COGNITIVE LOAD OR COGNITIVE ENGAGEMENT: WHICH LIMITS LEARNING IN THE MATHEMATICS CLASSROOM?

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ABSTRACT–This paper is based on a research study that investigated the effect of a cognitive-load based teaching method on the performance and engagement of a group of Grade 9 learners. Principles of cognitive load theory have been shown to be effective in improving understanding. The learning material for this study consisted of a series of graded worksheets with prompts, questions and completion problems. The worksheets covered the laws of exponents and the simplification of expressions involving integer exponents. This paper reports on evidence of cognitive overload and of limited cognitive engagement. Insufficient cognitive engagement was more prevalent than cognitive overload and was frequently the limiting factor in mathematics learning.

Keywords: mathematics learning; cognitive load; cognitive engagement; Grade 9; working memory; schema

1. INTRODUCTION

South African education is in crisis. Despite improvements over the past few years, most South African learners are substantially behind numeracy and literacy milestones by national and international standards (Spaull, 2013). And although literacy is fundamental to any learning ("learn to read; read to learn"), numeracy is not only a necessary life skill, but also the basis on which our technological society is built. Only around 15% of matric learners who wrote the National Senior Certificate examinations in 2016 obtained a pass in Mathematics of 40% or more (Department of Basic Education, 2017) – whereas enrolment at a university for an engineering degree requires a Mathematics mark of at least 60%. If more learners are to obtain quality passes in mathematics, the teaching of mathematics at every level needs to be improved.

This study, based on David (2016), examines learning in a Grade 9 Mathematics classroom with respect to two parameters: cognitive overload (when working memory is overwhelmed as a result of the complexity of learning material) and cognitive engagement (in brief, effort to learn). The aim is to identify the occurrence of both cognitive overload and engagement and to compare their relative importance in influencing learning outcomes.

2. THEORETICAL COMPONENT

2.1. Short-term memory and schema development

In human cognition, inputs such as sounds and images are perceived by working memory; when attention is directed toward these inputs, they are stored in short-term memory. Short-term memory has a very limited capacity – around five items – and can easily be overwhelmed if too much new input is received at one time (Cowan, 2008).

By repeated exposure to similar inputs and with the application of focus or engagement on the input, the human brain builds aggregations of knowledge as models of the world. These models, or schemas, are continually improved as more experiences provide further related data. Schemas are stored in long-term memory (which appears to be effectively unlimited) and recalled without effort when needed (Kalyuga, 2009). In working memory, a schema makes less demands on short-term memory than would its separate components, appearing to occupy only one "slot". In this way, the severe limitations on working memory can be circumvented.

Such schemas or “chunked” ideas serve as a guide to allow for better understanding and the development of new ideas by providing a link between a novel task and what the learner already knows (van Merriënboer, Kirschner, & Kester, 2003). A learner with a rich array of complex schema is therefore able to complete more challenging tasks than a learner who instead has to rely on the circumscribed capacity of short-term memory. The effort involved in learning comes from the need to engage with data in short-term memory and the cognitive processes required to link new data into existing schemas.

A fact such as “Paris is the capital of France” is an isolated element which can be readily memorised and stored in long term memory. However, in the process of learning mathematics the elements tend not to be isolated, but instead interact with each other. Consider for example the skill we teach in Grade 9 mathematics: how to factorise a trinomial. To succeed at this, the learner must be able to identify the factors of the constant term, and quickly add or subtract them to see which combination gives the coefficient of the x term. The interactivity between these elements in short-term memory makes this a memory-intensive process which can overwhelm the capacity of short-term memory and result in cognitive overload (Sweller, 2010).

Mathematics is a subject where new material builds upon previously mastered content; as a learner progresses, the schemas he can access should be growing denser and more elaborate. This allows him to hold complex ideas in short-term memory and improve on them by adapting them and by linking in new ideas.

