Review of research

Chemical education research in Glasgow in perspective

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Abstract: This paper describes the work of a large science education group (80+ workers) which, from 1969, has been tackling teaching and learning problems over a broad front. For much of the time, the group has worked within a Faculty of Science and has tried to take a scientific approach to the research. This approach is still followed although the Centre is now in a Faculty of Education. At the start, time was spent in gathering facts, looking for common factors, raising and testing hypotheses, generating working models and applying findings to real teaching and learning situations. This paper seeks to present an overview of the work up to about 1997, with illustrations from later work. Although the research applies to all science subjects, the emphasis here is on chemistry. The other papers in this issue exemplify the ongoing research which has arisen from this basic ground-laying and which has spread worldwide. [*Chem. Educ. Res. Pract.*, 2006, **7** (2), 49-63]

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Introduction

This is not a formal research paper, but rather a background presentation against which each of the other papers in this issue can be set and understood.

Research in Science Education began in the University of Glasgow in 1969 and was housed in the Faculty of Science for the next thirty years. The centre was staffed by practising scientists and science educators who were interested in solving research problems in the teaching and learning of the sciences at all levels: from early secondary school to post-graduate university.

In the early 1960s, in common with many other countries, Scotland adopted new curricula in chemistry, physics and biology for secondary schools (ages 12-18) and the author was heavily involved in the design of the chemistry curriculum.

Looking for difficulty

It was decided to begin research with the chemistry curriculum by questioning students who had undergone the new curriculum. As they arrived at the Universities of Glasgow and Strathclyde to begin their studies in chemistry, each student (N = 1000) was given a list of all the topics and sub-topics in the chemistry curriculum and asked to categorise each of them into one of four groups:

a) *"I understood this easily"*
b) *"I had some difficulty but I now understand it"*
c) *"I have never understood this and will need to be taught it again"*
d) *"I have never been taught this".*

The frequency of the choice of (c) was plotted against the topic list for each of the two university samples and the results gave almost perfect agreement.

The experiment was then repeated with 17-year old pupils in secondary schools and once more the frequency pattern was the same as that derived from the two universities.

The troublesome topics which they selected were:

i) Writing formulae and equations, and doing calculations from them (Howe,1971)
ii) Volumetric work involving molarities (Duncan, 1973)
iii) Ion-electron equations (Garforth, 1976)
iv) Avogadro's Number and the mole (Duncan, 1973)
v) Heats of reaction, Hess's Law and thermochemistry
vi) Redox reactions and E^{o} values
vii) Equilibrium (MacDonald and Webb, 1977)
viii) Organic formulae (various forms), (Kellet, 1980)

All these topics had (c) frequencies in excess of 50% of all respondents. Clearly this was a very serious situation requiring further research.

Looking for causes

The size of the research group was expanded so that each of the above topics could be analysed by a researcher looking for possible sources of the difficulties and for common factors among them. The reference after each topic above gives a link to the published material arising out of this phase of the work.

Results

Howe (Howe, 1971) working on formulae and equations at school level, tried to work backwards through the operations underlying the writing of 'simple' inorganic formulae looking for weaknesses. He asked pupils for:

i) the elements in a given compound,
ii) the symbols for these elements,
iii) the charges on the ions of these elements,
iv) the formula of the compound.

In more than 50% of the responses for familiar binary compounds, pupils made mistakes in steps (i), (ii) and (iii) and yet got the formula correct! However, when he asked about less familiar, but analogous compounds, e.g. lithium bromide instead of sodium chloride the errors occurred in all four stages. Interview revealed that pupils did not try to construct formulae from first principles, but simply memorised the ones most commonly used. Similar results were obtained for writing balanced equations: memory, not reason.

