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Learning Difficulties in Chemistry: An Overview

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ABSTRACT

Chemistry is often regarded as a difficult subject, an observation which sometimes repels learners from continuing with studies in chemistry. This paper seeks to bring together the general findings obtained from research over the past few decades for both school pupils and university students in an attempt to suggest the key reasons for this difficulty. Suggestions are made on ways to minimise the problems based on understandings of attitudes and motivation as well as the psychological understandings of how learning takes place.

Keywords: Learning Difficulties, Chemistry, Working Memory Space, Motivation, Previous Knowledge.

INTRODUCTION

At the beginning of any course, students start their study with a set of beliefs about the nature of learning and what they intend to achieve (Biggs & Moore, 1993). These beliefs are derived from earlier school and learning experiences as well as their current goals and motives.

An understanding of how students learn can help teachers to devise effective strategies for teaching. This requires that research into the learning process is made accessible (Clow, 1998). To facilitate the development of students' views of knowledge, students need to be supported at the appropriate level. A student, who strongly believes that there is only one correct answer, will find an exercise, which shows a multiplicity of possible interpretations confusing and unhelpful.

Chemistry is one of the most important branches of science; it enables learners to understand what happened around them. Because chemistry topics are generally related to or based on the structure of matter, chemistry proves a difficult subject for many students. Chemistry curricula commonly incorporate many abstract concepts, which are central to further learning in both chemistry and other sciences (Taber, 2002). These abstract concepts are important because further chemistry/science concepts or theories cannot be easily understood if these underpinning concepts are not sufficiently grasped by the student (Zoller, 1990; Nakhleh, 1992; Ayas & Demirbaş, 1997; Coll & Treagust, 2001a;

Nicoll, 2001). The abstract nature of chemistry along with other content learning difficulties (e.g. the mathematical nature of much chemistry) means that chemistry classes require a high-level skill set (Fensham, 1988; Zoller, 1990; Taber, 2002).

Chemistry is often regarded as a difficult subject, an observation that sometimes repels learners from continuing with studies in chemistry. With the establishment of new syllabuses in chemistry for secondary schools in different countries in the last decayed.

One of the essential characteristics of chemistry is the constant interplay between the macroscopic and microscopic levels of thought, and it is this aspect of chemistry (and physics) learning that represents a significant challenge to novices (Bradley & Brand, 1985). In his early study, Johnstone (1974) reported that the problem areas in the subject, from the pupils' point of view, persisted well into university education, the most difficult topics being the mole, chemical formulae and equations, and, in organic chemistry, condensations and hydrolysis.

Over a number of years, many of the above difficult areas was subjected to systematic study to try to identify the point of difficulty and to seek common factors among the nature of these difficulties (Johnstone *et al.*, 1977; Duncan & Johnstone, 1973; Kellett & Johnstone, 1974; Garforth *et al.*, 1976). Johnstone and El-Banna (1986) suggested a predictive model that enabled them to raise and test an important hypothesis, which was then applied to chemistry learning as well as to learning in other science disciplines.

Numerous reports support the view that the interplay between macroscopic and microscopic worlds is a source of difficulty for many chemistry learners. Examples include the mole concept (Gilbert & Watts, 1983), atomic structure (Zoller, 1990; Harrison & Treagust, 1996), kinetic theory (Abraham *et al.*, 1992; Stavy, 1995; Taylor & Coll, 1997), thermodynamics (Abraham *et al.*, 1992; Özmen & Ayas, 2003), electrochemistry (Garnett & Treagust, 1992; Sanger & Greenbowe, 1997), chemical change and reactivity (Zoller, 1990; Abraham *et al.*, 1992), balancing redox equations and stereochemistry (Zoller, 1990), chemical bonding (Peterson & Treagust, 1989; Taber, 2002; Taber & Coll, 2003; Coll & Treagust, 2003; Özmen, 2004; Ünal *et al.*, 2006), solution chemistry (Ravialo, 2001; Goodwin, 2002; Pınarbaş, & Canpolat, 2003; Çalık *et al.,* 2005, 2006), covalent bonding (Treagust, 1988; Peterson & Treagust, 1989; Peterson *et al.*, 1989; Boo, 1998; Tan & Treagust, 1999; Coll & Treagust, 2001a; Nicoll, 2001), ionic bonding (Taber, 1997; Robinson, 1998; Coll & Treagust, 2001a; Coll & Treagust, 2003), metallic bonding (Coll & Treagust, 2001a), intermolecular forces (Treagust, 1988; Peterson & Treagust, 1989; Peterson *et al.*, 1989; Taber, 1997; Boo, 1998; Tan & Treagust, 1999; Barker & Millar, 2000), chemical bonds and energetic (Boo, 1998; Barker & Millar, 2000), use of anthropomorphic language and analogies (Harrison & Treagust, 2000; Coll & Treagust, 2001a; Eshach & Garik, 2001; Nicoll, 2001), mental models (Coll & Treagust, 2001a, b, 2003; Coll & Taylor, 2002; Taber, 2002) and enhancing students' conceptual understanding (Barker & Millar, 2000; Harrison & Treagust, 2000).