2.2. Cognitive Load Theory

The element interactivity of a task places an inherent load on short-term memory – the “intrinsic cognitive load” of the task (Sweller, 2010). This intrinsic load is dependent on pre-existing schemas: for instance, when trying to memorise the position of chess pieces in a game, the intrinsic load is very high for a person who has no expertise in chess and thus no schemas to “chunk” the placement of pieces. But to a chess master, who has stored in long-term memory the relative positions of pieces in hundreds of different games, this would not be a high load task. Similarly, in a mathematics class, the same task makes different short-term memory demands depending on the learner’s state of knowledge. Learners are expected to arrive in a grade with schemas from previous grades already in place. However, a learner whose schemas are still rudimentary is unable to access complex ideas without overwhelming his short-term memory and experiencing cognitive overload – the task is perceived as difficult and the process of learning will be inhibited. The learner is reduced to more cumbersome and time-consuming techniques for solving the problem such as supplementing memory with pen and paper, breaking processes down into more elementary steps, or making use of means-end analysis (Sweller, van Merriënboer, & Paas, 1998). However, if the learner’s pre-requisite schemas are in place there will be less demand on short-term memory, so there is some “processing power” left over. By attention and engagement with the content to be learned this additional processing power (called “germane cognitive load”) can be applied to improve and develop existing schemas still further (Sweller, 2010).

Cognitive load theory suggests a number of learning effects that can help balance element interactivity to avoid cognitive overload, and still encourage the application of germane load to develop and improve schemas (see for example Sweller et al., 1998).

2.3. Cognitive engagement

According to Blumenfeld, Kempler, & Krajcik (2006), cognitive engagement is a multi-dimensional concept that combines the learner’s willingness to put psychological effort to bear on the problem that is under scrutiny with the effective use of learning strategies that promote understanding. Such strategies embrace cognitive strategies, metacognitive strategies (goal setting, planning and evaluating progress) and volitional strategies (being able to pay attention and exert effort despite external distractions). For low-demand tasks cognitive engagement can be superficial, needing only the elaboration of schemas that can be retrieved from memory. High demand tasks – in which the connections between new and existing ideas are not straightforward – require deep engagement and the application of organisational strategies.

In the mathematics classroom the learner's engagement with high element interactivity tasks plays a crucial role in the development of effective schemas; without engagement the learner cannot understand complex ideas and master difficult skills (Newmann, 1992). Thus where cognitive load refers to the demands made on short-term memory, cognitive engagement involves the effort the learner makes to effect those demands.

3. RESEARCH DESIGN

The purpose of this study was to explore learners' experiences of cognitive overload and their cognitive engagement with the learning material, with the aim of identifying which of these effects is dominant in influencing learning in the mathematics classroom. The study was conducted using a non-probability sample of 24 Grade 9 learners from one school. The research paradigm was pragmatic and the approach was mainly qualitative, supported by quantitative analysis of a portion of the data.

This paper addresses three questions: Under what circumstances is cognitive overload apparent?

- What evidence is there that learners are engaging (or failing to engage) with the learning material?
- Which has a more profound effect on learning: cognitive overload or cognitive engagement?

3.1 Intervention

The intervention was conducted over a period of six days, during which a group of Grade 9 learners completed a series of graded worksheets on the laws of exponents (see example in Figure 1).