Duncan (Duncan, 1973) working with equations and the mole found that this multi-concept exercise defeated the majority of pupils. On reflection, he realised that a 'simple' problem such as, "*What mass of calcium carbonate will exactly neutralise 100 ml of 0.2 M hydrochloric acid*", was far from simple. The following operations had to take place:

a) A pupil first had to recall the nature of the reaction
acid + carbonate = salt + carbon dioxide + water.
b) Formulae for each compound had to be recalled or worked out.
c) The equation had to be balanced to establish the 1:2 ratio between $CaCO_3$ and HCl.
d) The number of moles of HCl in 100 ml of 0.2 M had to be obtained.
e) The required number of moles of $CaCO_3$ would be half of that.
f) A fraction of the gram molecular weight had to be calculated.

Many of the problems found in text books and examination papers yielded an even more complex analysis.

Ion electron equations were another area of difficulty which made formula and equation writing far more complex than situations exposed by Howe and Duncan. Such equations required decisions about, symbols, ions (simple and compound), charges on the ions, spectator ions, state symbols and balancing.

Thermochemistry and equilibrium considerations yielded analyses of conceptual complexity in line with the problems exposed above. Not only did they need the underlying support of accurate equation construction, but they then added additional layers of thermochemical and algebraic manipulation.

Looking for common factors

The common factor of 'information complexity' was clearly emerging, but we needed some theoretical framework to link it all together. This was provided by the work of Kellett (Kellet, 1980) on organic formulae and equations. She wanted to 'see' organic formulae through the eyes of students. She prepared pictures of organic formulae written in various forms: expanded structural formulae, condensed formulae, formulae in different orientations, formulae of varying complexity.

Each formula was projected on a screen for a short period and students were then asked to draw it from memory. Some examples produced a 100% correct response for all students while the *same* formulae, in a different format, were often very poorly recalled. Ethanol written as C_2H_5OH was successfully recalled while the extended structural formula was badly recalled. Ethanoic acid written as CH_3COOH was easy, but its extended structural formula was a disaster. Putting together CH_3OH and $HOOCCH_3$ to give the ester was difficult, but the extended structural form was impossible for most.

Examination of the student scripts showed that the vast majority read the formulae from left to right and wrote them that way. Most errors took place at the right-hand side of each attempt. Interviewed about strategy, students explained that they memorised every chemical symbol and every bond as a symbol. The C_2H_5OH formula had six symbols, while the extended structural formula had 14 symbols.

Looking for a model

This immediately suggested a link with the work of Miller (Miller, 1956), who had done a similar exercise with digits. Subjects could recall 7+/ -2 digits in his Digit Span Tests, and this led him to his idea of a limited Short Term Memory Span. This made us re-examine the work of Howe, Duncan, Garforth, McDonald and Kellett to see if we had a common factor and if we now had a working hypothesis.

We had begun in 1969 with no fixed theoretical stance other than our awareness of the work of Ingle and Shayer (Ingle and Shayer, 1971) who were critical of the Nuffield Chemistry Syllabus in England. Their criticisms were based on the developmental stages proposed by Piaget. They had analysed the syllabus and classified each topic in terms of the Concrete and Formal Operational stages and declared that some topics were unsuitable for pupils around age 16 and proposed that these should be postponed until the pupils had reached the Formal Operational stage of development. Since we were dealing mainly with students at university level, they should have been well into that level and yet the problems persisted. We therefore sought another model on which to base our thinking.

