Chapter 5
The Learning of Chemistry: The Key Role of Working Memory

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Introduction

While some very general work is taught at primary school stages, chemistry is usually only taught as a discipline from about age 12. It is an interesting study to look at the textbooks which were used up to about 1960 in most countries. Chemistry teaching was built around '*preparations and properties*' where endless lists of compounds were discussed, with the methods to make them outlined and their properties described. Success in chemistry meant that the school students of that day had to memorise and recall accurately.

The early 1960s saw the beginnings of a revolution in school chemistry. One of the earliest countries was Scotland where a new syllabus was published in 1962 (Curriculum Papers 512). The chemistry content was greatly updated but the major change was in the emphasis. There was an overt attempt to encourage the development of *understanding* and the examinations reflected this. Thus, the school students were encouraged to carry out many experiments in class, under careful direction, which aimed to enable students to understand why matter behaved in the way it did. This approach proved to be successful in that chemistry was (and still is) a very popular subject at school level in Scotland (Scottish Qualifications Authority, http://www.sqa.org.uk/sqa/57518.4241.html).

With such new curricula, problems started to become apparent, in varying degrees in different countries. Chemistry was now seen as difficult by many school students. In most countries, we began to see a trend where the numbers opting to study chemistry started to fall (for England: Osborne et al. 1998, 2003; Ramsden 1998; Jenkins and Nelson 2005), despite the fact that qualifications in chemistry at school level were valuable for future studies or for careers. Did the problem lie in the chemistry being taught or in the way students were learning the chemistry? It turned out to be both and this chapter seeks to uncover what much careful research

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has shown to be the sources of the problems. Recent research has now provided many of the answers and these will be discussed as well.

Chemistry is Difficult

In a very early study, Johnstone et al. (1971) asked students of chemistry at two Scottish universities to look back at their school experiences. From this, they were able to identify the key areas where students had found problems. Four broad areas were apparent (Table 5.1).

Most of the new chemistry curricula had introduced the topic of the the amount of substance (Mole). Some aspects of the topic seemed intrinsically difficult but was it possible for us to teach it differently to gain greater student's confidence and success? Thermochemistry and thermodynamics were also introduced. These can offer very powerful insights into the nature and direction of chemical reactions but the students found the area difficult. Electrochemistry and redox often proved very confusing for students while the introduction of organic chemistry left students with a bewildering array of carbon, hydrogen and oxygen atoms.

Over many years, Johnstone et al. started to explore these broad areas to see if they could identify the nature of the problem and how to make life easier for the students. Although this resulted in a series of research papers (e.g. Duncan and Johnstone 1973; Johnstone and Kellett 1974a; Garforth et al. 1976a, b; Johnstone et al. 1977a, b), his work led to the publication of two textbooks which attempted to present chemistry on the basis of what his research had uncovered. Later, a paper summarised many of the research findings (Johnstone 2000).

Both textbooks were quite radical in nature and made a considerable impact at the time. One was a general text for middle school (age 14–16) chemistry students (Johnstone et al. 1980) and this ran to numerous reprintings. In this text, only the bare minimum of atomic and molecular structure was introduced before the organic chemistry was studied. The other areas followed. It was, perhaps, the first textbook deliberately to base its approach on the known research evidence related to how students learn. The other textbook was a brilliant monograph on thermodynamics (Johnstone and Webb 1977). Sadly, when both texts went out of print,

Table 5.1 Areas of difficulty

Curriculum Area	Example
Equations and the amount of substance (Mole)	Equations and the the amount of substance (Mole): volumetric and gravimetric work, Avogadro and the amount of substance (Mole)
Computational topics	Thermochemistry and thermodynamics
Electrochemistry and redox	E° and ion electron ideas and equations
Organic topics	Esters, proteins, amines and carbonyls, aromaticity

subsequent textbooks tended all to revert to traditional approaches and students problems continued.

In the 1970s, Kellett was looking at the difficulties that students had when studying organic chemistry at school level. Although she originally considered that it might be a perception problem (students could not *see* organic structures) (Johnstone and Kellett 1974a), she started to appreciate that the problem lay in the *amount of information* that a student had to take in and handle *at the same time* (Johnstone and Kellett 1974b). This turned out to be the key breakthrough.

Why is Chemistry Difficult?

While most studies have explored the areas *where* chemistry is difficult and have come up with all kinds of ingenious attempts to make life easier for our students, the real answer must lie in seeking to find out *why* the difficulties occur. Suggestions that chemistry is difficult because it is highly abstract or very conceptual may be true, but they do not take us forward in any way that can lead to making it more accessible. As teachers, we cannot change the nature of chemistry. However, we can change the way it is taught. The real question is *how* should we change it so that we retain the true nature and rigour of chemistry but, at the same tine, make it more accessible to young learners. The brilliant insight of Kellett led to a quite ingenious experiment being set up. However, before this is outlined, we need to look at some findings which had arisen from psychology research.

Medical research had shown that human memory had more than one component. Miller (1956) developed ways to measure the capacity of what he called short-term memory and found, amazingly, that the capacity of this part of the brain was very small. It is now known that it grows with age but the final capacity is fixed genetically. Miller found that the average adult (aged 16 or over) could hold seven pieces of information at the same time and that almost all adults have a capacity lying between 5 and 9. He described the pieces of information as '*chunks*'. The size of each chunk could vary but the key thing as that the individual person saw each chunk as *one* piece of information.

While Miller talked in terms of '*short-term memory*', much subsequent work uses the phrase, '*working memory*' (Baddeley 2000). This recognises that this part of the brain not only holds information temporarily but it is also the location where thinking, understanding and problem solving take place. It is a 'holding-thinking' space. It is finite in capacity and, if there is too much to hold, then little space is left for thinking and understanding. Was this the key to the reason why chemistry is so often perceived as difficult?

While the average working memory capacity of a 16-year old is SEVEN, 14-year olds have an average capacity of SIX and 12-year olds an average capacity of FIVE and so on. This offers an immediate explanation why certain topics cannot be introduced too early in a school student's career. As the working memory grows with age, increasing numbers of ideas can be handled at the same time, opening up more complex areas of knowledge to the learner.

Working memory limitations also offer an immediate explanation why mathematics is so often a problem when applied to chemistry or physics. The working memory simply cannot cope with the chemistry concepts *at the same time* as using the ideas from mathematics. When the mathematics is more or less automated (and requires minimal working memory space), then success is possible. However, this takes time and considerable practice.

