SCIENCE FOR ALL: AN INFORMATION PROCESSING PERSPECTIVE

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Abstract

This paper argued that although science reforms over the years have been worthwhile, they have neglected an important aspect of the learning process. This has created a breach to the success of these reforms, that is, achieving scientific literacy or 'science for all'. Content and context have been prescribed without recourse to the cognitive architecture of the students. The nature of this architecture as well as the structure of school science was briefly explained. The focus is on the working memory of the information processing system of the learner and how its structure might interact with the nature of school science concepts, the language of school science, and reasoning employed by students in school science. The" argument is that the limitation in capacity of the working memory interacts with these features in the science classroom to create a cognitive overload. If 'science for all" means anything, it must mean that the science experience becomes understood and is personalised by the individual. For that to happen, the science experience must be designed and executed in such a way that it is consistent with the way the learner functions in terms of processing information and making sense of the world around.

Introduction

Science education provision since the 1960s has witnessed a great deal of reform globally. From the 1980s, these reforms have been driven in part by the aim of making science accessible to all. However, the reforms have tended to look at the content and context dimensions. 'Science for all' assumes the individual differences that are inherent in accessibility, participation and achievement will be circumvented. In looking at this trend with its focus on process-based to application-related (Science, Technology and Society driven) curricula and delivery, it is obvious that the emphasis has been on aspects other than the way students learn. The reforms tended not to have looked at the sources of these individual differences in detail and incorporated the rationale into the innovations. Many relegate this important issue to the implications of curricula with a 'science for all' thrust (Hodson, 2002; Hodson and Reid, 1988).

Teaching itself has progressed, at least in aspiration, from positivism to constructivism. The constructivist paradigm comes close to taking care of these differences. However, none of the types of constructivism (personal, socio-cultural and psychosocial) (O'loughin, 1992 and, Tyson, Venville, Harrison, and Treagust, 1997) took into consideration the role of the cognitive architecture of the learner. Although the personal constructivist makes problematic the meaning structures an individual may have acquired through interaction with the environment, it stops short of the innate differences of processing capacities in the individual.

This paper suggests a new direction for science education research and provision. The new agenda will take into consideration the learner as an indivisible entity. The learner is seen as a processor of information. This understanding starts to bring together and interpret many of the findings of research in science education. (Understanding 'what the capacity limitation of this system may impose on the learner will make way for an understanding of the reasons why, despite much research on conceptual change and cognitive load in science education, *sciences not yet accessible 'for all'.* The paper argues for instructional designs that will take this into consideration and science education provision underpinned by this understanding.

Generalizations from the Different Models of the Information Processing System

A number of generalizations can be made about the human information processing system. These include:

- There are three identifiable components of the information processing system: the sensory memory, the working memory or primary memory and the long-term memory.
- Whereas the sensory memory and the long-term memory are unlimited in capacity, the working memory has very limited capacity. This limitation shows in two ways: limitation in storage capacity and limitation in handling processing resources.
- Information flow is two-way: from the long-term memory to the working memory and from the working memory to the long-term memory.
- Storage of information in the long-term memory, is dependent on the level or type of processing that has taken place.
- The working memory, with its limited capacity, is *absolutely critical* in that it is here that thinking, understanding and problem solving takes place.

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Information Processing and Personalization of Science Knowledge

Cobern (1996) argued that only knowledge that has both scope and force attains meaningful learning, while Aikenhead and Jegede (1999) asserted that only knowledge that has attained dependent or secured collateral status is meaningful. Personalization can be achieved if knowledge becomes meaningful, for only then can it be relevant over a wide range of contexts and central in the students cognition (Cobern, 1996), thus being very often and easily accessed (Mbajiorgu, 2003). The information processing system provides opportunity of understanding the stage-wise processes in personalization of information which is the goal of 'science for all'. That meaningful learning is achieved when knowledge has been personalised is axiomatic. Applied to science knowledge, this will take on the challenge of Hurd (2002) to the science education researchers.

Although, considerable efforts have been made in the past by the Centre for Science Education, University of Glasgow, Scotland, .the dearth of empirical work driven by information processing models in the leading science education journals is surprising. Information processing may well hold the key to the solution to the provision of 'science for all'. This paper will be looking at the working memory, the system's workspace (centre for control and processing); its interaction with school science knowledge and the prior knowledge of the learner.