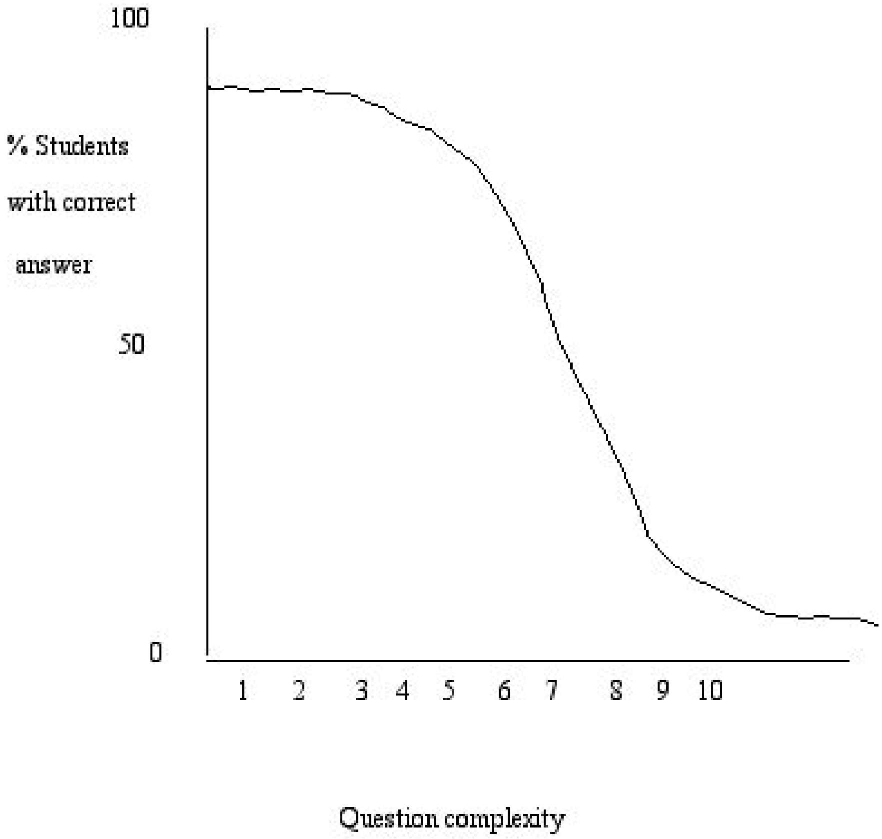
The work of Pascual-Leone (Pascual-Leone, 1970) and his group to seek a rational explanation for the Piagetian Stages, led to a neo-Piagetian treatment in terms of a limited, but growing, Working Memory in which increasingly complex operations could take place. This was not the same as Miller's Short Term Memory, which dealt with memorisation and recall (in exactly the same form). The Working Memory Space was a 'place' where information was temporarily stored and reworked before a response was made. A very full treatment of research into Working Memory can be found in the work of Baddeley (Baddeley, 1999).

To measure Working memory Space, Miller's Digit Span Test was modified to give a Digit Span Backwards Test (DSBT). A subject was given a series of digits and asked to give them back in *reverse* order. This involved a holding operation and a reversing operation. The number of digits retained correctly in this test was 5+/-2. The thinking operation was sharing the Working Memory Space with the holding of the information. This idea was closer to our situation in which students had been given, or had to recall, information and then convert it into another form to use in solving some problem.

El-Banna (El-Banna, 1986) tried to put our chemistry work alongside measures of Working Memory: Digit Span Backwards Test (DSBT) and Pascual-Leone's Figural Intersection Test (FIT). Five hundred students had their Working Memory Span measured by DSBT and sat a chemistry test in which the questions were of increasing complexity. The actual complexity was agreed by a panel of researchers, counting the pieces of information given in the question, plus the information to be recalled plus the operations required to produce an answer.

The Facility Values, (percentage of students getting a correct answer) for each item on the *y*-axis were plotted against the agreed complexity on the *x*-axis. We expected that the Facility Value (FV) would fall steadily as the complexity increased. It did fall, but in a surprising way (Figure 1)

Figure 1 Student success related to question complexity



All items with a complexity of 5 or less obtained a high Facility Value, but, as complexity increased, the FV plunged sharply, but not necessarily to zero. This is the kind of curve obtained in normal science when something is tested to a limit, e.g. tensile strength. It seemed that performance was good, provided the test stayed within Working Memory Capacity, but fell dramatically thereafter. El-Banna then replotted this curve, but this time he divided his sample into those with DSTB scores of 5, 6 and 7.

In the first curve, he found that the drop occurred when complexity exceeded 5; in the second when the complexity exceeded 6 and in the third when the complexity exceeded 7. At last we had our hands on something substantial; a model to direct our further research. However, this model raised some problems.

a) Although the fall in the graphs was steep, it was not vertical.
b) It did not drop to zero.
c) Miller's work suggested that the Short Term Memory could undergo an *instant* overload, but the questions in the chemistry test could be solved by a series of small sub-steps each of which would not cause an overload.

