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Cognitive Load Theory and its implications for high school teachers.

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Cognitive load theory developed as an understanding of the human cognitive system grew. Cognitive scientists began to discover that our working memory is severely limited in both storage and processing capacity. Questions arose. How can we determine how much cognitive load is imposed by different learning processes and materials? What can we do to reduce cognitive load so that we can understand information that places high demands on working memory capacity? The implications of cognitive load theory for learning, and particularly for instructional design, became of interest. This resulted in a variety of applications for the learner and instructor. Cognitive load theory aims to provide a framework for these investigations into cognitive processes and the ramifications of cognitive architecture on instructional design and procedures.

Unlocking the mind, memory, and the way we process and learn information has been a favourite topic of researchers since the days of the Ancient Greeks when Aristotle propounded the idea of the soul as the seat of rational thinking. The work of two modern researchers in particular, Miller and Baddeley (cited in Gerjets and Scheiter 2003), seems to form the basis of many of the recent concepts in cognitive load theory. In the fifties Miller proposed that working memory could only hold 5 to 9 new items of information at one time. A few decades later Baddeley then expanded upon this concept. Gerjets and Scheiter discuss the critical distinction Baddeley makes between the long term memory, which seems to be without limitation, and the bottleneck of learning or the working memory which is quite restricted in the number of elements that can be held simultaneously. Cooper (1998) explains that the fundamental tenet of cognitive load theory is that through consideration of the limitation of working memory we can improve instructional design.

As the knowledge base of cognitive architecture grew, models were developed to explain the workings of memory. Woolfolk (1995) describes a coherent model of memory, based on an information processing explanation that forms a good basis for the background to cognitive load theory. The process of memory creation can be outlined as follows. We receive information though the body's receptors. Our sensory register, which has a large capacity but short timeframe, holds this information very briefly (for about 1-3 seconds). Based on our perception, that is our existing knowledge and the interpretation of the input, we begin to organize the information for further processing. The information from our senses is so vast that we need to then select which elements we choose to pay attention to and retain for this future processing. Once selected and encoded into images and sound patterns, the information can then pass into temporary storage or short term memory where it remains for about 20-30 seconds. To keep the information activated, learners need to either repeat the chunks of information to themselves (maintenance rehearsal) or associate it with something they already know (elaborative rehearsal). Once the information is well-learned its durability has increased and it is stored in long term memory, where, with effort, it can be retrieved. The information in long term memory is stored as a schema, where vast amounts of information are organized for a particular concept or skill.

It is necessary not to neglect work done by researchers such as Rumelhart and Norman (1978) who stress the importance of realizing that learning involves more than just committing facts to memory. Rumelhart and Norman propose that learners can create schemas in a number of different ways. Accretion is where new information is matched to the existing information in previously available schemas. If the new information does not fit in the framework of existing schemas, restructuring will need to take place. Schemas also need to be tuned to improve accuracy and generalizations. This means that schemas can be constructed by patterned generation where the new schema is based upon that of the old or by induction where old patterns are recombined to create new schema.

The idea of schemas is also central to Pass, Renkl and Sweller's (2003) outline of the three categories of cognitive load and their effect on the learning process.

All material to be learned has intrinsic demands on working memory. The complexity of the learning materials, that is, the level of interaction between the elements of the information to be learned, determines the cognitive load that is intrinsic to this particular material. Of course, the experience of the learner is also a determining factor of this complexity. Low element interactivity means that the information can be processed and understood without reference to any other information. High element interactivity means that although individual elements can be learned separately, it is not until the learner processes not only all of the elements simultaneously, but also their multiple interactions, that complete understanding can be gained.

In order to explain the first category of cognitive load, intrinsic cognitive load, Pass, Renkl and Sweller give a brief background to the knowledge we now have of our cognitive architecture. Our conscious cognitive processing takes place in working memory and Pass, Renkl and Sweller indicate that it is possible that 2 to 3 interacting elements are as much as working memory can handle. How then can we possibly learn information that has high element interactivity?