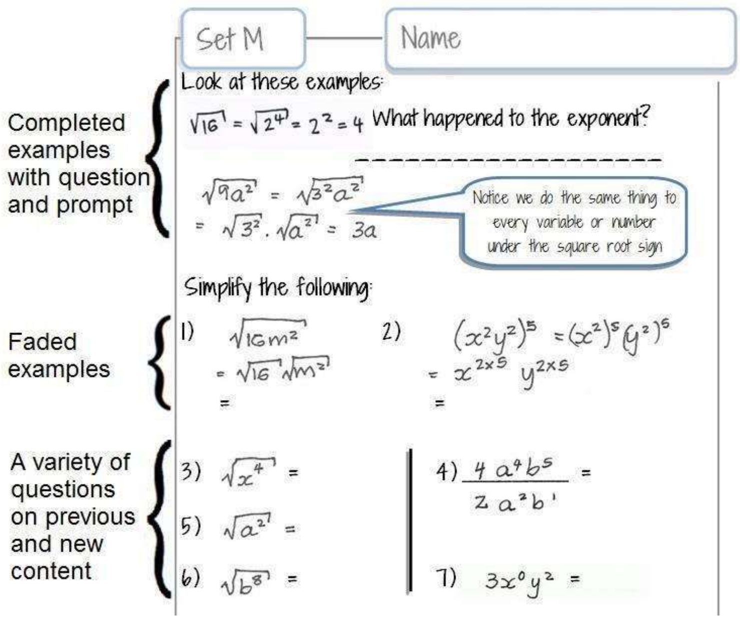

Figure 1: Typical layout of a worksheet including questions, hints, completed examples, faded examples and variation in problem types

The worksheets were developed based on the following principles of cognitive load theory:

Worked (completed) examples: If a learner is provided with an expert's model answer to a problem, he can apply his working memory to understanding each step so that he can emulate the method (Tuovinen & Sweller, 1999). Such worked examples will typically show every step required to solve the problem and may include notes explaining what is being demonstrated. Worked examples are only effective if the learner applies his freed cognitive capacity to "self-explain" each step in the example. This will help advance understanding and avoid the situation in which the learner follows a sequence of steps that they can copy but not transfer to other contexts (Chi, Bassok, Lewis, Reimann, & Glaser, 1989).

The completion strategy: As a learner becomes more able to solve problems, fully worked examples are less effective. This can be counter-acted by providing incomplete examples in which the final step or steps are omitted or faded, thus balancing the cognitive support of worked examples with the challenges of solving a problem independently (Sweller, 2006). The timing of fading the problems is important. If the fading is too quick, the cognitive load is too high. If the fading is too slow, self-explanation is extraneous and the learner may lose motivation. Correctly managed, fading can be effective at developing problem solving skills, and when combined with self-explanation can generate good results for the transfer of skills within related domains (Renkl & Atkinson, 2003).

The variability effect: When learners solve the same type of problem over and over they will develop automation, accuracy and speed (Renkl & Atkinson, 2003), but their schemas do not improve. In order to develop dense, robust schemas, learners must be faced with a variety of problems – these may include different variants of a problem, changes in the way the question is asked, in the context, the familiarity, or the characteristics of the questions. Variability allows learners to identify the range of applicability of schemas they have learned (van Merriënboer & Sweller, 2005), to pick out the important features of a problem from the unimportant ones and to recognize common features in differing problems (Sweller et al., 1998).

Validity and reliability: Within qualitative research, validity and reliability are conceptualized as "trustworthiness, rigor and quality" with the aim of increasing the researcher's truthfulness about a proposition (Golafshani, 2003). These concepts are not readily measurable. However, the development of the worksheets was based on the Curriculum and Assessment Policy Statement (Department of Basic Education, 2011). Furthermore, although for the purposes of this study the layout and organisation of the worksheets followed the precepts of cognitive load theory, the content was patterned after typical examples and exercises from a variety of learning material sources.

3.2 Analysis of data

A qualitative approach was used for the analysis of the completed worksheets. The learners' responses were coded for evidence of engagement and cognitive overload. One particular worksheet was also selected for in-depth analysis to determine whether the learners were sufficiently engaged with the content to be able to connect the prompts to the problems that followed.

4. RESEARCH RESULTS

4.1. Evidence of cognitive overload

The concept of negative exponents and the Rule of Exponents for negative exponents was challenging to some of the learners. To succeed in typical problems as shown in Figure 2 Samples A, B and C below, the learner must switch the variable between numerator and denominator and change the sign of the exponent. In Sample A we see that this learner was unable to mentally track switching the sign and inverting the number simultaneously; instead he broke the process into two separate operations. In Sample B he performed only half of the operation.