Further thought and experiment, and the consideration of Miller's ideas of chunking, helped to make sense of this. Depending upon how students had been taught previously, a question of complexity 7 could be reduced to 6 or less by some 'tricks' or 'shortcuts' and so these students were able to solve problems beyond their nominal Working Memory Capacity.

Those who were performing on the down slope were coping with problems slightly beyond their capacity and those who were on the low line parallel to the *x*-axis were a very small minority who were chunking problems well beyond their measured capacity. This might explain objections (a) and (b), but what about (c)? A question will be at its highest complexity when a student first reads it. If he is unable to apply some demand-reducing strategy to break the problem and organise the sub-problems, the problem will exist for that student at its maximum demand. Experienced teachers will have witnessed this in class when a problem is presented. Nobody knows where to start, but if the teacher indicates what to do first and then next, the problem ceases to be a problem. If students are taught algorithms they can effectively reduce the demand of a question, but, without prompts of this kind, problems beyond the Working Memory Capacity of the student are apparently insoluble.

Writing formulae and balancing equations could well be intractable problems for pupils at school because Working Memory (WM) Space is age dependent. Pascual-Leone suggested that Working Memory Space increases by one unit for every two years reaching a maximum by about age 16.

Ion-electron equations would also exceed Working Memory and so would mole calculations. Electro and thermo-chemistry would likewise be liable to overload late school and early university students. Patterns were emerging which led to further developments.

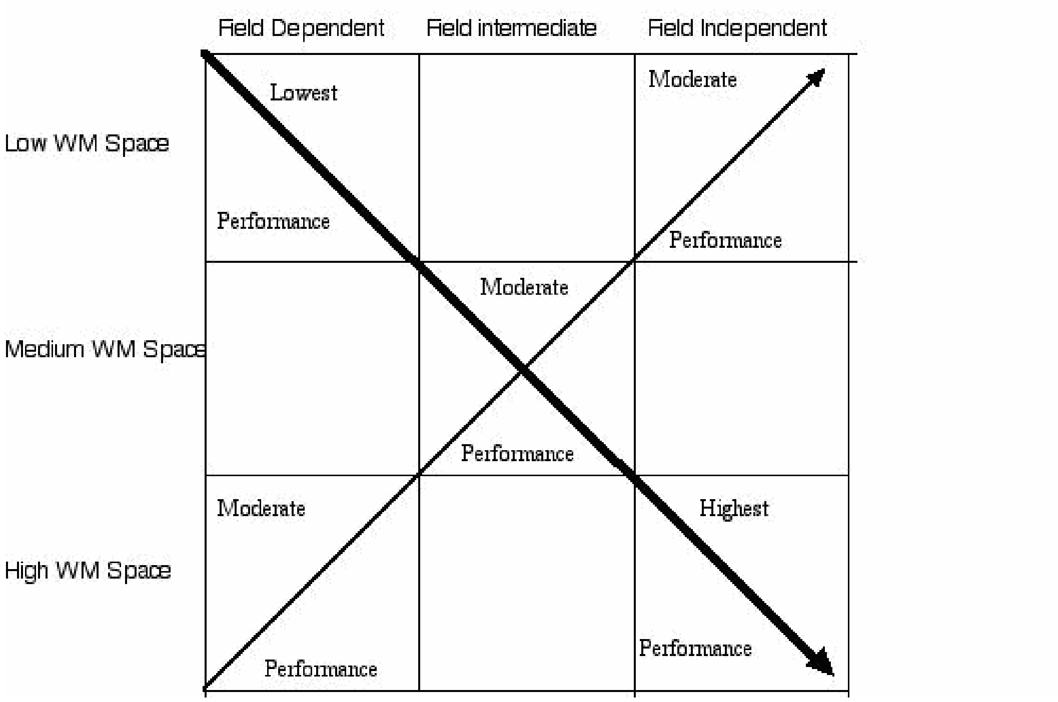
Further work by El-Banna and later by Al-Naeme (Al-Naeme, 1991) opened up other factors which affect students' effective use of their Working Memory.

