasks) can be combined with insights from educational psychology (e.g., cognitive load theory) to generate novel approaches to mathematics instruction and task construction.

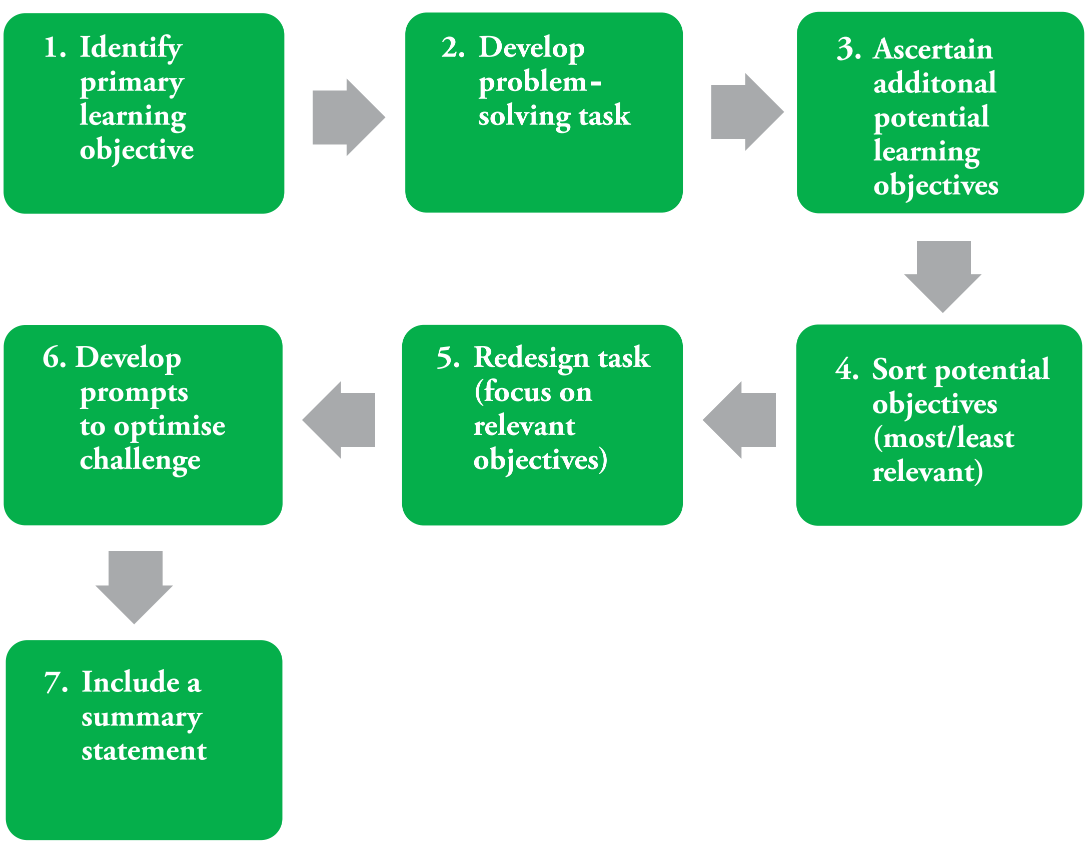


Figure 5. Seven step process outlining CLASS Challenging Tasks.

References

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556-559.

Beckmann, J. F. (2010). Taming a beast of burden—On some issues with the conceptualisation and operationalisation of cognitive load. *Learning and Instruction, 20*(3), 250–264.

Bokosmaty, S., Sweller, J., & Kalyuga, S. (2015). Learning geometry problem solving by studying worked examples: effects of learner guidance and expertise. *American Educational Research Journal, 52*(2), 307–333.

Hollingsworth, H., McCrae, B., & Lokan, J. (2003). *Teaching mathematics in Australia: Results from the TIMSS 1999* video study: Australian Council for Educational Research.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist, 41*(2), 75–86.

Leppink, J., Paas, F., Van Gog, T., van Der Vleuten, C. P., & Van Merrienboer, J. J. (2014). Effects of pairs of problems and examples on task performance and different types of cognitive load. *Learning and Instruction, 30*, 32–42.

Marshall, J. C., & Horton, R. M. (2011). The relationship of teacher-facilitated, inquiry-based instruction to student higher-order thinking. *School Science and Mathematics, 111*(3), 93–101.

Russo, J. (2015). How challenging tasks optimise cognitive load. In K. Beswick, Muir, T., & Wells, J. (Ed.), *Proceedings of 39th Psychology Of Mathematics Education Conference* (Vol. 4, pp. 105–112). Hobart, Australia: PME.

Schnotz, W., & Kurschner, C. (2007). A reconsideration of cognitive load theory. *Educational Psychology Review, 19*(4), 469–508.

Stein, M. K., Engle, R. A., Smith, M. S., & Hughes, E. K. (2008). Orchestrating productive mathematical discussions: Five practices for helping teachers move beyond show and tell. *Mathematical Thinking and Learning, 10*(4), 313–340.

Sullivan, P., Askew, M., Cheeseman, J., Clarke, D., Mornane, A., Roche, A., & Walker, N. (2014). Supporting teachers in structuring mathematics lessons involving challenging tasks. *Journal of Mathematics Teacher Education, 18*(2), 1–18.

Sullivan, P., & Mornane, A. (2013). Exploring teachers' use of, and students' reactions to, challenging mathematics tasks. *Mathematics Education Research Journal, 25,* 1–21.

Sullivan, P., Mousley, J., & Zevenbergen, R. (2006). Teacher actions to maximize mathematics learning opportunities in heterogeneous classrooms. *International Journal of Science and Mathematics Education, 4*(1), 117–143.

Sweller, J. (2010). Element interactivity and intrinsic, extraneous, and germane cognitive load. *Educational Psychology Review, 22*(2), 123–138. doi: http://dx.doi.org/10.1007/s10648-010-9128-5

Sweller, J., Kirschner, P. A., & Clark, R. E. (2007). Why minimally guided teaching techniques do not work: A reply to commentaries. *Educational Psychologist, 42*(2), 115–121.

Sweller, J., van Merrienboer, J. J., & Paas, F. G. (1998) Cognitive architecture and instructional design. *Educational Psychology Review, 10*(3), 251–296. doi: http://dx.doi.org/10.1023/A:1022193728205