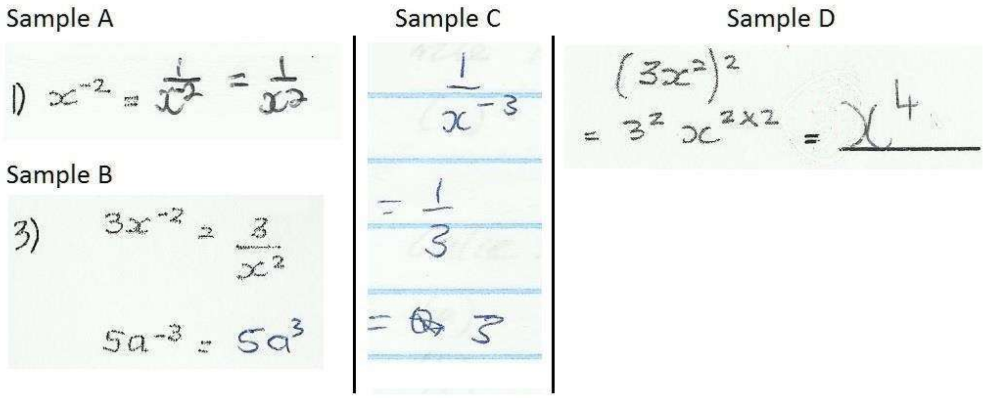

Figure 2: Evidence of cognitive overload

In Figure 2 Sample C the learner changed –3 to a positive 3, but lost track of the variable she was operating on. She then switched the number from the denominator to the numerator. She was apparently unaware of the incongruity of writing 1/3=3. Sample D also appears to show cognitive overload: the learner correctly applied the power rule to the x exponent, but was unable to apply it to the 3 at the same time.

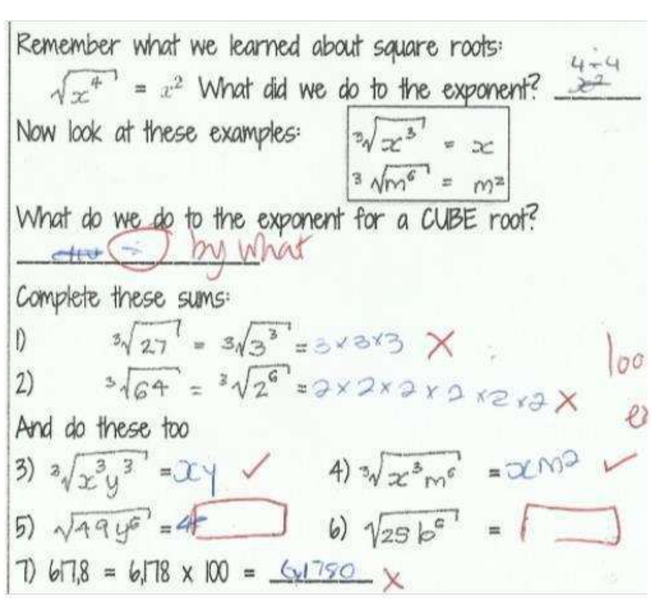

Figure 3: Lack of engagement – but not cognitive overload

As proposed in Cognitive Load Theory (for example Sweller, van Merriënboer, & Paas (1998), van Merriënboer, Kirschner, & Kester(2003)), this study showed cognitive overload can be mitigated when learners work through completed and faded examples.

4.2. Evidence of lack of cognitive engagement

A typical example showing lack of cognitive engagement is shown in Figure 3: the learner is able to find cube roots (questions 3 and 4 are correctly answered), but most of the worksheet was completed without engaging with the content.

The worksheet selected for in-depth analysis (see Figure 4) carefully laid out reminders, examples and prompts to lead learners to be able to solve a new type of problem. An element of cognitive engagement was required to see the connection between the examples, reminders and questions at the top of the worksheet and the problems at the bottom of the page. A learner who engaged with the clues and was able to answer the prompts correctly should have been able to make the required cognitive connection and answer the problems correctly.