Refining a model

Witkin's work (Witkin, 1977) on Field Dependence led us to examine its effect on the efficient use of potential Working Memory Space as measured by Digit Span Backwards Tests (DSBT). It was observed by El-Banna that a minor but significant proportion of students failed to solve questions the demand of which was within their DSBT measures. These were examples which did not seem to support our hypothesis that, "*Students should be able to solve problems if their demand did not exceed the measured Working Memory Space*".

However, when Al-Naeme (Al-Naeme, 1991) applied Witkin's Test of Field Dependence and the DSB Test to students and then analysed their scores on conventional chemistry tests, a very interesting trend appeared (Figure 2).

Figure 2. Effect on Chemistry performance of Working Space and Field Dependence



The underlying idea of Field Dependence (FD) and Field Independence (FI) is that some students, while learning, are easily affected by the 'field' against which the learning is done. They are easily distracted by irrelevant material and have difficulty in discriminating between the 'signal' and the 'noise'. At the other extreme, there are students who are Field Independent and can focus sharply on the relevant and ignore the irrelevant 'noise'. There is a continuum between these extremes. The scores in the FD/FI test were categorised as follows: Students who came within plus or minus one half of a Standard Deviation (SD) on either side of the mean score were classified as Field Intermediate (FInt). Those attaining less than the mean minus one half SD were classified as FD and those who attained more than the mean plus one half SD were classified as FI. This division gave us roughly equal numbers of students in each cell.

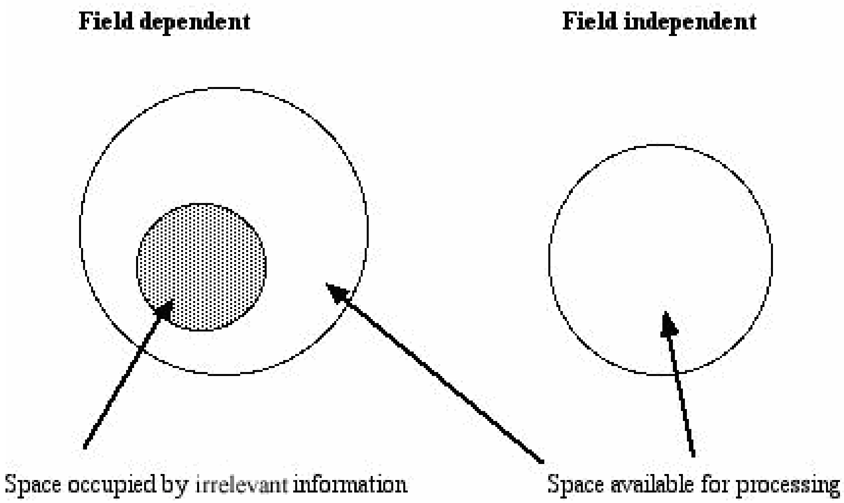
Looking at the results in Figure 2, it is possible to see the interaction of Working Memory Space and Field Dependence/Independence in their influence on scores obtained on a chemistry test. The vertical cells of Table 1 show improvement in chemistry scores as Working Memory Space increases. Also, the horizontal cells show improvement in chemistry scores as FD gives way to FI.

The strongest improvement trend is that from Low Working Memory Space coupled with FD (top left-hand corner) to High Working Memory Space linked with FI (bottom right- hand corner). Another striking trend appears along the other diagonal. The chemistry scores for High Working Memory Space linked with Field Dependence are almost the same as those for Low Working Memory Space coupled with Field Independence.