With that background in mind, let us now return to the experiment. In this work, a large number of first-year university examination questions were examined in detail to see how many ideas had to be held at the same time for a student to have some prospect of success. Student's success in these questions was explored. The success rate was plotted against what the research called the 'information load' (the number of ideas to be held at the same time). The researchers expected to obtain some kind of linear relationship (see Fig. 5.1).

What, in fact, they obtained was closer to Fig. 5.2. The relationship was not linear but was more like a titration curve.

The researchers went further. They measured the working memory capacities of the students and divided the students into three groups: those with above average capacities (mainly 8), those with average (which is 7) and those with below average (mainly 6). They then plotted the three curves for each sub group. Figure 5.3 shows the kind of outcomes they obtained. The curves are drawn more

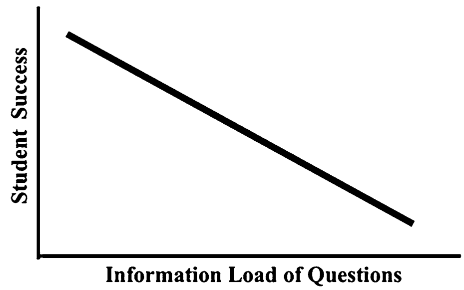

Fig. 5.1 Predicted relationship

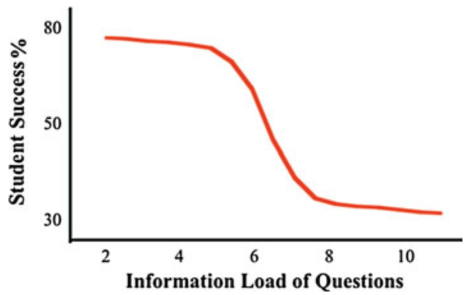

Fig. 5.2 Experimental relationship between load and success

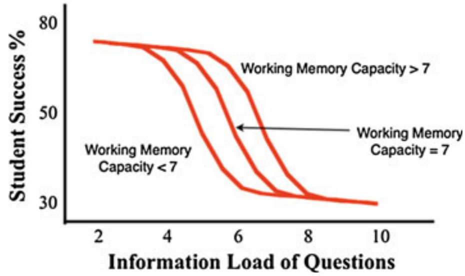

Fig. 5.3 Experimental relationship between load and success, with working memory capacity

precisely here than the original experiment, simply for clarity but the pattern is unaltered.

What this experiment showed was that it was the *actual capacity of working memory which was controlling success* in the test items. It revealed much more as well. The performance of the students with a measured working memory of 7 started to drop dramatically when the information load of the question reached 6. It has been found that we cannot work right up to the actual limits. We seem to need some room for manoeuvre in using our working memories. For those who had less than 7 (mainly 6), performance dropped at 5 while those with more than 7 (mainly 8) showed a performance drop at 7. The whole experiment is described in two papers (Johnstone and Elbanna 1986, 1989).

Enabling working memory to work more efficiently turned out to be an important idea. Miller (1956) had used the word '*chunk*'. A chunk was what the individual person saw as one unit of information. Was it possible that some students were able to group items of chemistry information together so that they saw them as one chunk of information? This only took up one space in the working memory, leaving enough space to handle the other chunks.

The possibility is that we teachers might be able to teach our students to chunk information, thus reducing load on limited working memory capacity. It was found that teaching what might be called '*chunking skills*' is not easy in that we all tend to do it in so many different ways. However, specific chunking strategies can be introduced and we shall return to this later. In passing, developing chunking skills is almost certainly the explanation of what has been called cognitive acceleration (Shayer and Adey 2002). It is interesting that the authors admit they do not know why cognitive acceleration works. However, the observation that cognitive acceleration only benefits about half of the pupils suggests strongly that their materials are giving opportunities for the school students to develop chunking skills. A careful scrutiny of the teaching materials they produced is certainly consistent with this explanation. Some students respond to the approaches offered while others do not, simply because there are so many diverse ways to chunk.

Let us return to the Johnstone and Elbanna experiment. When the papers were first published, there was some surprise that such a simple idea explained many learning difficulties in chemistry. There was also surprise that the outcomes were so predictively precise. Nonetheless, the results of the experiment seem to be highly reproducible and particularly marked for mathematics (Christou 2001). The experiment showed that, if faced with a task where the load was more than the working memory capacity, then success was highly unlikely. The working memory capacity of students could be measured reliably and easily (Reid 2009a).

Much research then followed and the experiment was repeated with different ages, different subject areas. The same outcomes were obtained. Later, the relationship between measured working memory capacity and performance was summarised in terms of correlation coefficients. Reid (2009a, p. 134) has drawn together some of the findings for school courses (see Table 5.2).

Table 5.1 needs some interpretation. First, it shows that working memory capacity is related to performance in many subjects at many ages (the Johnstone and Elbanna study shows it is actually cause-and-effect). Second, two tests were used to measure the working memory capacity: the digit span backwards test (DSBT) and the figural intersection test (FIT). Although very different, the same effect is observed. The digit span backwards test involves the recall of a series of number in reverse order while the figural intersection test requires students to find the area of common overlap between increasing numbers of geometrical shapes.

Third, the correlation coefficients obtained vary considerably. Indeed, in one study in mathematics, the researcher designed a test in mathematics for 12-year olds in such a way that no question placed a load on the working memory above the minimum in the sample (190). She obtained a correlation value very close to zero although the test was not easy and the pupils did not perform that well. However, it tested mathematical ability and *not* the capacity of their working memories (Reid 2002).

This leads to an important principle that '*performance will only correlate if one or both of two conditions are fulfilled:* (a) The learning process is such that those with higher working memory capacities have an advantage; (b) The assessment questions place demands on the working memory such that those with higher working memory capacities have an advantage' (Reid 2009b, p. 246).

Working memory capacity can have a profound effect on the marks obtained in an examination as Danili discovered. She found that students with below average working memory capacities performed, on average, 16 % less well when compared to those with above working memory capacities. The effect of working memory capacity can, therefore, be very considerable. The student with a less than average capacity faces a very large disadvantage in the examinations which we typically set today. Indeed, the study of Ali and Reid (2012) showed the highest correlation found so far, the capacity of working memory accounting for nearly half of the marks gained. The test used in the schools in this study was clearly measuring working memory capacity to a quite unacceptable extent.