It is our long term memory that provides us with the potential to vastly expand our ability to process information and work around the issues caused by high element interactivity. Through effective instructional design, learners can create schemas. Pass, Renkl and Sweller define schemas as ‘cognitive constructs that incorporate multiple elements of info into a single element with a specific function’ (2003, p.2). Once a schema is constructed, this combination of multiple elements can be brought from long term memory into working memory and processed as a single element. This allows the learner to process information that would exceed working memory capacity if each element and its interactions had to be processed individually. Pass, Renkl and Sweller also point out that automation of a schema will also further reduce cognitive load.

Although intrinsic cognitive load cannot be reduced through instructional design, the second category of cognitive load is greatly affected by the manner in which information is presented to learners and the activities required by the method of instruction adopted. When the instructional design creates unnecessary load upon the learner, this extraneous cognitive load will interfere with schema acquisition and automation. Extraneous load is effectively any mental activity that is generated during learning that does not contribute directly to the achievement of the learning goal. If the intrinsic cognitive load is particularly high there is little available processing power, and high extraneous cognitive load can result in no learning taking place. Cognitive load theory aims to reduce extraneous cognitive load through designing instructional materials in a way that allows the learner to focus on processing intrinsic cognitive load together with the final category, germane cognitive load.

Germane cognitive load consists of any demands placed on working memory capacity that are imposed by mental activities that contribute directly to the learning goal. For example, processing that allows the learner to create and automate new schemas. Like extraneous cognitive load, germane cognitive load is influenced by instructional design, but unlike extraneous cognitive load enhances rather than interferes with learning and needs to be fostered in the instructional design process.

Cognitive load theory can be equated to the fundamental issue in economics – scarcity and efficient allocation of resources. We can only process so much in our working memory so how can we allocate that processing power to make learning most efficient and effective? Intrinsic cognitive load must be the starting point. As this cannot be reduced without some compromise in understanding, all remaining processing capacity needs to be used by germane cognitive load and extraneous cognitive load. Obviously the more extraneous cognitive load that can be eliminated, the more processing power is available for effective acquisition of schemas. Once schemas are acquired, the intrinsic load is reduced and more capacity is freed to acquire even more advanced schemas, and the understanding of more complex material can take place.

Cognitive load theory has expanded since the 1980s from the initial goal of developing of instructional techniques to reduce extraneous cognitive load. Research in the late 1990s takes a more dynamic approach where intrinsic cognitive load is no longer regarded as completely fixed. Factors such as the experience level of the learner and the type of task with which they are presented means that intrinsic cognitive load can actually be affected by instructional design.

What then are the implications of this new research into cognitive load theory for high school teachers? How does it affect the way that information should be presented to students?

There has been a focus for some time on presenting learners with real-life tasks that are as authentic as possible. Gone are the days of rote learning a score of facts in isolation. Schools are concerned with making learning applicable to real-life. Difficulties may arise for learners though when trying to process complex information. Van Merrienboer, Kircshner and Kester (2003) discuss ways to manage cognitive load by decreasing both intrinsic and extraneous cognitive loads when these rich learning tasks are used.

In the framework discussed by Van Merrienboer, Kircshner and Kester scaffolding refers to 'a combination of performance support and fading' (2003, p.5). This initial support allows the learner to achieve learning goals previously unobtainable, and as the learner develops the support is gradually faded away until it is no longer needed at all. The difficulties for instructors arise in determining the appropriate amount and type of support and in deciding the point at which fading techniques are necessary. Too little or too much support is detrimental to the learning process so it is vital that this is determined correctly.

Van Merrienboer, Kircshner and Kester stress the need for integrated support as opposed to traditional means of guiding the learner such as 'coaching by providing hints, prompts, feedback, modeling the use of cognitive strategies by thinking aloud, presenting cue cards, checklists and process worksheets, asking leading questions, giving part of a solution' (2003, p.6).

Cognitive load theory has demonstrated that this type of guided support increases the extraneous cognitive load as the learner has to try and mentally integrate the information they are trying to learn and absorb with the extra support material requiring them to split their attention between these two elements. The more novice the learner is, the more important it is that the support is integrated as the novice learner is already under high cognitive load pressure.