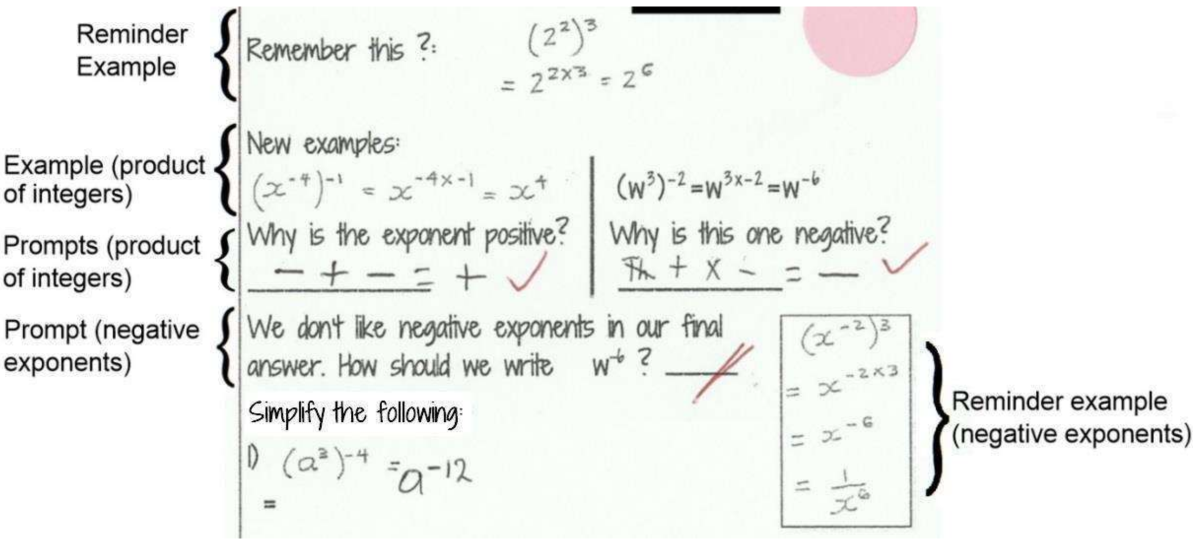

Figure 4: In-depth analysis of this worksheet was used evaluate cognitive engagement

During the qualitative analysis of these worksheets it became apparent that some learners completed all the prompts correctly but did not seem to see the connection between the prompts and the problem to be solved. Quantitative analysis using Fisher's Exact Test showed that correctly working through the prompts and reminders, and being able to solve the problem correctly were not dependent events (David, 2016). This led to the conclusion that learners were not engaging sufficiently to infer the connection.

Fredricks, Blumenfeld, & Paris (2004) report that there are numerous studies that demonstrate the importance of cognitive engagement and the link between engagement and achievement in middle and high-school years. Conversely, a persistent lack of cognitive engagement as evidenced in this study can result in superficial learning at best.

5. CONCLUSION

Analysis of the data showed that some learners in the class experienced cognitive overload frequently over the course of the intervention, when element interactivity was even slightly elevated. The methods of cognitive load theory – in particular the worked and faded examples – were effective in mitigating this overload, as long as the learners put in the mental effort to follow and emulate the examples. The greatest improvements in academic performance were seen among the weaker learners.

Learners were not effectively engaging with the problems they were attempting to solve. Examples of this included failure to make connections between examples and problems; not applying skills from previous worksheets when extension of ideas was required; careless and slipshod answers beyond what could reasonably be attributed to cognitive overload. Overall the evidence for lack of cognitive engagement was persistent across different levels of problems throughout the worksheets.

Figure 5 below illustrates the effects of mental effort with respect to the difficulty of the problem. Bear in mind that level of difficulty in mathematics problems is determined by the richness of the schemas a learner has in place – not all learners experience a problem as having same level of difficulty. In Quadrant 1 a learner can do a problems without too much mental effort and is assured of getting the right answers. Many learners expect their mathematics problems to fall into this category and consider that they are succeeding when every problem in their exercise books is marked correct. Little or no schema growth is effected by these low-intensity problems; however a learner who applies a high level of engagement may yet develop insights into the nature of mathematics or of their own cognitive processes (Quadrant 3).