Working memory capacity is not neatly linked to what we might call ability. It is simply the capacity of part of the human brain and varies slightly from person to person. The problem lies in our teaching and our assessment. The way we teach chemistry and, even more importantly, the way we test chemistry is giving a considerable advantage to those students who happen to have higher working memory capacities.

Table 5.2 Some correlations of working memory with performance

Age	Country	Sample	Subject	Test used	Pearson correlation	Probability	Source
13-15	India	454	Science	DSBT	0.34	$p < 0.001$	Pidikiti 2005
13	Kuwait	641	Science	FIT	0.23	$p < 0.001$	Hindal 2007
15	Greece	105	Chemistry	FIT	0.34	$p < 0.001$	Danili 2004
13	Taiwan	151	Physics	FIT	0.30	$p < 0.001$	Chen 2005
13	Taiwan	141	Biology	FIT	0.25	$p < 0.001$	Chu and Reid 2012
13	Taiwan	141	Genetics	FIT	0.62	$p < 0.001$	Chu and Reid 2012
16-17	The Emirates	809	Physics	DSBT	0.11	$p < 0.01$	Al-Ahmadi 2008
16-17	The Emirates	349	Physics	DSBT	0.32	$p < 0.001$	Al-Ahmadi 2008
16	Greece	90	Mathematics	DSBT	0.40	$p < 0.001$	Christou 2001
11	Pakistan	700	Mathematics	FIT	0.69	$p < 0.001$	Ali and Reid 2012

An Interim Summary

After 25 years of using the concept of working memory, Baddeley (2002) published a paper with the enigmatic title: '*Is Working Memory still Working?*' After reviewing the evidence, Baddeley argues that working memory is still working. The concept is certainly valid. However, Reid (2009b, p. 250) remarks that, '*for some pupils, it is perhaps having a struggle*'.

Working memory is a psychological and physical space in the brain where incoming information is held temporarily, into which information may be drawn from long-term memory, and where information can be manipulated. In educational terms, it is where the learner thinks, understands, makes sense of information, solves problems. Information can be transferred from the working memory and stored in long-term memory, leaving the working memory space free for further tasks. Because working memory has finite capacity, it is a controlling step for all learning, when learning is seen as understanding. This controlling nature is critical: it is a kind of 'bottle neck' for learning. Indeed, the work of Kirschner et al. (2006) demonstrates the imperative of taking working memory limitations into account in considering any new approach to learning.

Chemistry, by its very nature is conceptual and often abstract. It is world of atoms, molecules, electrons and protons and energy. It is full of representations like equations, along with numerous abstract ideas like the amount of substance (Mole), free energy, reaction rates and electron spin, delocalisation and quantum numbers. Almost by definition, if a concept is to be understood, many ideas must be held *at the same time* by the learner. The only place where such ideas can be held is the working memory and capacity is highly limited. St Clair-Thomson and

Botton (2009) offer a useful overview of the structure of working memory in the context of science education.

The new curriculum developments introduced in the 1960s and which have continued on until today have rightly emphasised understanding. However, in the way the material is taught and the way we assess it in typical examinations, we have inadvertently given a massive disadvantage to those school students who have less than average working memory capacities as well as placing a considerable potential cognitive overload on all learners. This explains why chemistry is perceived as difficult by so many. The real question is what we teachers can do about it.

Before looking at that, we need to expand further the understandings of how the brain works when understanding is the goal. This leads us into the world of processing information.

Learning as Information Processing

It is strange quirk of history that the research on how the brain works ran in parallel with the development of the modern computer. The language of the latter found its way easily into the former. The human being can be seen as a highly complex processor of information. Through our senses, every waking moment, we take in enormous amounts of information. Piaget has shown that the natural way the learner tries to work is to try to make sense of the information coming in. Of course, we all sometimes make mistakes, interpreting things wrongly and sometime drawing wrong conclusions. However, the natural process is that, as we learn: we correct and expand our understandings continually (Atkinson 1983).

The way the brain was working in taking in and interpreting this endless flow of information has been studied for over 40 years. Pascual-Leone (1970) focussed on the load of information, laying the foundation for later understandings while the work of Atkinson and Shiffrin (1971) on information processing is considered a key foundation in cognitive research.

In the context of chemistry education, Johnstone (1997) developed a model which will be used here (Fig. 5.4). It has to be stressed that the various models only differ in small details, the essential ideas being well established from a long series of research studies. Indeed, the literature is replete with information processing models used as the basis for some very elegant research. The power of the model lies in its ability to predict in relation to learning. In the sciences and in mathematics, the model has offered a powerful way to understand and predict what is happening during the process of understanding as well as success in assessment (see Reid 2009b).

We are bombarded with information all the time. We select what we take in and the basis of selection is controlled by what we already know as well as our attitudes. What is taken into the brain goes into the working memory. Here, we attempt to make sense of the incoming information, drawing in information held in

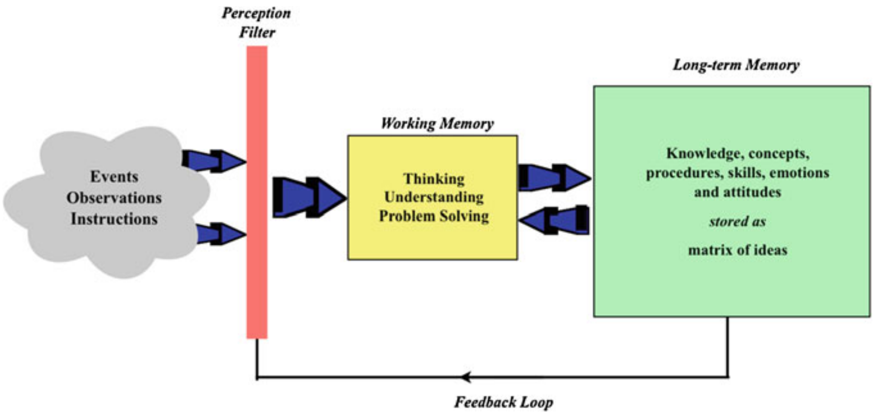

Fig. 5.4 An information processing model (derived from: Johnstone 1997)

long-term memory as required. We may store incoming information in long-term memory. If we understand what we are learning and can link it to what we already know, then the new information is added to a network of inter-related ideas in long-term memory, enriching all the ideas.

The model absorbs most of the key findings from other research. For example, the feedback loop captures the insights of Ausubel et al. (1978) while the fact that each individual seeks to understand incoming information in the working memory and linking it in their own way to what is already held in long-term memory underpins constructivism. It is the natural process of the learner to try to make sense of new information. Each constructs meaning in their own way.