So how does the instructor actually go about embedding this support? Van Merrienboer, Kircshner and Kester describe two approaches: simple to complex sequencing and the use of alternative tasks. Let us first consider simple to complex sequencing.

If the learning task is quite complex and requires coordination between the different parts of the task the research indicates that traditional piecemeal part-task approaches are not suitable for this type of task. This implies that a whole-task approach is needed but we are back again to the issue of the high intrinsic cognitive load imposed by the complexity of the task.

The solution to reduce this intrinsic cognitive load is to present the learner with the simplest version of the whole task that still allows them to coordinate and integrate the constituent skills from the beginning and move progressively towards the most complex version of the task. This way the learner develops a holistic or global overview of the whole task and has a framework upon which to hang the elements of the learning and to understand how these interact. The learner will work upon what Van Merrienboer, Kircshner and Kester have labeled 'task classes' (2003, p.7) where the tasks in that class require approximately the same cognitive strategies and have approximately the same cognitive load. As the learner progresses to a higher task class, support may need to be provided in order to reduce the extraneous cognitive load that comes with a higher level of understanding.

It is also necessary for instructors to carefully consider the type of learning task that is provided within each task class and the associated extraneous cognitive load as many problems arise from some of the more traditional methods of instruction.

This leads to the second approach suggested by Van Merrienboer, Kircshner and Kester which is to embed support for the learner through the use of alternative learning tasks. There are also a number of other considerations that arise when looking at alternative learning tasks such as the fading principle, expertise reversal effect, split attention and redundancy effect.

Cognitive load theory suggests that although traditional means-end problem solving encourages the learner to be actively involved in the learning process, it imposes a high extraneous cognitive load upon learners and does not encourage the construction of schemas. Although there is a place for conventional problem solving, this does not lie with the novice learner.

These ideas are supported by Renkl and Atkinson (2003). They explain that cognitive load theory has demonstrated that learning from worked out examples, in comparison to problem solving, is very effective in the initial stages of cognitive skills acquisition. In later stages problem solving is superior. The argument for this is that as a learner develops the intrinsic cognitive load decreases which allows gradual increase of problem solving demands to be possible without inducing cognitive overload. In the later stages however, different learner activities constitute either germane or extraneous load as different instructional goals are to be achieved. Therefore Renkl and Atkinson propose a fading procedure where problem solving elements are successively integrated into example study until learners are expected to solve problems on their own.

Van Merrienboer, Kircshner and Kester also explain that worked out examples are better in that by providing the learner with the problem, the solution steps and the desired outcome, the learner can focus on understanding generalizations and creating schemas. This provides a high level of in-built support. Ineffective problem solving methods are eliminated thus reducing the extraneous cognitive load.

The main issue that arises is that these worked out examples are only of benefit to the learner if they study them carefully and ensure they understand them in order that schemas can start to develop. As Renkl (1997) has shown, many learners only consult the examples when they are facing difficulties, thus creating the split attention effect and high extraneous cognitive load as they try to integrate the problem they are solving with the worked example.

Van Merrienboer, Kircshner and Kester have suggested that a solution to this is the use of completion tasks as an alternative to fully worked out examples. In these tasks a partial solution is given to the learner who must make the effort to study the example carefully in order to complete the task. Although most of the extraneous cognitive load is removed, the learner must still play an active role in the learning process. Other examples of tasks with an intermediate level of support are goal-free tasks and reverse tasks.

There are a number of implications of alternative tasks for instructional design. VanLehn (1996) distinguished between early, intermediate and late phases of skill acquisition and it is these different stages that will determine the appropriate instructional design.

Renkl and Atkinson explain that instructional design in the past often gave students problems to solve in too early a stage of the learning. As their knowledge of the problem domain at this point in time is low, they have no task specific procedures to implement and this causes high intrinsic cognitive load to be imposed as they attempt to apply general problem solving strategies. The load is imposed as they try to simultaneously maintain the problem, the desired outcome and manipulate possible means-end approaches to the problem in working memory. If in contrast the learner is given a worked out example, the learner is able to concentrate solely on understanding. Issues arise as to the effectiveness of this technique though when it is considered how well learners engage in actively self-explaining the solutions of the worked examples. As previously discussed, Renkl and Atkinson's work showed that most learners do not actively self-explain the solutions or use their cognitive capacity productively. It is necessary for learners to be taught how to do this before embarking on the learning process.