Structure of School Science Knowledge

As the information from the sensory memory is attended to, it can reside in the working memory for upwards of 30 seconds through the process of rehearsal. The information so held in the working memory, is processed or else it is lost by displacement, interference or decay. Processing of science concepts involves two major functions: holding the information in the working memory space and applying resources to it in order to compare, rearrange, classify and interpret it. As we noted earlier, the working memory is limited in its holding capacity and the availability of resources for processing. This introduces a 'trade-off between the two (Daneman and Carpenter, 1980). During processing, if the number of information elements to be held in the working memory is high, it reduces, the availability of space for resources to be applied to the information in order to assign meaning to it (Johnstone, 1997). This is critical since there is a limit to the duration the information can be held in the working memory. This has grave implications for performance in the sciences as a consideration of the structure of school science knowledge will reveal.

Nature of School Science Concepts

While all subject disciplines have themes which are highly conceptual, the problem with the sciences is that, in many syllabuses, the concepts are introduced very early. The nature of science concepts demands multilevel thought from the students (Han and Roth, 2005; Johnstone, 1991; Treagust, Chittleborough and Mamiala, 2003). Johnstone has described this in terms of a triangle (Figure 1).

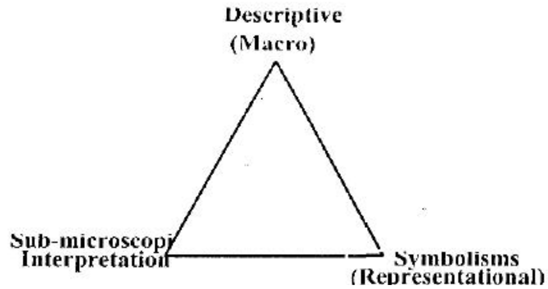

Figure 1 Three levels of science concept representation

Consider, for instance, the topic of genetics well known as one of the major areas of student difficulty in biology: the student is expected to think in terms of the visible or phenotypic features, which is the macro level. At the same time, the student has to think of the genotype or micro level for the same phenomenon and finally, the student has to be able to represent the phenomenon symbolically. All these take place simultaneously as the lesson is going on. In chemistry as well as physics, similar thought levels exist. For chemistry, this might be the macro description of a reaction, the interpretation in terms of molecules and their representation as formulae. Certainly, for students who are experiencing these subjects for the first time, this poses a serious task and can easily overload the working memory. There may well be simply too much to hold in working memory to allow any space for thought. A huge amount of research supports this understanding (e.g. Bahar and Johnstone, 1999; Johnstone, Hogg and Ziane, 1993).

Reasoning Employed in School--Science

The nature of school science concepts as described above requires a certain form of reasoning. Tytler and Peterson (2004) characterized the reasoning at the beginning of formal school science as model-based. For students who are not yet experts and whose knowledge base is at its rudimentary level, this is even more crucial. Thus, model-based reasoning is used more than rule-based reasoning. This can introduce yet another potential source of working memory overload. The limitation of the working memory constrains the construction of as many models as would have been necessary to draw valid conclusions that would hold true in all the premises based on the three levels at which each concept operates. Again, school science does not involve procedural knowledge as much as semantics or conceptualization. Thus, it requires model-based reasoning. Algorithms or rules are involved usually in answering of examination questions and not in the personalization of scientific knowledge. This is the reason why we can have a successful student in the science classroom that never uses scientific knowledge in day-to-day reasoning, the goal of 'science for all'.

Johnson-Laird (2001: 434) asserted that reasoning "is central to science, society and the solution of practical problems[1]'. Model-based reasoning is necessary when a representation of "spatial relations, events and processes, and the operations of complex systems'[1] (Johnson-Laird, 2001: 434) is to be made. Science no doubt is about natural events, processes, spatial relations and systems. Therefore, before much domain-specific knowledge is built up and automaticity approached, or the students transit to rule-based reasoning in familiar problems, they must necessarily use mental models. Since to solve scientific problems or reason scientifically for the novice, involves the use of. models and often more than one model is required, the working memory is usually overloaded (Cherubini and Mazzocco, 2004). In situations where multiple models are required, the limitations of the working memory constrain the students not to construct some of the models and so, inferences, are based on only some models consistent with the premises. This leads invariably, to wrong conclusions or imperfect inferences, otherwise referred to as misconceptions.