If the problem a learner is faced with is not easy and he continues to apply limited mental effort, he will be operating in Quadrant 2. These learners put in a token effort without success before giving up. The lack of engagement suggests that cognitive overload will not occur. Their experience in mathematics will continue to be one of failure and frustration.

Difficulty in terms of current schemas → Level of cognitive engagement ↓	Easy problem (low element interactivity)	Challenging problem (high element interactivity)
Low mental effort	**Quadrant 1** Success in problem solving; no growth of schemas.	**Quadrant 2** Little or no success in problem solving. No growth of schemas.
High mental effort	**Quadrant 3** Quick success; may result in some growth of schemas.	**Quadrant 4** Growth of schemas. Learner may experience cognitive overload. Success is not guaranteed.

Figure 5: Interactions between cognitive engagement and element interactivity

Ideally learners should be operating in Quadrant 4: deeply engaged in challenging problems which promote schema growth. These learners may experience cognitive overload and will need to apply techniques to work around this in order to succeed. Success is not guaranteed for problems of this nature; however engaging with challenging problems will result in some schema development taking place.

It was evident from the results of the study that cognitive overload was occurring especially among the weakest learners, and that the worksheets assisted in managing or overcoming this. On the other hand, a low level of cognitive engagement was pervasive among the learners and appears to be a more important factor in limiting mathematical learning.

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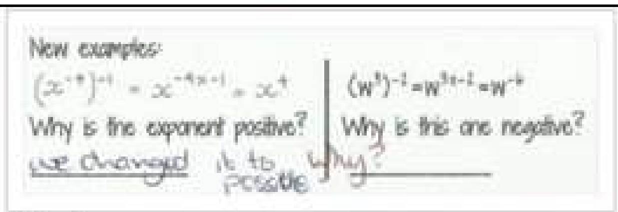
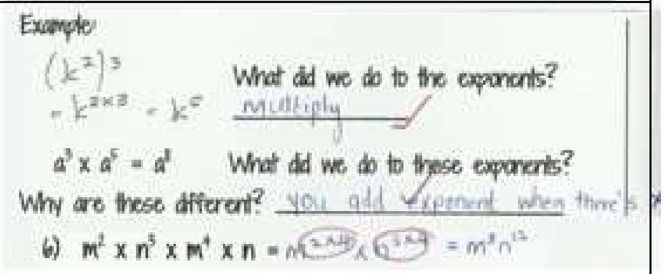
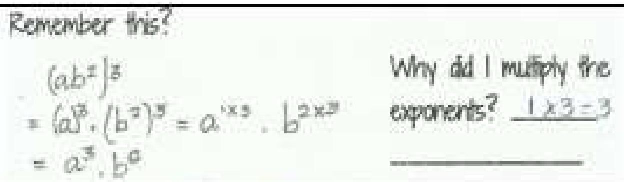
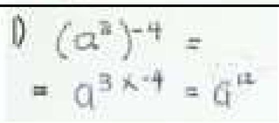
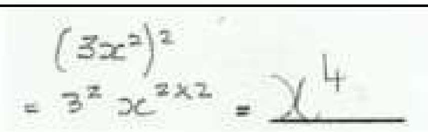
APPENDIX A

Table 1. Examples of coding used for worksheets

Category	Sub-category	Example
[illegible]	Didn't answer the questions which required them to study examples; skipped over examples; apparently didn't look at examples at all	
	Forgetting what was done in previous worksheet; can't apply previous work to later questions	
	Sheer carelessness: slip-ups in basic such as 3x2; answers apparently unrelated to questions	
Cognitive overload	Losing track of the variable being used; incorrectly copying a number	
	Unable to perform operation on a number and track the negative sign simultaneously; weakness in working with negative numbers	
	Losing track of the steps required half way through a problem	
	Breaking a one-step operation into multiple steps