Chemistry, by its very nature, is highly conceptual. While much can be acquired by rote learning (this often being reflected by efficient recall in examination questions), real understanding demands the bringing together of conceptual understandings in a meaningful way. Thus, while students show some evidence of learning and understanding in examination papers, researchers find evidence of misconceptions, rote learning, and of certain areas of basic chemistry which are still not understood even at degree-level (Johnstone, 1984; Bodner, 1991): What is taught is not always what is learned.

This paper seeks to bring together some of the main findings from research over the past few decades, attempting to establish some key general principles which may be of value in curriculum development, policy makers, teachers, teaching strategies as well as in the generation of more research work. An examination of the aims of each study will reveal the motive of the researchers who undertook the study. Because the foundation for student conception research is the nature of learning, teachers will be able to easily translate the methods used for research into classroom practice.

The focus questions for this overview of the literature are:

1. What are the main areas of learning difficulty?
2. What are the main aspects of reducing obstacles to learning?

Research reported in the literature for each of these themes is now presented in turn.

1. Areas of Difficulty

In looking at the enormous range of papers, which have addressed various facets of the learning difficulties, related to chemistry, it is not easy to categorise the work into neat compartments. In the analysis presented here, the work has been divided into five main areas of concern, recognising that there are overlaps and potential omissions. Each is discussed briefly.

(a) Curriculum Content

The advent of revised school syllabuses in the 1960s and 1970s in many countries saw a move towards the presentation of school chemistry in a logical order, the logic usually being that of the experienced academic chemist. Similarly, early chapters in almost all textbooks for first level higher education courses start with topics like atomic theory, line spectra, Schrödinger equations, orbital, hybridisation, bonding, formulae, equations, balancing ionic equations, calculations, and stoichiometry. This is the 'grammar and syntax' (Jenkins, 1992) of chemistry but is daunting for the student. Johnstone (2000) has made arguments against this 'logical' presentation cogently: The logical order may well not be psychologically accessible to the learner.

Much school chemistry, taught before 1960, laid great emphasis on descriptive chemistry, memorisation being an important skill to achieve examination success. The sub-microscopic interpretation and symbolic representation were left until later (see Figure 1). Today, the descriptive is taught alongside both the ‘micro’ and ‘representational’. Johnstone (1982) has argued that the learner cannot cope with all three levels being taught at once, and Gabel (1999) supports this argument. Indeed, today, there is a danger that chemistry depends too much on the representational, with inadequate emphasis on the descriptive.

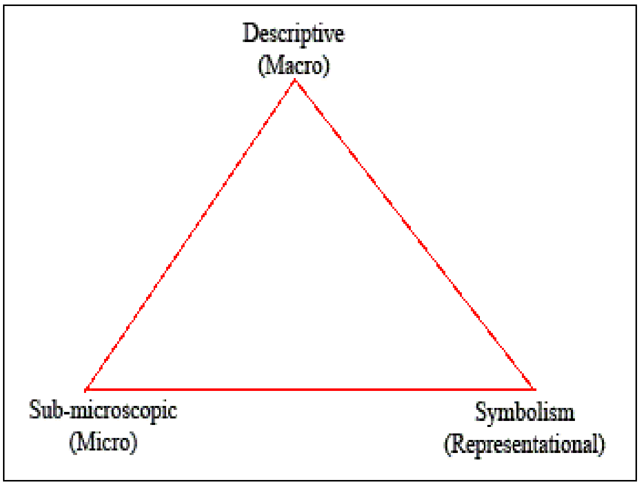

Figure 1: *The Chemistry Triangle*

Chemical knowledge is learned at three levels: "sub-microscopic," "macroscopic" and "symbolic", and the link between these levels should be explicitly taught (Johnstone, 1991; Gabel, 1992; Harrison and Treagust, 2000; Ebenezer, 2001; Ravialo, 2001; Treagust *et al*., 2003). Also, the interactions and distinctions between them are important characteristics of chemistry learning and necessary for achievement in comprehending chemical concepts. Therefore, if students possess difficulties at one of the levels, it may influence the other. Thus, determining and overcoming these difficulties should be our primary goal.