In the early stage, Renkl and Atkinson explain that learners strive to gain a basic understanding of the problem environment without necessarily attempting to apply any knowledge they have acquired. Therefore learners need to be presented with more worked examples than is traditionally presented before expecting them to engage in problem solving.

The steps of the worked examples are then faded out so that learners start to engage with the problem and form schema and begin to learn how to take the abstract principles and use them to solve a concrete problem. It is in this intermediate stage that learners are attempting to discover flaws in their knowledge base and correct relations and misunderstandings. But for this to take place, learners need to study examples actively and self-explain the solutions or consider the rationale of the solutions.

Renkl and Atkinson explain that the intermediate learners need to undertake a number of these self-explanation activities. The learner needs to identify the general principles that lie beneath the examples, identify the sub goals of the operators, and develop a coherent picture of the problem and its domain.

In the later stages of skill acquisition, the emphasis is on increasing speed and accuracy of performance so that skills (or subcomponents) become automated. During these stages it is important that learners actually solve problems. Providing worked examples at this point in the learning process has a negative effect on the learner. For expert learners, devoting working memory to redundant information takes away a portion of the learners' cognitive capacity that could instead be devoted to germane load.

The overall essence of this particular approach is highlighted by Jeroen, van Merrienboer, Kircshner and Kester: 'fading principle suggests giving sizeable early support for learning tasks and no support for the final tasks in the same learning class' (2003, p.8). Within one task class instructors can control cognitive load by starting with worked out examples then leaving more and more of the solution out until students arrive at solving a conventional problem.

The effects of fading in the use of worked examples confirm the expertise reversal effect postulated by Kalyuga, Ayres, Chandler and Sweller (2003). The expertise reversal effect is the phenomenon where instructional techniques that are highly effective with beginners can lose effectiveness and even have negative consequences for experienced learners. When this occurs, the instructional design recommendations are reversed. This means that to be efficient instructional design should be tailored to the level of expertise of the intended learner. Without tailoring, the effectiveness of instructional design is likely to be random and can end up being counter productive. The level or knowledge of the learner is an important, and often neglected, consideration when determining the appropriate level of support.

But what difference does level of expertise actually make? Kalyuga, Ayres, Chandler and Sweller explain that when faced with a problem, expert users are able to recognise relationships between multiple elements and treat these as a single unit. Although this single unit is of a higher level, it requires much less processing capacity than a group of lower level multiple elements. These acquired schemas, held in long term memory, allow experts to significantly reduce the load imposed upon working memory. The more automated these schemas become, that is, the more expert the learner, the more the load is reduced. Unlike a novice learner who requires instructional guidance as a substitute for these schemas in order to manage cognitive load, providing instructional guidance to the expert learner will actually increase rather than reduce the load imposed upon working memory.

If an expert is unable to ignore this information, they will attempt to cross reference and synthesize their schemas with the instructional guidance provided. Given that their schemas were adequate for the task, this new processing task means that working memory that could have been allocated to the solving of the problem is engaged in trying to analyze and relate what is essentially redundant information. Using both schema-based and instruction-based cognitive constructs may impose cognitive overload.

There are a number of other situations where instructional design needs to consider the expertise reversal effect.

One of the concerns of cognitive load theory is that when learners are presented with related sources of information, often in different representations, in order to construct schemas they need to mentally integrate information that may be separated in space or time. This process of integration can impose strong cognitive load.

Kalyuga, Ayres, Chandler and Sweller suggest two methods to deal with this situation that have been advanced by cognitive load theorists. Instructors can physically integrate the material, such as text and pictures, particularly if the materials will not be intelligible in isolation. This will reduce the search and match process that learners would otherwise be forced to undertake and attempt to eliminate the split attention that results from such separation. Alternatively, if one of the sources is unnecessary or redundant, elimination is the best approach.