These patterns were replicated in ten different studies in chemistry, physics and biology and at different educational levels in schools and universities. How can this be interpreted? We saw from El-Banna the relationship between Working Memory Space and complexity of question, but it was not a perfect fit. Al-Naeme then showed that students, although having high Working Memory Space, could perform less well than expected when they were Field Dependent. In fact, they performed almost exactly as well as students who had low Working Memory Space, but who were Field Independent (Figure 3).

High WMS and FD = Low WMS and FI

Figure 3. Effect of Field Dependence upon available Working Memory Space

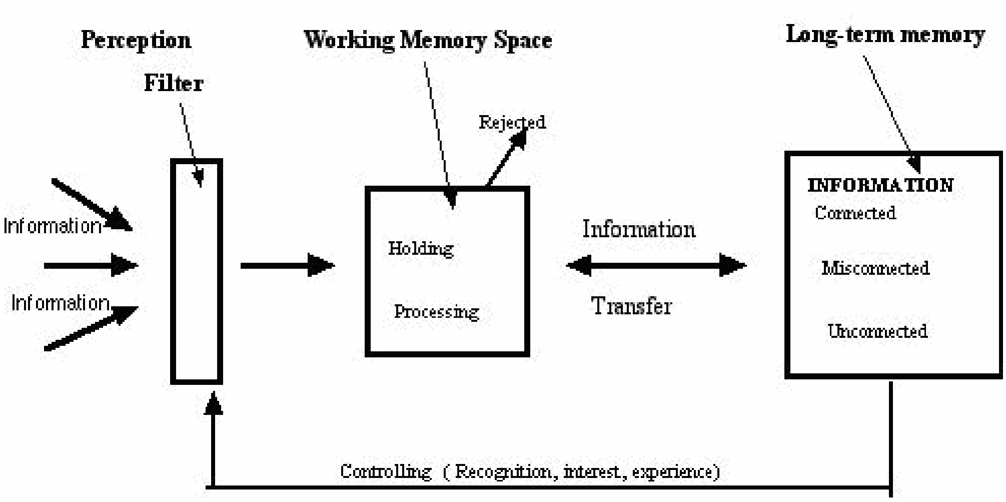


The potential usable Working Memory Space was effectively reduced by the space taken up by the irrelevancies introduced by Field Dependence. The low Working Memory Space students, who were Field Independent, had all the potential space available for use. These two models, El-Banna's and Witkin's, come together to rationalise the experimental results. Other factors that might moderate the available Working Memory Space were investigated, but FD/FI had by far the strongest effect.

We now had a working model to help us to interpret earlier results, to plan further studies and to look for solutions to the areas of difficulty isolated at the beginning of the 1970's. However, any model of learning which did not include the ideas of (a) perception (the initial interaction between the senses and the new information) and (b) of long term storage and retrieval, would be sadly incomplete. Our empirical model fitted well into existing models of Information Processing and we eventually adapted and adopted, as a working basis for our research, the model shown in Figure 4.

This indicates that external stimuli, such as those presented in teaching and learning experiences, are perceived by our senses and filtered. The learner attends to what is familiar, stimulating, interesting, surprising or exciting. To do this, the filter will be controlled, to a large extent, by what is already held in Long Term Memory. Something cannot be familiar, interesting or surprising unless it is being compared with some previous experience or expectation. What is held in the Long Term Memory store is crucial for this perception stage. This fits with Gestalt Theory (Koffka, 1933) and with Ausubel's (Ausubel, 1978) ideas that the most important factor in learning is what you already know.

Figure 4. Information Processing Model



The information admitted through the filter enters the conscious processing part of the mind, the Working Memory Space. The space has two functions:

a) to hold the incoming information in temporary store and
b) to operate upon the information to make 'sense' of it and prepare it for some response and/or to store it in Long Term Memory.

The sense-making operation will require information to be recalled from Long Term Memory to interact with the new incoming information. If the synthesis of 'sense' is achieved, it can be stored in Long Term Memory attached to (or filed along with) existing knowledge and understanding. Sometimes 'sense' is achieved by faulty attachment and this is very difficult to undo, because the learner has seen it as sensible and even satisfying. An Alternative Framework has been born. We shall look at the origins and consequences of this later. If a correct association is made, the learned material is more likely to be accessible and usable.