Johnstone (1984, 1991) indicated that the nature of chemistry concepts and the way the concepts are represented (macroscopic, microscopic, or representational) make chemistry difficult to learn. The methods by which students learn are potentially in conflict with the nature of science, which, in turn, influences the methods by which teachers have traditionally taught (Johnstone, 1980).

In order to determine whether student's understanding of chemistry would increase if the particulate nature of matter (sub-microscopic level) was emphasised, Gabel (1993) conducted a study involving students in an introductory chemistry course. Introducing extra instruction to the experimental group that required students to link the particulate nature of matter to other levels (macroscopic and symbolic levels); Gabel found that the experimental group performed higher in all levels than the control group. It seems that this kind of additional instruction is effective in helping students make connections between the three levels on which chemistry can be both taught and understood.

Sawrey (1990) found that, in an introductory chemistry course, significantly more students were able to solve the problems that used symbols and numbers than could solve those depicting particles. Bunce *et al*. (1991) interviewed students who had solved problems out loud. This study indicated that students rarely thought about the phenomenon itself but they searched in their minds until they came upon something that fitted the conditions of the problem.

Osborne and Cosgrove (1983) showed how students (at several school age levels) understood little about the particulate nature of matter or about chemical phenomena in their everyday lives. Surprisingly, some of the incorrect explanations that students gave to common phenomena are concepts that they developed AFTER formal school instruction. Bodner (1991) then used the same questions developed by Osborne and Cosgrove to determine how prevalent these ideas were among the graduate students. His findings indicated that non-scientific explanations persist for some students even after they had graduated with a major in chemistry. He concluded that students have difficulty in applying their knowledge and they do not extend their knowledge into the real world.

This last aspect has been discussed (Reid, 1999, 2000) where it was suggested that the chemistry syllabus to be taught should not be defined by the logic of the subject but by the needs of the learner while Johnston's complementary paper (Johnstone 2000) emphasises that the order and method of presentation must reflect the psychology of the learner. These two fundamental principles would offer a constructive basis for dialogue in re-structuring the way Chemistry is offered at school and higher education: in simple terms, define the material to be taught by the needs of the learner, and define the order of presentation by the psychology of learning.

Such a statement is relatively easy to make but it may well prove to be very difficult to implement. Most curricula are defined by the needs of the next stage and are not defined by the needs of those (often the majority) who will *not* study chemistry at the next stage (Reid, 1999, 2000). Similarly, chemistry is a logical subject and its inherent logic is a tempting structure on which to build a syllabus. However, the logic is that of the expert not the learner.

(b) Overload of Students' Working Memory Space

The working memory space is of limited capacity (Baddeley, 1999). This limited shared space is a link between, what has to be held in conscious memory, and the processing activities required to handle it, transform it, manipulate it, and get it ready for storage in long-term memory.

When students are faced with learning situations where there is too much to handle in the limited working space, they have difficulty selecting the important information from the other less important information. The latter has been described as “noise”, the student having difficulty in separating the signal from the noise (Johnstone & Letton, 1991).

Faced with new and often conceptually complex material, the chemistry student needs to develop skills to organise the ideas so that the working space is not overloaded. Without the organising structures available to the experienced teacher, the student frequently has to resort to rote learning, which does not guarantee understanding. To solve this type of problem, Johnstone (1999) has argued that teachers have to look more closely at what is known about human learning and also look at the nature of the discipline of chemistry and its intellectual structure in an effort to harmonise them.

The ability to develop strategies to cope with information overload depends heavily on the conceptual framework already established in the long-term memory. Working space cannot be expanded but it can be used more efficiently. However, this depends upon some recognisable conceptual framework that enables student to draw on old, or systematise new, material. Miller (1956) suggested the idea of "chunking" (the ability to use some strategy to bring together several items into one meaningful unit, thus reducing working space demands).

Difficulties in conceptual understanding have been related to working memory space and the idea of chunking (Johnstone & Kellett, 1980; Johnstone, 1980). Salvaratnam and Frazer (1982) discuss the use of summary frameworks while Johnstone outlines ways by which extraneous excess information ("noise") can be reduced (Johnstone, 1980; Johnstone & Wham, 1982). Some practical ways to avoid information overload will be discussed later.

(c) Language and Communication

Language has been shown to be another contributor to information overload (Johnstone, 1984). Language problems include unfamiliar or misleading vocabulary, familiar vocabulary which changes its meaning as it moves into chemistry, use of high-sounding language, and the use of double or triple negatives (Cassels & Johnstone, 1985). An interesting example of the effect of language on working memory space overload is the work carried out to measure working memory space, using the second language of the pupils. They found that, where the learner was operating in a second language, the usable working memory space dropped by about one unit. It was suggested that this unit was being "used" to handle the language transfer (Johnstone & Selepeng, 2001).