Determining whether information should be integrated or eliminated depends not only on the nature of the information being presented but also on the level of expertise of the learner.

For the expert learner, if the information has been integrated, the process of having to also analyze, what is to them, redundant information may interfere with the acquired schemas and place unnecessary load on working memory. This redundancy effect means that often it is better to eliminate this information for expert learners as if it is physically integrated it is very difficult for them to avoid creating interference with the learning process.

It may also be necessary to eliminate or trim down information from the one source. Kalyuga, Ayres, Chandler and Sweller present a number of examples that demonstrate that the expertise reversal effect is also evident in learner text processing. They highlight that less knowledgeable learners benefited from additional explanatory material but more knowledgeable learners were better off without the additions.

Another way Kalyuga, Ayres, Chandler and Sweller suggest of dealing with the split attention effect is to present some information visually and some in an auditory modality as the capacity to process information is then distributed over several partly independent subsystems. It has been demonstrated that learners can integrate words and diagrams more easily when the words are spoken rather than presented as text. However, the expertise reversal effect is again evident, as with experienced learners auditory explanations can become redundant and the diagram alone can be more advantageous to learning.

The expertise reversal effect is also indicated to a lesser extent when instructors take a mixed instructional approach method. The novice learner needs to attend to each new element as well as learn all interactions between the elements individually. Once this is done they have acquired a new schema which can act as a single element each time the learner encounters similar tasks or situations. The problem is novices may struggle to keep all the elements simultaneously in working memory much less be able to process each element and its interactions. To this end, Kalyuga, Ayres, Chandler and Sweller review the idea of an isolated elements approach. Information is initially presented as individual elements learned in isolation. This reduces element interactivity and although it means that at this stage of the process learners do not have a grasp of the schema as a whole, it allows the learner to develop partial schemas which can be integrated at a later stage in order to develop a fuller understanding of the interacting elements.

More experienced learners can use their schemas to group together at least some of the elements of incoming information and process these in working memory as a single element. This allows them to keep the cognitive load within the limits of working memory. Kalyuga, Ayres, Chandler and Sweller report that using a mixed method of instruction with expert learners did not benefit them but at the same time did not demonstrate any detrimental effects.

In addition to the approaches for scaffolding outlined above, simple to complex sequencing and the use of alternative tasks with the attendant complexities of the fading principle and the expertise reversal effect, Van Merrienboer, Kircshner and Kester recommend that to manage cognitive load effectively, 'just-in-time information presentation' (2003, p.8) is needed. This includes both timely presentation of supporting information during learning tasks and step-by-step presentation of procedural information.

Learners will need certain task specific information in order to perform the learning tasks and learn from them – this information needs to be active in working memory when they are processing the information.

For tasks with high intrinsic complexity and variable non-recurring tasks that require reasoning and problem solving, Van Merrienboer, Kircshner and Kester suggest that this supporting information should be presented to learners before they start work on the task so that cognitive schemas can be constructed around it and then re-activated in working memory when needed. This retrieval of a schema is much less demanding than activating the external information in working memory during the task completion. If novice learners had tried to process the task information and the task itself simultaneously cognitive overload would likely occur. They need to first construct the appropriate cognitive representations in order to guide their problem solving. This approach is reminiscent of the isolated elements approach for novices previously outlined.

The process of elaboration, where relations are established between the learner's prior knowledge and understanding and new information elements results in the construction of mental schemas, allowing learners to chunk the information they need to know as a single item that can be quickly retrieved from long term memory and used for a variety of purposes. As learners work on the task, they also develop and modify their existing schemas to take into account the knowledge they absorb while actually working on a concrete task. This process of induction helps refine the general body of knowledge that they have obtained which may be helpful with particular parts of the problem solving process.

Therefore the just-in-time approach should be maintained with supporting information and it should be presented to learners just before the task class for which it is relevant.