The idea of teaching in a constructivist way is very misleading. Constructivism is related to the natural process of understanding in all learners. It is nothing really to do with teaching. Each learner will *inevitably* construct their own meaning. Indeed, writing from a cognitive load perspective, in a brilliant analysis, Kirschner et al. (2006, p. 78) raise very serious doubts about the whole enterprise of 'constructivism' as a predictive tool: '*The cognitive description of learning is accurate but the instructional consequences suggested by constructivism do not necessarily follow*'. The fundamental problem is that such approaches have not taken into account the rate determining control of working memory on all understanding and problem solving.

The power of the model lies in its ability to predict. For example:

(1) If the perception filter works well, then less unnecessary information enters the working memory and information overload is less likely. This leads to better learning and better test results. Many studies have looked at this and demonstrated that the prediction is supported but, perhaps, the work of Danili is particularly useful in chemistry (Danili and Reid 2004);
(2) If the working memory has to handle more than its capacity allows, learning more or less ceases and the assessment task provides more or less impossible.

This has been reviewed by Reid (2008). As teachers, we must learn to teach and to assess *within* the capacity of the working memories of our students.

(3) If information is stored in such a way that ideas are linked to each other in a sophisticated matrix in long-term memory, then gaining access to these ideas is easier at a later stage. This was studied in relation to open-ended chemistry problem solving by Yang (Reid and Yang 2002) and, later by Al-Qasmi, in relation to open-ended problem solving in biology (Al-Qasmi 2006). The idea is really straightforward. If ideas held in long-term memory are linked extensively to each other, then there is greater chance of finding some route into what we need to recall.

Of greater importance is the fact that the model predicts how we as teachers can re-think teaching chemistry so that difficulties in understanding are reduced. This will be discussed in a moment. Before that, we turn to a very useful insight from Johnstone when he looked, in the context of his information processing model, at the learning of chemistry in general terms (Johnstone 1999).

He noted that, in chemistry, there are three kinds of activities:

(1) There is what he called *macro chemistry*: here we see colour, detect smells, observe reactions and describe materials.
(2) There is what he called the *micro* level: this is the world of atoms, molecules, bonds, electrons and so on. None of this is directly accessible to the senses.
(3) Finally, there is the *symbolic*: as chemists, we represent the world of chemistry by means of formulae, equations, diagrams and mathematical representations.

The experienced chemist can move happily at all three levels. The learner simply cannot do this as the amount of information involved simply overwhelms limited working memory capacity. Johnstone (1999) pictured this in terms of triangle (Fig. 5.5).

Since the publication of the triangle for chemistry, the idea has carried forward into biology where Chu and Reid (2012) developed a biology tetrahedron while Ali and Reid (2012) has suggested a tetrahedron for mathematics learning (see Reid 2009b). However, in all three subjects, the same principle is being applied.

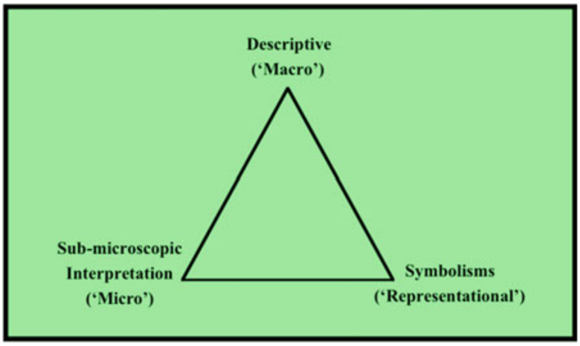

Fig. 5.5 Chemistry learning triangle

The novice learner cannot cope with the cognitive load in trying to work at all the corners *at the same time*.

Johnstone (1999) argues that early courses in chemistry must concentrate on the macro, the descriptive. When the school students are more familiar with the way materials behave in descriptive terms, then the micro level can be gently introduced as a way of explaining why the familiar macro-chemistry takes place in the way it does. The symbolic must be introduced carefully, always ensuring that it is perceived as a way of simplifying what the student already knows. An example of a totally descriptive approach but involving rigorous chemistry for 13-year old students is described by Reid (1999). In this course,

> The pupils started to look at their world (the air, water, the sea, rocks and minerals, the atmosphere) with a simple agenda: what elements could be found and what was mankind doing with what was there? Many fundamental chemical ideas just arose naturally, e.g. the concept of bonding, reactivity, physical properties of matter, energy and bonds, states of matter. The course was descriptive, based on the world around, applications orientated and it avoided quantitative aspects.

This approach was found to highly effective with the school students and stands in complete contrast to the typical kind of approach: atoms are introduced, with atomic structures, arrangements of electrons, to be followed by bonding and the whole panoply of molecular theory. This approach places excessive demands on limited working memory capacity as well as being perceived as largely irrelevant by most school students at early stages. Indeed, considering that the vast majority of younger school students will never become chemists or, even, scientists of any description, it is an irrelevant approach.

Improving Understanding: Pre-learning

We now return to the model of information processing again. We can now use the model to explore how we might make learning more accessible and allow the school students to understand more of what they are doing. Firstly, we look at the perception filter. The question is how to make it function more efficiently.

Four studies in first-year university chemistry offer major insights. Two relate to labwork and two to learning from formal presentations. We shall look first at labwork where the potential for information overload is very considerable: new chemicals, unfamiliar equipment, written and verbal instructions and chemistry understandings all to be handled *at the same time*. Johnstone and Wham (1982) found that working memory overload was a major problem. Later the idea of pre-learning was used to reduce the problem.

In pre-learning, knowledge already learned is revised and brought to the surface. This offers the learner the key landmarks for the new material which is to be presented. Therefore, in the laboratory, the learner has the key ideas brought to the surface and, thus, the selection of what is important is much more efficient.

Table 5.3 The effects of pre-learning

Year	Pre-learning	Upper group average	Lower group average	Difference between groups	Statistical significance
1993–1994	Yes	50.9	48.8	2.1	Not significant
1994–1995	Yes	49.2	49.0	0.2	Not significant
1995–1996	No	46.9	38.7	8.2	Significant
1996–1997	No	48.2	42.0	6.2	Significant
1997–1998	No	46.7	41.3	5.4	Significant
1998–1999	Yes	49.8	47.7	2.1	Not significant

Pre-learning has a very large effect in making laboratory learning much more effective. One experiment in physics found a rise of 11 % as a result of the pre-laboratory experiences (Johnstone et al. 1998). An earlier study was conducted in chemistry, with even larger numbers and, yet again, the power of pre-learning to improve understanding was very marked (Johnstone et al. 1994). This is exactly in line with what the information processing model predicts. The work on pre-labs was later followed up by Reid and Shah (2010) while Carnduff and Raid (2003) collated examples of pre-lab exercises for university chemistry and offered guidance on how such pre-lab exercises could be developed.