Language of School Science

The language of school science is another feature that can create an overload of the working memory (Fang, 2005 and Johnstone, 1991). Science discourses often have high information density. In other words, many of the words and terms are imbued with meanings and these are known as content words (Fang, 2005). Fang went on to explain that, "content carrying words include nouns, the main part of the verb, adjectives and some adverbs; non content carrying words include prepositions, conjunctions, auxiliary verbs, some adverbs, determiners, and pronouns" (p. 338). Science discourses are usually dense with content words. As Fang noted, everyday spontaneous speech has about 2-3 content words per clause, written language about 4-6 content words, whereas scientific writings and discourses have 10-13 content words per clause. The information density in a piece of scientific writing or discourse is therefore high. Fang explained that this is achieved by the use of extended noun phrases. "These extended noun phrases condense information that would normally be expressed, as in everyday spontaneous speech, with more than one clause" (Fang, 2005: 338).

Consider what will be going on in the mind of a beginner in biology who is told as part of the first lesson that the cell is the smallest structural and functional unit of the organism. To the teacher, this statement carries very low information load. But to the beginner the word structural, functional *and organism* may pose serious comprehension problems. For the processing of this information, the beginner has to hold these words in the working memory while trying to interpret them. Again, the beginner at the end of the interpretation of these words has to combine the interpretation so given to make sense of the sentence. As this is going on, the teacher moves on to some other aspects of the lesson. Because there are no previous knowledge structures or schemes built up to anchor these and make processing easy, the beginner has to deal with these as discrete bits of information simultaneously. This will occupy a large portion of the working memory leaving very little space for processing. What we therefore have is a high level of working memory overload. For students of working memory capacity of five and below, science classes can be agonising and very confusing.

Science deals with abstract knowledge and the process of abstraction is another potential source of overload for the working memory. In science discourses, abstraction is often achieved through nominalization of actions and events (Fang, 2005). An instance is the description of the movement of food down the oesophagus: *as the food travels down the oesophagus the walls engage in a wave of involuntary muscular contraction. These peristaltic movements aid to transport the food into the stomach.* The action underlined is nominalized In the following sentence by the phrase *'peristaltic movement'*. In this example, the student has to be able to keep in mind the different features from the first sentence that constitute the *'peristaltic movement'* in order to follow through with the logic. Sometimes, nominalization can obscure meanings, or introduce ambiguities which have to be reconciled in the working memory. Nominalization therefore requires students to hold some information elements in the working memory while processing a given discourse.

Another feature of scientific language is that many of the words are technical. Fang explained once more that technical terms could be in the form of technical vocabulary (expressing field-specific meanings, nonvernacular adjectival words and phrases describing physical objects/phenomena, or verbs describing field-specific activities or processes); and verbs of relational processes "used- to define (e.g., *are, is called],* classify *(are made of, belong to),* compare/contrast (e.g., *is younger than, have twice as much),* or characterize (e.g., *vicious, have sharp claws)* the thing in question" (p.342). Since one of the major aims of science is to describe and explain natural phenomena, it calls into use the processes of classification, categorization, inferring, predicting etc, in order to make generalizations about natural phenomena and 'establish taxonomic relationships' among its entities. The working memory in science classes is involved in two major processes therefore: the processes of language development and comprehension of scientific facts and processes. As Roth and Lawless (2002: 368) assert,

> a major achievement in the sociology and philosophy of science over the past decades has been the recognition that science is a form of culture with its own creeds, language, material, practices, perceptions, theories, and ' beliefs. Learning science then amounts to participation (from more peripheral to central ways) in the particular practices of this culture.

There is yet another source of working memory overload. Science often uses *ordinary* words, with their own, 'normal' meaning and gives such words a specialised meaning. Cassells and Johnstone (1977, 1978, 1984 and 1985) have explored this in some detail and offered lists of words, which cause problems. For example, to talk of a volatile compound in chemistry may generate all kinds of confusions in that the word 'volatile' already may hold several different meanings in normal usage. Again, the working memory is given the task of transmuting these words from common sense or everyday words to technical and scientific words (with different meanings). At the same time, the student is expected to grasp the logic of the lesson. This invariably, introduces dual task for the working memory.