In USA, Gabel (1999) has noted that difficulties students have with chemistry may not necessarily be related to the subject matter itself but to the way of talking about it. In Australia, Gardner (1972) made a study of the vocabulary skills of pupils in secondary schools. He drew up word lists to show which non-technical words were inaccessible to pupils at various stages. He also examined the words and phrases which connect parts of a sentence and which give logical coherence to it (development of logical arguments are impossible without these logical connectives). He found that many words used frequently by science teachers were just not accessible to their pupils.

In Scotland, similar investigations were conducted and extended into higher education. The study by Cassels and Johnstone (1980) has shown that the non-technical words associated with science were a cause of misunderstanding for pupils and students. Words, which were understandable in normal English usage, changed their meaning (sometimes quite subtly) when transferred into, or out of, a science situation. For example, the word "volatile" was assumed by students to mean "unstable", "explosive" or "flammable". Its scientific meaning of "easily vaporised" was unknown. The reason for the confusion was that "volatile", applied to a person, does imply instability or excitability and this meaning was naturally carried over into the science context with consequent confusion.

White (1977) argued that learning involves the interaction of the information that the learner receives through his sensory system and the information that he or she already has available in his or her long-term memory. This enables the learner to recognise and organise the incoming information and make sense of it. Unfamiliar or confusing words and constructions come into conflict with the organisational process. White also emphasised that the cognitive processes may be considered to involve the interaction of the components of memory: Working memory and long-term memory.

Language influences the thinking processes necessary to tackle any task. This is supported by the following observations made by Cassels and Johnstone (1984). They noted that memory span is not determined by the number of words but by the grammatical structures (e.g., embedded clauses) that may themselves load the memory. They stress that the important factor in the sentence is its meaning while sentences with a negative require more of working memory capacity than do otherwise identical sentences lacking the negative.

The whole area of language, including the use of representational symbolisms, needs careful thought. Previous work has established the reality and nature of the problem. Language helps or hinders interactions with long-term memory but it also can be a source of significance information overload. Perhaps this suggests that there has to be more opportunity for the learner to verbalise and discuss ideas as they are being presented. This would give opportunities for misunderstandings and confusions to become more apparent, allowing the learner to adjust thinking and clarify ideas.

(d) Concept Formation

Chemistry learning requires much intellectual thought and discernment because the content is replete with many abstract concepts. Concepts such as dissolution, particulate nature of matter, and chemical bonding are fundamental to learning chemistry (Abraham *et al*., 1992, 1994; Nakhleh, 1992).

Unless these fundamentals are understood, topics including reaction rate, acids and bases, electrochemistry, chemical equilibrium, and solution chemistry become arduous. Therefore, inquiring into students' conceptions of the fundamental concepts in chemistry has been a research focus of several researchers in many countries for the last two decades (Stavy, 1988; Peterson & Treagust, 1989; Ebenezer & Gaskell, 1995; Quiles-Pardo & Solaz-Portoles, 1995; Ayas & Demirbaş, 1997; Ayas & Coştu, 2002; Çalık *et al*., 2005).

Real understanding requires not only the grasp of key concepts but also the establishment of meaningful links to bring the concepts into a coherent whole. Ausubel's important work (1968) has laid the basis for understanding how meaningful learning can occur in terms of the importance of being able to link new knowledge on to the network of concepts, which already exist in the learner's mind. Concepts develop as new ideas are linked together and the learner does not always correctly make such links. This may well lead to misconceptions.

Conceptions or pieces of intellectual thought either reinforce each other or act as barrier for further learning. To overcome obstacles in learning, student conception researchers have been focusing on identifying and assessing students' "misconceptions" (Helm, 1980), "alternative frameworks" (Driver, 1981), "children's science" (Gilbert *et al*., 1982), or "preconceptions" (Novak, 1977). These labels are attached when students' conceptions are different from the scientific ideas and explanations (Nakhleh, 1992; Taber, 2000; Nicoll, 2001; Ayas, Köse and Taş, 2002).

There have been an enormous number of studies on misconceptions in chemistry and there are several reviews of this area (Anderson, 1990; Stavy, 1991, 1995; Nakhleh, 1992; Gabel & Bunce, 1994; Wandersee *et al.*, 1994). In addition, various studies indicate that student' difficulties in learning science concepts may be due to the teachers' lack of knowledge regarding students' prior understanding of concepts (Driver & Easley, 1978; McDermott, 1984). Bodner (1986) makes a salutary point when he notes that, 'We can teach - and teach well - without having the students learn".