In another experiment, a large university first-year chemistry class was followed for six successive years. They were given pre-learning experiences in the first 2 years, these being discontinued in the next three and then, finally, pre-learning was re-introduced in a paper form known as 'chemorganisers' in the final year. The original pre-lectures took the form of a series of short activities based on previous knowledge and this was undertaken *before* each lecture course. When these were discontinued, the extra time was given over to the lectures. The aim of pre-learning was to bring to the surface previous ideas so that these ideas then enabled the selection filter to work more efficiently. The new material then was more easily understood as the working memory was less likely to overload. The full experiment is described in Sirhan and Reid (2001).

This experiment is unusual in that those who were *least* well qualified (The Lower Group) gained the most (Table 5.3). Those who were least well qualified did not have a set of clear landmarks in their long-term memories. The revision of key ideas led to these landmarks becoming clearer. The perception filter then could select more efficiently in the light of these landmarks and working memory was less overloaded.

In the final study, Hassan et al. (2004) looked at the underlying key ideas in an introductory university organic chemistry course. These ideas would be established from school courses. They were able to relate very precisely which key ideas were well established from school and show how this affected university performance in quite specific ways.

Such pre-learning is evident in many school classrooms where, by skilful use of questions and recapitulation, the class is reminded of previous learning which, in turn is then able to inform the perception filter. Working memory overload is less likely and subsequent understanding is enhanced. This offers a simple explanation of a practice which good teachers have used for generations.

Improving Understanding: Reducing the Load

The information processing model predicts that, if teaching is re-cast in order to reduce the overload on working memory directly, then better understanding will take place. This is difficult to test in that it is not easy to control all the variables. However, three experiments are described in the literature and, together, these make compelling support for the hypothesis. In all three, there was no change in subject matter covered, no change in time taken, no change in teachers employed, no training of the teachers involved. The changes were in how the material was presented, mainly in the form of written text in that, in the countries involved, this reflected the normal way teaching took place.

The explicit aim of these studies was to re-design the teaching approach so that pressure on the working memory was reduced. In places, the teaching order was changed while speed and sequencing of the presentation of ideas was modified. Complex areas were broken into smaller parts and ideas were developed and expanded step by step. Graphics were used where these were likely to reduce the information overload. All this was achieved by thinking through each difficult theme and then making sure that it was presented in a step-by-step way, thus reducing the load on working memory. It is worth remembering that working memory causes a problem when too much has to be thought about *at the same time*. By careful sequencing of ideas, by reminder and illustration, by a stepwise approach, the working memory is not faced with too much at the same time. It was predicted that learning will increase (Reid 2008).

Danili re-designed a large section of chemistry teaching at middle secondary school level (aged 15–16) in Greece, specifically to reduce working memory overload problems (Danili and Reid 2004). About 100 pupils followed the approach in the traditional way while a similar sized and matched group used materials which had been modified to reduce working memory load. There were no changes to content, time allocations or teachers. The experimental group improved performance by 22 % while the control group improved performance by only 13 % in pre and post tests, the difference being statistically highly significant.

In a much larger experiment, this time in the Emirates, with a total sample of 800, pupils in 2-year groups towards the end of their studies in school chemistry experienced being taught by new materials covering major sections of the school syllabus. The new materials aimed to minimise working memory overload, to use relevant applications, to encourage understanding, not memorising, and to link new material to previously taught material in a meaningful way. All of this was based on the information processing model considered here.

Four areas of the curriculum were covered: in Year 10 (age 16 and 17), two major topics were included: The Periodic Table; Chemical Equations. 400 students were divided into two groups, each group completing only one of the two topics using the new approach and completing the other using a traditional approach. In year 11, the same system was used but the topics were: Organic Chemistry; Acids and Alkalis (Table 5.4).

Table 5.4 Improved performance (Hussein and Reid 2009)

Year	Topics	Groups	Average mark	Differences
10	Periodic table	Experimental group	79.2	18.2
		Control group	61.0	
	Chemical equations	Experimental group	80.2	9.2
		Control group	71.0	
11	Organic chemistry	Experimental group	71.0	14.0
		Control group	57.0	
	Acids and alkalis	Experimental group	75.0	10.7
		Control group	64.3	

Each group was measured after completing each topic and the examination outcomes are shown in Table 5.4.

The remarkable thing is that, with large samples and large areas of the curriculum, the average performance rose for the four areas by so much, completely transforming the examination performance of these pupils. In this experiment, there was no contact at all with the many teachers involved. The teachers only had to give the new materials to the students and allowed the students to follow these instead of the normal textbook. Attitudes were also measured and it was found that the student attitudes towards their studies in chemistry had improved quite dramatically. Indeed, the statistical analyses showed that the improvement was one of the most marked ever observed. As with the examination performance, attitudes had been *transformed* simply by applying the ideas predicted from the information processing model (Hussein and Reid 2009).

The third experiment took place in Taiwan where the entire syllabus in genetics was re-cast specifically to reduce the load on working memory (Chu and Reid 2012). Here, with large samples of school students aged about 13, there was observed the same marked improvement in performance and also considerable changes in attitudes.

In each of three experiments described here, the researchers deliberately try to re-cast the teaching approaches so that there was less demand on the limited capacity of working memory. They used a variety of approaches. In all three, there were very large improvements in examination and test performance compared to control groups. In two of the experiments, attitudes in relation to their studies were observed to improved quite remarkably. Attitude changes will be considered again later but let us first look further at the vexed problem of the amount of substance (Mole).

The Problem of the Amount of Substance

The literature is replete with references, descriptions and carefully conducted research all of which demonstrate that the amount of substance (Mole) concept is one which causes school and university students considerable difficulty. Nearly 40 years ago, Johnstone et al. (1971) noted the amount of substance (Mole) as one of the difficult areas in school chemistry, following this up with further exploration of the difficulties a year later.