If, on the other hand, the task is of low complexity with consistent recurrent routine tasks, this procedural task information which explains how to undertake these routine tasks is probably best presented exactly when it is needed during the task. These routines are performed by experts almost automatically as they have repeatedly practiced and strengthened them in a particular learning environment embedding the information and automating the schemas. Van Merrienboer, Kircshner and Kester explain that this learning process of 'knowledge compilation' (2003, p.10) needs to take place in a highly domain-specific representation and therefore is preferably presented just as it is needed. It is also best if it is connected to the first learning task to which it is related. Then in subsequent learning tasks the procedural information is quickly faded in order to decrease extraneous cognitive load.

One advantage of this method is that temporal attention splitting as previously discussed is prevented – the learner does not need to try and integrate information presented in two different time spans. However the procedural instructions and information need to be presented in such a way that they are fully integrated with the task in order to prevent spatial attention splitting effects.

Van Merrienboer, Kircshner and Kester also point out that if a very high level of automation is required for particular recurrent tasks the learner may not get enough practice from whole tasks activities and so may need additional part-task practice. This should start only after learners have grasped the context of the learning tasks so that part-task practice takes place in a meaningful cognitive context that allows learners to identify the activities that are required to integrate the recurrent aspects in the whole task.

In summary, the implications of this new research into cognitive load theory for high school teachers are as follows.

Teachers should take a whole task approach wherever possible. Begin with the simplest version of the task that can be found in the real world in order to reduce the intrinsic cognitive load of the problem. Then proceed towards increasingly more complex versions. Move students through differentiated task classes – sets of tasks that have the same level of complexity.

Within each task class, control the cognitive load imposed and negate the expertise reversal effect by starting with the use of alternative tasks with a high level of in-built support such as worked examples, then progress to completion tasks or goal free problems until the student is ready to move to conventional problem solving and focus on improving speed and accuracy. This provides a way to scaffold whole-task practice through a combination of performance support and fading and reduce extraneous cognitive load.

It is also important for teachers to consider the expertise reversal effect in a number of other circumstances when designing instructional materials. If there is more than one source of information such as text and pictures, the material is best physically integrated, particularly if the sources cannot be understood in isolation. If any of the material becomes redundant due to the experience of the student, it is best to eliminate this information in order to avoid creating interference and additional cognitive load for the more experienced student. The split attention effect can also be dealt with by presenting some information visually and some in an auditory modality (such as a diagram with spoken explanation) as the processing is then spread across different sub-systems allowing a greater capacity to be processed in working memory. The expertise reversal effect indicates though that for the expert student again some of this information may need to be eliminated due to redundancy.

The amount of information that should be presented in textual form will also be affected by the expertise of the student. Although less knowledgeable students generally benefit from additional explanatory material, more knowledgeable students are better off without the additions.

To a lesser extent the expertise reversal effect is demonstrated in the isolated elements approach where novice students are given an opportunity to understand individual elements before attempting to integrate them and understand the interactions. For the expert student, this approach has little effect either positive or negative.

In addition to scaffolds and the ramification of the expertise reversal effect, students also need relevant task-specific information in order to perform the learning tasks. With each task class will be associated information that needs to be given to the student to help them complete the task. The nature and complexity of the task determines when this information is best given to the student – the optimal timing for presentation.

If the material has high intrinsic complexity and non-recurring tasks that require reasoning and problem solving, this supporting information should be presented to students before they start work on the task. The information takes the form of direct, step-by-step or how-to instruction and is quickly faded away for subsequent learning tasks. This just-in-time approach allows the novice student to construct cognitive schemas for this part of the information and then re-activate them in working memory when needed. For each subsequent task class, additional supportive information should be presented to enable the students to perform the more complex version of the whole task. The process of elaboration and induction can then take place.

If the task is of low complexity with consistent recurrent routine tasks, this procedural task information is best presented exactly when it is needed during the task in order to prevent temporal attention splitting.

It is clear that the development of cognitive load theory has resulted in a number of practical recommendations to improve instructional techniques. It is difficult to express the impact more succinctly than by using the seemingly prophetic words of Sweller who over a decade ago wrote: ‘the theory and findings have the potential to substantially alter our preconceptions concerning instructional processes’ (1993, p.8). As outlined above, this has certainly proven to be the case.

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