Alternative conceptions may not be just students' fault. Chemical knowledge structures, for example, in "combustion," "physical and chemical change," and "dissolving and solutions" by their very nature lead to alternative conceptions argues Griffiths (1994). Students' conceptions are constrained both by the perceiver (learner) and the perceived (chemical phenomena) (Ebenezer, 1991). Thus, learning involves knowledge that needs to be restructured, adapted, rejected, and even discarded (Duschl and Osborne, 2002).

Various other studies have focused on students' concepts and their inter-connections. Fensham and George (1973) investigated problems arising from the learning of organic chemistry while Kellett and Johnstone (1974) indicated that students had little conceptual understanding of functional groups and their role. This caused difficulties with, for example, esterification, condensation, and hydrolysis. Kempa and Nicholls (1983) found that problem-solving ability, above the algorithm level, depends on the strength of concept interlinking in a student's mind. They also found that a student's ability was dependent on context, such that individual students can do well in some areas and badly in others.

Bodner (1991) has listed several factors that may lead to misconceptions in the minds of learners. He notes the problems of rote learning where students possess knowledge without understanding. When the teacher first introduces an idea, the learner may already possess previous experience (derived from the world around, including the media), which leads to confusion. In addition, there is also the problem where the scientific language remains constant while the meanings of the terms change until they become misleading. Many research tools appear in the literature to identify students' misconceptions. Examples include the diagnostic tests developed by Treagust (1988) and Krishnan and Howe (1994).

While the literature is replete with papers, which provide evidence of misconceptions, fewer papers suggest potential remedies. It is worth recognising that misconceptions will occur - learner does not come to chemistry with empty minds. The process of learning chemistry will involve the modification or alteration of previously held ideas and this is a natural process. It is individual in nature and there is no way by which the teacher has the time or capacity to approach each learner on an individual basis. However, in practice, if concepts are developed with care, building on the language and thought forms already present, while allowing concepts to be approached from several directions, the learner will be enabled to develop ideas more meaningfully. In addition, learners need the opportunity to "play with ideas', to share ideas, to verbalise concepts so that, in a natural, step-wise fashion, concepts steadily move forward on a secure base. This will allow inadequate conceptions to be modified in an acceptable way. Nonetheless, misconceptions will always occur, even among those highly experienced in chemistry!

The whole area of misconceptions (including alternative frameworks and the ideas in constructivism) probably needs some re-thinking. It appears to be a natural part of the developmental process and it appears to be individually idiosyncratic. However, strategies can be adopted to take advantage of this natural process in the development of more secure concept understandings. A useful future line of research might be to explore the effects of strategies, which teachers might use to take advantage of this natural process in order to give the learners an enriched understanding of important concepts. Group work, dialogue and the exchange of ideas may all be very important in allowing misconceptions to be corrected effectively.

(e) Motivation

There is no doubt that motivation to learn is an important factor controlling the success of learning and teachers face problems when their students do not all have the motivation to seek to understand. However, the difficulty of a topic, as perceived by students, will be a major factor in their ability and willingness to learn it (Johnstone & Kellett, 1980).

Students' motivation to learn is important but does not necessarily determine whether they employ a deep or a surface approach: Aspects of students' motivation to learn can be classified as either intrinsic (e.g. wanting to know for its own sake) or extrinsic (e.g. wanting to learn what is on an exam syllabus) (Entwistle *et al*., 1974). There is also a third class, called 'amotivational' learning, which covers the situation where students do things (like attending lectures) without any conscious belief that this will help them learn anything (Vallerand & Bissonnette, 1992).

Resnick (1987) found that students will engage more easily with problems that are embedded in challenging real-world contexts that have apparent relevance to their lives. If the problems are interesting, meaningful, challenging, and engaging they tend to be intrinsically motivating for students. However, Song and Black (1991) indicated that students may need help in recognising that school-based scientific knowledge is useful in real-world contexts.

White (1988) argued that the issue of long-term and short-term goals is relevant to the learning of science. The student who goes to lectures with a short-term goal of passing examinations often has a specific approach to learning. Scientific laws and potentially meaningful facts are learned as propositions unrelated to experience. Too often examinations reward the recall of such facts. On the contrary, the students who have a stronger sense of achievement, or who want to learn about science, may attend the lectures with a long-term goal of a deeper understanding and appreciation of science. They may approach it involving advanced learning strategies of reflection and inter-linking of knowledge. With the pace of normal lectures, there is unfortunately little opportunity for this to occur during the lectures. Ames and Ames (1984) have pointed out that students' motivations for learning from lectures have important consequences for what they are attending to, how they are processing information, and how they are reacting to the lectures.