It appears that many learners can cope with the idea of the amount of substance (Mole) as it relates to gram formula masses and some can manage to apply it to simple reaction equations. Many can make sense of the amount of substance (Mole) as it relates to gas volumes under given physical conditions and some can also apply that to simple equations. However, in all these situations, there is clear evidence that coping does not necessarily imply understanding. As soon as the amount of substance (Mole) is brought into solution, problems increase even further.

Introducing the Concept of Power

The major problems arise when substances are dissolved in water and concentrations and volumes are involved. It is a classic case of information overload. Is there a way round this? A suggested way has been described (Reid 1982) but this monograph is now not easily obtained.

It was suggested that we need to invent what is called: '*neutralising power*' (when thinking of acids and bases). The ability of an acid to neutralise a base can be thought of as depending on three factors:

the volume used
its molarity
its 'power'.

For simple acidimetry, *power* is defined as the *number of hydrogen ions produced or absorbed by one molecule of the acid or base*. Thus, hydrochloric acid and sodium hydroxide both have a power of ONE while sulfuric acid and calcium hydroxide have a power of TWO. [The molecule was defined in terms of the written formula.] This leads to the relationship:

$$\underset{\text{(acid)}}{V_1 \times M_1 \times P_1} = \underset{\text{(base)}}{V_2 \times M_2 \times P_2}$$

The usefulness of such a relationship in obtaining 'correct' answers is obvious. The argument against using such a relationship is that it could be seen as removing the necessity to *understand* the chemistry of the reaction. However, this is *not* true in that the reaction has to be understood *before* using the concept of 'power'.

Consider the following problem

> Calculate the molarity of potassium hydroxide if 25 ml is exactly neutralised by 10 ml of 0.1 M sulfuric acid.

The student needs to know the formula of the acid and base and, hence, deduce the 'power' of the acid as 2 and the 'power' of the alkali as 1. The rest is easy. If an acid like ethanoic (acetic) is used, the student has to *understand* the reaction and that only one hydrogen is involved in the formation of water. The method has the great advantages in that it gathers all the variables into one easily remembered relationship which can be applied in a straightforward fashion. This generates confidence for the first-time learner, so important for future success.

However, there is another even greater advantage. The same relationship can easily be extended to redox reactions as well. Power is now defined in terms of the *electrons lost or gained per molecule or ion of reactant.*

Consider the following analysis.

If 20 ml of 0.02 M potassium permanganate is acidified and treated with excess potassium iodide solution, iodine is released. When this iodine is titrated against 0.1 M sodium thiosulfate solution, using starch indicator, what volume of thiosulfate would be used?

Ion electron equations have to be developed and balanced:

$$MnO_{4^-} + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O$$

$$2I^- \rightarrow I_2 + 2e^-$$

$$2S_2O_3{}^{2-} \rightarrow S_4O_6{}^{2-} + 2e^-$$

From these, the relevant values for 'power' are easily observed under these conditions:

Power of permanganate ion = 5

Power of iodine molecule = 2

Power of thiosulfate ion = 1 (note: electrons per molecule or ion)

The whole calculation can be done easily:

$$\underset{\text{(permanganate)}}{V \times M \times P} = \underset{\text{(iodine)}}{V \times M \times P} = \underset{\text{(thiosulfate)}}{V \times M \times P}$$

The student can see easily that all that is need is the permanganate-thiosulfate relationship, the iodine not being relevant. The calculation reduces to:

$$\underset{\text{(permanganate)}}{V \times M \times P} = \underset{\text{(thiosulfate)}}{V \times M \times P}$$

$$20 \times 0.02 \times 5 = V \times 0.1 \times 1$$

giving the volume of thiosulfate as 20 ml.

The relationship can be extend to complexometric titrations where power is defined in terms of ligand attachment points while another useful application is to give the relationship to technicians. For example, in finding the volume to be added to 900 ml of 0.585 M sulphuric acid to obtain exactly 0.500 M acid:

$$\underset{\text{original acid}}{V \times M \times P} = \underset{\text{desired acid}}{V \times M \times P}$$

$$900 \times 0.585 \times 2 = V \times 0.500 \times 2$$

This gives the required volume as 1053 ml and the 900 ml must be diluted to 1053 ml.

In passing, the product, VMP, is meaningful and, in the units used above, is the *number of millimoles of the reactant*. Thus, the method could be extended to calculations where masses are also involved.

Reaction of Learners

The approach has been tried out with twenty 15-year old students, twenty 16-year-old students and a small group of the 17-year-old school students. Not only were they all highly successful in calculations (including redox) but they seemed confidently to *understand* what they were doing.

In almost every application of the amount of substance (Mole) concept, the working memory space for the novice learner quickly becomes overloaded, causing almost no learning to occur: understanding is virtually zero; confidence plummets. The formula (VMP) is a remarkable 'chunking' device, reducing the working memory space demand immediately. 'Chunking' is the ability to group several variables, facts or ideas together into a meaningful unit so that working memory space is not overloaded and was first described by Miller (1956) and applied extensively by Johnstone (1997). The whole area has recently been reviewed extensively by Reid (2008, 2009a, b).

In the VMP relationship, six variables are brought together in a way that is easy to remember and easy to apply. Nonetheless, *the relationship cannot be applied blindly: there MUST be understanding of the chemistry.* In this way, the use of the method is consistent with the psychology of the learner but is also a means of encouraging sound understanding. As an added bonus, it leads to quick success, with the concomitant rise in confidence.

Working Memory and Attitudes

There are many reports of poor attitudes towards chemistry among school students (Schibeci 1984; Ramsden 1998; Reid 2006). Is it possible to explain this drop in positive attitudes in such a way that it gives clear direction to a better way forward? There are several research studies which do offer key insights.

In a major study in physics, Skryabina looked in detail at the way attitudes towards physics changed with time, from age 10 to age 20. One of the problems with most attitude studies is the use of inappropriate methodologies (see Reid 2006 for an analysis of this issue). Skryabina (2000) used some very imaginative approaches and built up a picture in fascinating detail. The work was set in Scotland and much has been reported (Reid and Skryabina 2002a). Both chemistry

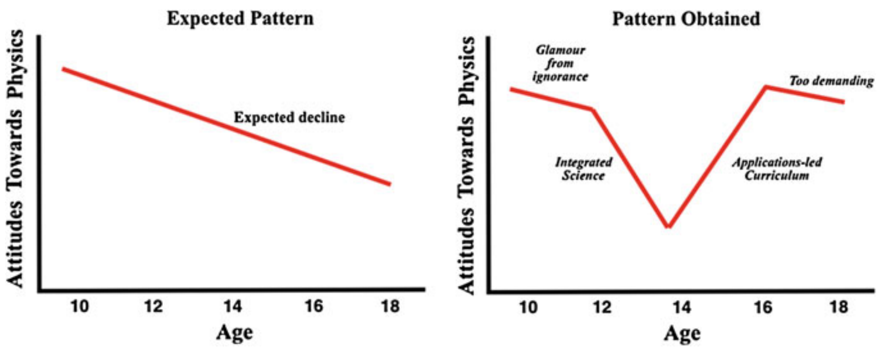

Fig. 5.6 Attitudes to physics in Scotland (derived from Skryabina 2000)

and physics are highly popular subjects at school and university levels on Scotland but Skryabina expected some decline in positive attitudes with age.