However, a third possibility exists for the fate of the processed material in the Working Memory Space. No 'sense' is made of it because no links can be found in the Long Term Memory, and yet the learner feels that it is important and must be stored. Such information enters Long Term Memory as rote learning, unattached and sometimes unlabelled. In this state, such information is often difficult to recall.

Before we leave the model and show how it informed our research, we must return to the Working Memory Space. Two functions of Working Memory Span were mentioned above: temporary holding and processing of information, but the Working Memory Span has a finite capacity. The consequence is that, if there is too much information to hold, there is not enough space for processing and the system overloads and seizes up. Similarly, if complex processing is needed, little information can be held for processing. This may also lead to overload and unsuccessful processing and storage.

In the Science Education literature there have been a very large number of studies reported under the general heading of Alternative Frameworks, Children's Science or Conceptual Misunderstandings, in which researchers have analysed the wrong ideas constructed by learners. These have generally been reported with little or no scientific explanation for the occurrence of such misunderstandings, and little indication of how the problems should be overcome. Our model indicates that the learner's frameworks occur as the products of the pupil's efforts to 'make sense' of the incoming taught information, but, in so doing, forming mis-linkages and storing them in Long Term Memory. The remedy suggested by our model is to help the learners to have the right attachment points in Long Term Memory alerted *before* teaching the new material so that correct interlinking will have a better chance of taking place in Working Memory Space before storage in Long Term Memory. This is just another way of looking at Ausubel's Advance Organisers which prime the Long Term Memory. In the light of this, Sirhan et al. (Sirhan, 1999) devised pre-lecture and pre-laboratory work to enable undergraduates to have Long Term Memory activation for new learning. Sirhan and Reid (2001) took this further and showed the overall picture of the development.

The Constructivist Movement has grown out of the Alternative Frameworks literature in an effort to help learners to construct their learning by correct preparation and shaping before storage. Since we, as researchers, are all looking at the same phenomenon, 'human learning', it should not be surprising that a comprehensive model of Information Processing embraces perception, processing and storage and in so doing provides a mechanism and a rationale for the research of Alternative Framework and Constructivist protagonists: to harmonise their work and to provide insight for their future research. The model suggests how to present material to avoid overload, to optimise processing and sense-making and to facilitate storage and recall. It also has a developmental, age-related basis which harmonises well with Piaget's work. What the model does not attempt or profess to deal with is 'attitude' and 'motivation' although it would suggest that constant overload which prevents 'sense-making' is a sure recipe for frustrating students and driving them along a series of steps: "*I don't understand*"; "*I can't understand*"; "*I shall never understand*"; "*I do not want to understand*". Many of the students voting with their feet and leaving the sciences may well have had this experience.

Using the model

Five important lines of research have opened up as a consequence of, and informed by, the Information Processing Model:

a) the function of language in science teaching and learning,
b) the problems of learning in a laboratory,
c) multi-level learning,
d) the assessment of science learning,
e) problem solving.