Adar proposed the existence of four motivational traits that are attributable to students' needs (cited in Trumper, 1995). She introduced the notion of motivational pattern and implied that learners differ with respect to their preference for and responsiveness to different instructional features. She was also able to identify empirically the four major motivational patterns in her student sample, and accordingly she divided students into four types: the achievers, the curious, the conscientious, and the sociable. Hofstein and Kempa (1985) followed this line of research and found that students of different motivational patterns have their preferred modes of learning as well.

Kempa and Diaz (1990a) found that a high proportion of the total student population could be clearly assigned to one of the four motivational patterns. Kempa and Diaz (1990b) went on to suggest that students with the conscientious or achievers type of motivational pattern would exhibit a strong preference for formal modes of teaching. Numerous other studies have sought to probe motivational features of learning (such as Ward & Bodner, 1993; Nakhleh & Mitchell, 1993). Together, they give an insight into the vital importance of considering motivational features in a learning situation.

2. Reducing Obstacles to Learning

It is, of course, the aim of chemistry teachers at all levels to make the subject accessible in such a way that maximum meaningful learning can take place. Salvaratnam (1993) has listed a number of important aspects to aid such learning. These are consistent with two broad principles:

(1) The need to avoid working memory space overload;
(2) The importance of taking into account concepts already held.

These two fundamental ideas are explored now in some detail:

(a) Working Memory Space Overload

The problems associated with limitations in working memory space have already been outlined. The importance of these limitations cannot be underestimated. The working memory space not only has to hold incoming information, it also has to draw information from long-term memory AND process information to make sense of it. The potential for overload is, therefore, considerable.

One of the greatest difficulties in avoiding working space overload lies in the fact that the learner does not yet have the experience (such as the development of "schema, tricks, techniques and previous knowledge" which may be called "strategies") to be able to reduce the working space overload (Johnstone & El-Banna, 1986). Unfortunately, the acquisition of such strategies (e.g. chunking, Miller, 1956) is a highly personal process. Therefore, it is not easy to teach the learner how to chunk although it is possible to present information in such a way that the learner can more easily develop personal chunking skills.

According to White (1988), we chunk the world that is we combine our sensations into a small number of patterns. Therefore, chunking is a function of knowledge. The size and number of chunks perceived in a situation is one of the big differences between the knowledgeable person (e.g. expert, teacher, adult) and the novice (e.g. beginner, student, and child). The knowledgeable person can collect the phenomena or events into a smaller number of meaningful units. The teacher already has such strategies but no students can necessarily apply these. It is important, therefore, to minimise working space demands and to provide several routes to meaningful learning, allowing the learner to seek to develop their own strategies, which might enable them to reduce the overload.

Items are handled in the working memory as 'chunks' of information. These can vary from single characters to abstract concepts and complex images (Johnstone & Kellett, 1980). It is possible to compensate for the limited capacity of working memory by restructuring the information. For example, a telephone number (009722799753) is difficult to remember as eleven digits, but if the same number is broken up into three smaller groups (00972-279-9753- representing area, district and number), it is much easier to remember. The effect is to reduce the storage required from eleven chunks to three.

Therefore, chunking is a process of organising information, which allows a number of items to be viewed as a single unit, with probably a name or label. It is an important factor in both communication and learning (White, 1988). Ability to chunk information is a learned strategy, and the act of chunking will show how well the topic is known. The more you know about the topic the easier it is for you to chunk within it. The number of chunks a person can hold may be a fixed characteristic for an individual but will vary from person to person.

Johnstone (1984) has pointed out that "The teacher's working memory is already organised, but this is not the case for the learner. Each learner has to analyse the information coming in and organise it for himself, or be helped to organise it, if the learning is to become part of him. If he tries to take on the teacher's information and structure, he has to resort to rote memorisation which certainly does not guarantee understanding".

In trying to solve a problem, the student may find his working memory under stress. Solving problems is full of "noisy" things, "noisy" in the sense that they distract from the "signal" or "message" that is to be conveyed. The "noise" can occupy a substantial part of working memory leaving little space for the "signal" and even less space for thinking about what they are all trying to say. Information crowds in, from lecture notes, textbooks, workshops, tutorials, peer discussions, things to recall, and then to interpret.