The early positive attitudes with primary school children rapidly deteriorated in the first 2 years of secondary school, this being attributed to the use of an integrated teaching approach. For those who continued on, their attitudes rose steadily during the next 2 years (aged 14–16), and the curriculum structure was found to be the reason. During the final 2 years, attitudes did decline but very very slightly, the reasons being that the course was excessively difficult.

It has to be stressed that Fig. 5.6 offers a very simplified picture of what Skryabina (2000) found. The graphs cannot be treated quantitatively. However, they do show the general trend of what was found and a possible interpretation of the findings.

There were clear messages from this observed pattern. The foolishness of asking a teacher who was not committed to, and qualified in, physics to teach physics (the way integrated science usually works) is obvious. This is consistent with other evidence which shows that integrated teaching is a highly ineffective way to teach the sciences and usually causes marked attitude deterioration. An interesting summary of many of the issues can be found in Venville et al. (2002).

The course structure in the years 14–16 was an applications-led curriculum. This can be described in the following way: the biology, chemistry or physics to be taught and its teaching order are determined by the learners—their needs, what is perceived by them to be related to their context and lifestyle (Fig. 5.7).

This type of curriculum structure has been discussed (Reid 1999, 2000) but few have followed up the ideas. These papers give examples and outline the principles in detail as well as offering some evidence to support this approach. In the case of the physics course here, the themes covered included topics like Telecommunications, Health Physics, Transport, Leisure, Space Physics. Major areas of life, of direct relevance and importance to the school students, were the themes. The physics was unpacked so that the students could make sense of these aspects of life. The end goal in terms of the physics covered was little different from

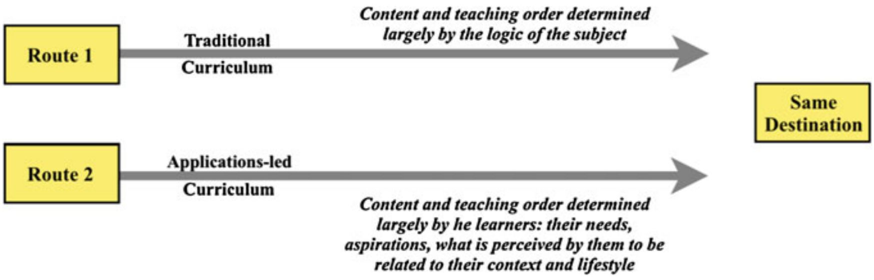

Fig. 5.7 Approaches to the curriculum

traditional courses. The way the material was covered was very different: the goal was the same; the route to get there was completely different.

The implications for chemistry are very considerable. Chemistry lends itself to such an approach and the paper by Reid (1999) describes an approach which did offer some highly positive outcomes. However, in some of the previous work (especially Hussein and Reid 2009), there were hints that working memory might also be involved in this. This was explored further by Jung in South Korea and her work is now described.

Jung and Reid (2009) have shown that it is possible to see attitude development in terms of three factors shown in Fig. 5.8.

The role of the teacher is critical and it has been shown that positive attitudes are encouraged by teachers who are competent in their subject and are supportive of the learner (Skryabina 2000). However, it is worth considering further the nature of the communication and the way the brain processes information. This can be thought of in terms of the way the chemistry is presented and whether the subject matter can be understood. The power of the applications-led curriculum has been discussed already.

Of great importance, the school student needs to see that the chemistry they study offers interpretations and understandings of the world of the student. Abstract ideas, unrelated to the world of the student, may well seem irrelevant

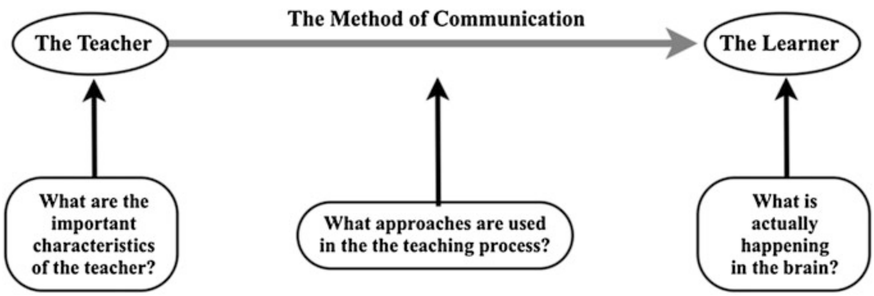

Fig. 5.8 Attitude development in education (from Jung and Reid 2009)

while the use of contexts which do not relate to the daily life and context of the young leaner may well be counterproductive in terms of the development of positive attitudes. Fundamental to all this is that the students are able to *understand* what is taught and this is heavily dependent on working memory capacity.

The key is the extent to which the learner can actually understand what is presented. It has been noted that understanding is the natural process. Too often, teaching and, especially, assessment, have focussed strongly on recall and recognition. This does not match the school student's aspirations. It also misses a wonderful opportunity for chemistry is ideally placed to enable the students to understand how their world actually works, in terms which are of direct importance and relevance to them. Working memory capacity is critical in enabling understanding to occur. Therefore, it might be expected that working memory capacity might well relate to the development of positive attitudes.

Festinger (1957) has offered brilliant insights into how attitudes can develop and change. He related attitude development tightly to the idea of dissonance. The idea is very common in life. When faced with information which is inconsistent with what we understand, then dissonance is set up. Festinger demonstrated that the possibility of attitude change or development is controlled by what he called '*total dissonance*' and this involves taking into account what is consonant as well as what is dissonant. Dissonance seems to be a natural process throughout life.