The interaction of scientific language and the working memory in science learning has vital implications for the personalization of science and thus on literacy, participation and performance, that is, 'science for all'. Efforts have to be made and research directed to find more effective ways of circumventing the capacity limitations imposed by the wohung"memory in a science lesson. This is highly important for the beginning students because the process of enculturation or acculturation, for that matter, is achieved over a long period of lime. As we have seen, learning science amounts to acculturation. The limited time for school science does not make room for this process. Perhaps, more attention should be given to the strategies of Aikenhead (1996), and other strategies of achieving this in the face of time constraint. Fang (2005: 337) therefore argued that:

> ...Learning the specialized language of science is synonymous with learning science.... Learning science means learning to control the unique linguistic forms and structures that construct and communicate scientific principles, knowledge, and beliefs. Thus, developing literacy in science is fundamentally a semiotic process involving systematic remodelling of everyday grammar and concomitant resconstrual of everyday ordinary life experiences.

In a rather neat experiment, the effect of working memory on language was demonstrated by measuring the working memory space twice with the same pupils, once in the native language of the. pupils and once in their second language (Johnstone and. Selepeng, 2001). The measured working memory space was consistently *less* for the second language by a fixed amount, showing how part of the limited working memory space was being used for some kind of linguistic translation.

Working Memory Architecture

Again, to provide 'science for all' requires us to pay attention not just to the limits of the working memory but to its structure as well. It is obvious that the sub-components can be developed to different degrees making room for individual differences. For students with less well-developed phonological loop, science learning presents very daunting tasks. As we have noted above, learning science is tantamount to learning the scientific language. For others whose visuospatial scratchpads are less developed, learning with symbols and diagrams as often is the case in science lessons, will pose the greater difficulty. For those whose episodic buffer is impaired, integrating science into the long-term memory becomes a problem especially, since science involves lots of practical work and an integration of knowledge from different modalities. Finally, for those with impaired executive control, the problem can only be exacerbated.

It is obvious that processing in science involves input from different modalities and this might inadvertently, give rise to concurrent task processing if the instructional variables are not properly manipulated. Given that the executive control does not support[1] multiple-task processing effectively, the reason for the low achievement in the sciences would seem to be apparent. As the teacher is talking and drawing, the student is expected to follow these concurrently and at the same time, process the main flow of the lesson. Thus, Conway and Engle (1996: 577) argued that, "individual differences in working memory capacity will have implications for any task that requires controlled effortful processing" and there is no doubt that school science does. We need to understand therefore, the distinctive working memory profiles of our students because the nature of the differences in achievement and participation in the sciences, may well be the result of the distinctiveness of their working memory profiles. This is supported by the work of Pickering and Gathercole (2004) who demonstrated that students with different working memory profiles are characterised with different special educational needs.

Given these findings, it is obvious that in subjects like the sciences, individual differences in achievement will be marked by distinctive working memory profiles. Firstly, the student has to store and process the highly technical language of science as well as the pervasive symbols. Secondly, he/she has to retrieve the already stored domain specific concepts and principles and access the discrimination network on which further processing depends. Thirdly, the intermediate products from the processing operations have to be stored in the working memory until final processing. Success in science it would seem, requires efficiency of all the four components of the working memory. This is crucial since the sciences deal with the realm of the physical. The student has to comprehend the text or lesson as well as personalize it by way of reconciling it with already developed schemata from everyday interactions with the environment in order to achieve meaningful learning.

In the light of the foregoing, what is the role of science instruction? Very little has been done by science education researchers in this area. Much of the researches have been in language studies and by psychologists. The first hint about cognitive load was by Johnstone and Kellett (1980) in the area of chemistry and biology. At the University of New South Wales, Sydney, Australia, much has been done to take this theory forward. However, much of this is in the areas of mathematics and technology. Not much has been done so far in the core science subjects of biology, chemistry and physics. The following sections are, therefore, a suggestion of areas of research based on a theoretical analysis of works done so far and the nature of the problem.

Conclusion

If science knowledge is to be understood (and not just memorised) and then made personal, three key steps must be taken:

(a) The actual curriculum design must be developed taking into account the limited working memory of pupils at a given age;

(b) The way the science is presented must also take into account the mediating role of available schemata;

(c) The way the science is assessed (assuming it has to be assessed) must be re-thought so that it does not penalise unfairly those with low working memories, thus leading to a sense of failure.

If science for all' means anything, it must mean that the science experience becomes part of the individual and is understood. For that to happen, the science experience must be designed and executed in such a way that it is consistent with the way the learner functions in terms of processing information and making sense of the world around.

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