To overcome these limitations, expansion of the size of each chunk of information is necessary. For example, experienced instructors (unlike novices) can condense a complicated stoichiometry problem to one chunk by recognising a key relationship. Similarly chemists do not see a carbon atom, two oxygen atoms, two hydrogen atoms, a double bond, and three single bonds (nine pieces of information), instead they see it as a carboxylic acid (one piece). Pattern formation is one way of chunking, which is, integrating a larger number of information bits into a smaller number.

Kellett (1978) proposed a relationship between Information Content, Conceptual Understanding, and Difficulty. It stated that where the learners had a lack of conceptual understanding then those learners may perform reasonably in low information load situations, but their performance would decrease in high information load situations, causing complaints of difficulty.

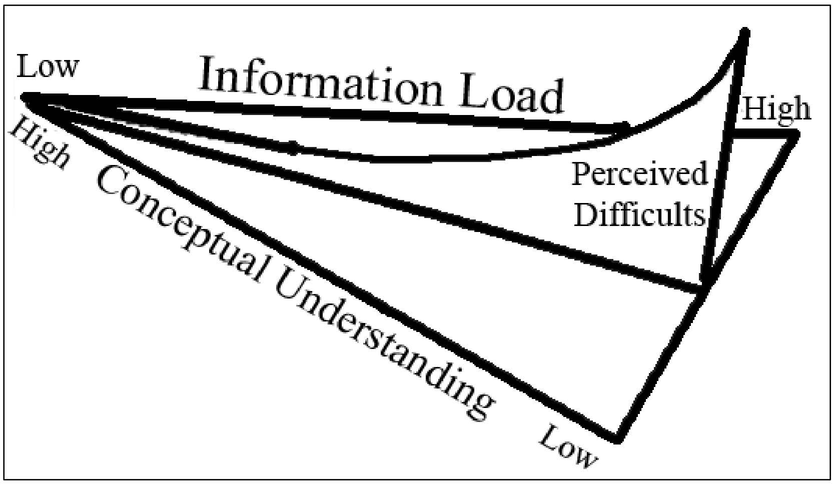

Figure 2. *The "Concorde" Diagram from Johnstone (1980)*

Those with high conceptual understanding could use this to chunk information, and thus reduce the information load to one, which their working spaces could handle. High conceptual understanding would also allow the learners to separate relevant from irrelevant and focus in on the relevant only, which would also reduce the information load burden.

This relationship between Information Content, Information Load, and Perceived Difficulty was summarised by Johnstone in the "Concorde" diagram, which is shown in figure 2 (Johnstone, 1980). As the Information Load increases, for a student with low Conceptual Understanding, so the Perceived Difficulty barrier increases, the reverse being the case for a student of high Conceptual Understanding.

A new learner is naturally at the Low end of the Concept Understanding axis. If the teacher presents his new learner with material at the High end of the Information Load, then the Perceived Difficulty barrier will prevent the learner from "seeing" what is going on. If this continues, then a student's complaint of "I don't understand" may easily become "I will never understand". Such an attitude towards a topic may prove difficult or impossible to alter later. If the teacher adopts a lower Information Load, increasing it only as the learner's concept understanding develops, then the difficulty should remain (essentially) constant.

(b) Paying Attention to Incoming Information

Learners have to focus on a specific task within a 'noisy' environment (irrelevant material), but also, within the task, they have to select specific information that is relevant (meaningful) for them. Teachers can only really find out whether learners are attending by ascertaining what they are learning (Ausubel, 1968). Learners need to know when and where to pay attention, and to what to pay attention.

Fox (1993) claimed that attention is affected by the complexity of the task and the motivation of the individual. The focus of the learners' attention determines what information is processed. Learners can attend to only a very limited number of the demands that compete for their attention. Johnstone and Percival (1976) found that attention breaks do appear to exist and occur generally throughout lectures. The observer can detect such breaks relatively easily and those attention breaks appear as genuine loss of learning in subsequent diagnostic tests. A learners' ability to select the important information to attend to is a key strategy for effective learning. Selective or discriminatory attention has been shown to underlie learners' rates of learning.

Preparing the mind of the learner is one way to help students to focus their attention on the new information by linking it to their previous knowledge (the knowledge they already know and understand). This is discussed in more detail in Sirhan *et al*. (1999) where the use of pre-lectures is shown to be powerfully effective as a way to prepare the minds of learners, with special emphasis on those whose background knowledge and experience is less than adequate. Students who know more about a topic find it easier to identify and focus on important information. For this reason, carefully choosing the delivered material may greatly facilitate learning. This has been explored in detail in Sirhan (2000) and is outlined in Sirhan and Reid (2001, 2002).