The important observation is that dissonance involves thinking: weighing up ideas, considering options and making judgements. This takes place in the working memory. This implies that the working memory is a critical factor in attitude development. More precisely, dissonance occurs in the working memory as former knowledge, feeling or experience are drawn from long-term memory to interact with new knowledge, feeling or experience. The role of the working memory is critical for it is here that all thinking, understanding and problem solving take place. If the working memory is overloaded, then dissonance is impossible. If learning is reduced to rote learning or is the passive reception of information, then dissonance is highly unlikely.

In the process of learning, information is processed cognitively by the learner and the information processing model of Johnstone (1993) offers valuable insights into the processes involved. However, as information is processed, held attitudes may affect information selection and the way it is handled. Equally, new information, as it is integrated into the long-term memory may bring about attitude development. These two aspects occur simultaneously in real educational situation and interact with each other continuously. We shall now consider the interaction of these two factors.

Attitudes have a powerful and continuous influence on the learning process. Indeed, attitudes may influence what the learner allows to enter their working memory (Reid 2008). Many students state that they do not want to continue with chemistry because they perceive it as too mathematical, too abstract and too difficult. It might be hypothesised that those with low working memory capacities tend to demonstrate lower understanding and, in order to pass their chemistry examinations, they may well be forced to resort to rote learning. It might then be hypothesised that high dependence on rote learning leads to little intellectual satisfaction, thus encouraging the development of less positive attitudes towards chemistry and aspects of the learning experience.

Jung explored the relationship between aspects of attitudes and measured working memory capacity working with 714 South Korean school students aged between 12 and 15 who were following an integrated science course. Jung and Reid (2009) asked,

(a) Are there significant relationships between students' beliefs and attitudes and their working memory capacity?
(b) Is there any relationship between students' ideas about various aspects of learning science and working memory capacity?

When she related measured working memory capacity to the response patterns on a five point scale to questions of interest, enjoyment and perceived importance, she obtained low but very significant ($p < 0.001$) correlations using Kendall's Tau-b correlation (Table 5.5).

What Table 5.6 tell us is that the students who said they enjoyed studying science found it interesting and thought it was important tended also to be those with *higher* working memory capacities. The correlation values, although low, are statistically highly significant.

She then went on to ask them if they were interested in science (forcing them to respond 'yes' or 'no') and relating their responses to their measured working memory capacity. She looked separately at two age groups and divided each age group into three subgroups: those with above average working memory capacity [high], those with average working memory capacity [mid] and those with below average working memory capacity [low]. The results are shown in Table 5.6.

The data in Table 5.6 brings a clear message. There is a strong pattern that those with the *higher* working memory capacity tend to be the groups where there

Table 5.5 Attitudes and working memory (Jung and Reid 2009)

Sample = 714, Aged 12–15, South Korea	Kendall's Tau-b
I am enjoying studying science	0.17
Science is interesting	0.13
Sciences is an important subject for my life	0.16

Table 5.6 Working memory capacity and interest in science

Are you interested in science?	Age 12–13			Age 14–15		
	Working memory capacity			Working memory capacity		
	High ($N = 100$) (%)	Mid ($N = 166$) (%)	Low ($N = 98$) (%)	High ($N = 95$) (%)	Mid ($N = 172$) (%)	Low ($N = 83$) (%)
YES	66	55	39	48	36	22
NO	33	42	57	53	64	78

Table 5.7 Preferred ways of learning and working memory capacity

	Age 12–13			Age 14–15		
	Working memory capacity			Working memory capacity		
	High ($N = 100$) (%)	Mid ($N = 166$) (%)	Low ($N = 98$) (%)	High ($N = 95$) (%)	Mid ($N = 172$) (%)	Low ($N = 83$) (%)
I have tried to understand science	71	54	50	70	61	37
I have tried to memorise science	24	34	39	21	35	45

are far more with an interest in science. The pattern is highly significant statistically. Is it possible that there is cause-and-effect relationship? The hypothesis is that loss of interest is caused by possessing a lower than average working memory capacity.

To gain further insights into this, she asked the students how they preferred to learned in their science studies. She offered them only two alternatives and related their responses to their measure working memory capacity (Table 5.7).

The results here suggest what is happening. Those with higher working memory capacities are tending to try to understand much more. Those with lower working memory capacities may well be unable to understand and are having to resort to memorisation. This process is not the natural way to learn and attitudes towards the subject tend to deteriorate.

This leads to a simple hypothesis (Fig. 5.9).

The findings from Jung and Reid (2009) suggest very strongly that working memory capacity is important in the development of positive attitudes towards chemistry. Because those with lower than average working memory capacities find to difficult to understand, they resort to memorisation to pass examinations and then lose interest in chemistry as this is not their natural way of learning.

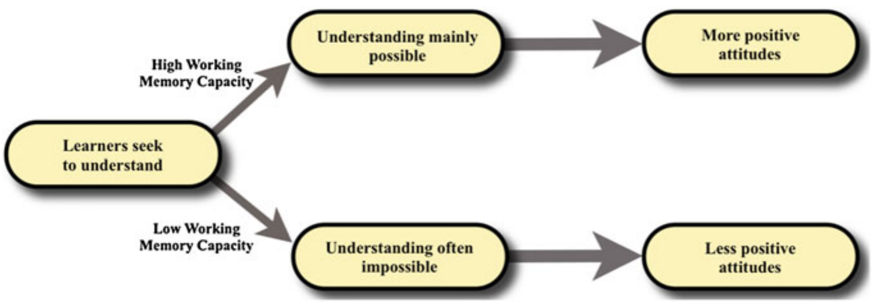

Fig. 5.9 A working hypothesis

Conclusions

This chapter has noted that understanding chemistry can be difficult because, being highly conceptual, understanding makes high demands on limited working memory space. Indeed, the study of chemistry is often not popular because students often have to resort to memorisation to pass examinations because they are *unable* to understand due to limited working memory capacity. Understanding always takes place in working memory and, if there is overload, understanding is impossible. Positive attitudes towards the study of chemistry depend on being able to understand and also being able to perceive that what is being taught is of relevance and value.

The aim of all chemistry teaching is to give young people at school stages an insight into the place of chemistry in the development of modern day society as well as offering an elegant insight into the way the world is constructed and changes take place. If we do not take the limiting capacity of working memory into account, then understanding will prove elusive and positive attitudes will rapidly deteriorate. Some of the clear evidence has been presented here and, on the basis of clear research evidence, ways have been suggested by which the exciting world of chemistry can be made more accessible for our students.

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