(c) Recalling Previous Knowledge Easily

To make the material easier for recall, learners actively need to construct, organise, and structure internal connections that hold the information together. The systematic organisation of knowledge, which may be considered to be the ordering of the component knowledge items in a logical, coherent, concise, and principle-based manner, is of fundamental importance for the effective learning, recall, manipulation, and use of knowledge.

Salvaratnam (1993) found that effectiveness of knowledge organisation is increased if the:

(i) Knowledge stored in memory is principle/concept based, coherent, systematic and concise, and
(ii) Organisation is around the minimum amount of essential knowledge (number of principles and concepts).

This latter point is one that has been confirmed in very recent work (Otis, 2001). It was found that the concept maps generated by medical students at various stages in their learning shows that many students move from a simple, but inadequate, concept maps at early stages of learning through increasingly complex maps until they move back to much simpler but more adequate maps when concepts have been grasped much more fully. It is, therefore, important that unnecessary principles, concepts, definitions, and terms be excluded as concepts are built up in the minds of learners.

Salvaratnam (1993) also listed five aspects, which would aid the learning, understanding, recalling, and application of knowledge:

(1) Use the underlying principles and concepts as the sole basis for knowledge organisation;
(2) Exclude unnecessary laws, concepts, definitions, and terms;
(3) Use systematic and meaningful terms and definitions;
(4) Link the component items of knowledge sharply and coherently; and
(5) Store knowledge concisely.

These ways could help to reduce memory overload, aid learning and understanding, and avoid mistakes. In this complexity and because knowledge construction is not easy, students often are tempted to engage in rote learning rather than meaningful learning. The teachers' task is to try to find ways to increase meaningful learning, possibly by actively involving students in the process of knowledge construction (Novak and Gowin, 1984). They suggest that it is useful to empower students to become responsible for their own learning.

Learners need to decide on the level of complexity at which they will process new information. For example, a student can take notes and either writes them as key words or makes connections between this information and the previous knowledge (Su, 1991). The more elaborative, or complex, the learner's processing of the information, the more he tries to make meaningful the new information, the more likely he is to remember it. This could be done by giving different examples on the same problem and making interconnections between it and the learners' knowledge to facilitate memorisation.

CONCLUSIONS

It is not being suggested here that chemistry can be made simple by avoiding teaching difficult topics! Indeed, trivialising the chemistry to be taught is likely to be perceived by the learner as a devaluation of the importance of the subject. The key lies in seeing chemistry from the point of view of the student learner. Such learners approach each topic with all kinds of ideas already stored in long-term memory. New material will link on to previous ideas and this can cause confusions and misunderstandings. A set of ten principles, based on evidence gathered by studying learning, has been suggested by Johnstone (1997a) while Sirhan (2000) has also provided a list of key proposals to aid meaningful learning. These can be summarised:

(1) It is vital for the teacher to know what the learners already know and how they came to acquire the knowledge. Many students come to a class with wrong ideas, confused ideas or even a complete lack of background knowledge. Learning experiences need to be offered to prepare students to grasp new material by clarifying or correcting previously held concepts or by providing fundamental instruction on such concepts. The idea of pre-laboratory and pre-lecture experiences have been explored in detail at university level and have been shown to be highly effective in increasing meaningful learning (Dawson, 1978; Ebenezer, 1992; Johnstone, 1997a, 1997b, Johnstone *et al*, 1994; Kristine, 1985, Sirhan *et al.*, 1999). Parallel experiences at school level will also be vital.

(2) It is important to take into account the way the learner gains knowledge and to present material in a way that is consistent with patterns of human learning. In particular, the limitations of working memory space have been shown to be important (Johnstone & El-banna, 1986). Their model of learning has been found to be extremely useful in predicting ways by which learning can be made more effective.

(3) The process of learning should allow for the development of links between "islands" of knowledge. The teacher must link concepts so that the learner can make a coherent whole of the key ideas. This allows the development in the learner of simple but meaningful concept maps (Otis, 2001). The seminal work of Otis may well prove to be very important is showing the way conceptual development takes place in the learner and may point to all kinds of strategies, which will assist effective concept growth.

(4) Attitudes and motivation are both important aspects for the learning process. Success in learning, positive attitudes to learning and motivation to learn are linked. The two major factors influencing attitudes towards a subject are teacher quality and curriculum quality (Skryabina, 2000). The former is not discussed here but the latter has been found to be strongly influenced by the perceived curriculum relevance, in the sense that the learner perceives what is taught being related to their lifestyle (Skryabina, 2000).

(5) Although not discussed in this paper, the place of assessment is critical in that, where the assessment does not reflect the aims of the course (usually because the assessment emphasises knowledge recall too highly), learner motivation to seek for meaningful learning, with understanding of concepts, is less likely.

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