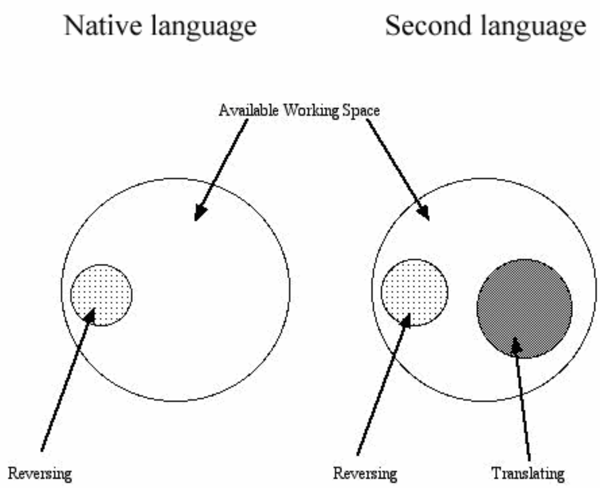
Language

The language study was conducted mainly by Cassels (Cassels,1985) and, 20 years later, by Selepeng (Selepeng, 2001). Cassels reasoned that the language held in Long Term Memory would affect the filter and the Working Memory processing, and he set out to find the vocabulary which might cause misunderstandings and has the potential for the construction of Alternative Frameworks. He eventually isolated more than 100 words, commonly used in school science, which caused trouble. These were words that teachers could easily assume that the pupils had a grasp of their scientific meaning. A word such as 'volatile' could be interpreted by pupils to mean 'unstable', 'explosive' or 'easily vaporised', based upon their common, everyday experience. All the meanings could make sense of a piece of chemistry, but two would have the potential for the construction of Alternative Frameworks. Another word is 'equilibrium' which carries with it a cluster of ideas from physics and from everyday experience, all of which contain the seeds of problems leading to Alternative Frameworks. 'Equilibrium' suggests balance and static state, an idea which is unhelpful in chemistry.

Cassels also found that the problem was even greater for pupils whose first language was not English. This had important consequences for those teaching ethnic minority groups, but even more so for pupils in ex-colonial countries where English was used as the instructional medium for science teaching despite the fact that the native language and culture was something very different.

Selepeng followed this problem further and measured the effective Working Memory Space for pupils when the Digit Span and Digit Span Backwards Tests were applied in the native language *and* in the second language. The effective Working Space was, on average, 1.6 units (20%) less in a second language than in the native language. In other words, pupils were handicapped in their science learning by the reduction of their Working Memory Space in a second language. The processing of the second language was taking up some of the valuable processing space needed for the understanding of the science (Figure 5).

Figure 5. Loss of Working Space when using a second language



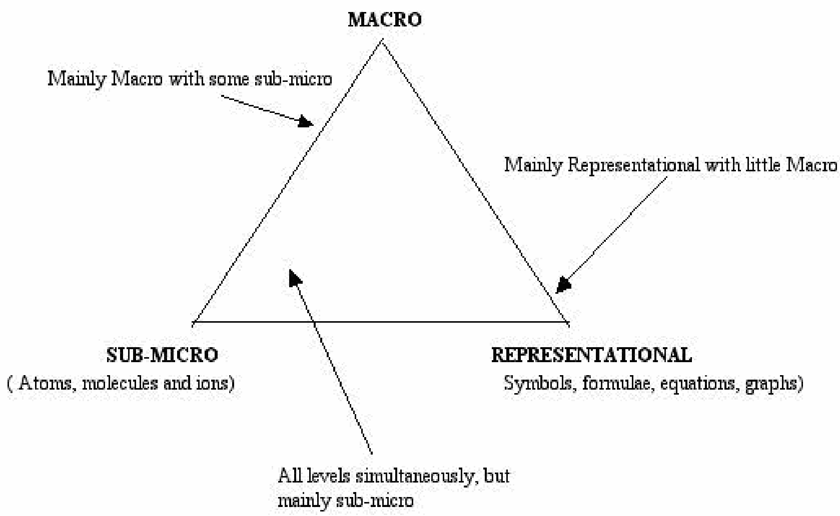
Laboratory work

Work by Wham (Wham, 1982), Letton (Letton, 1991) and Sleet and Vianna (Sleet, 1994) showed that there was little cognitive gain achieved in formal laboratory work at university level. Students gained hand skills and techniques, but lacked the connections to underlying theory. It became clear to those workers, that the structure of a conventional laboratory session had a gross potential for Working Memory Space overload. Written and verbal instructions, unfamiliar equipment and chemicals, observing and recording; all these together occupied Working Memory Space leaving no room for cognitive processing. Students, in an effort to reduce the discomfort of the overload, used the written instructions as a 'mind-in-neutral' recipe. This behaviour is often deplored by teachers, but the Information Processing Model indicates that the fault lies with the teacher for creating situations of gross overload. Several workers, such as Letton (Letton, 1991), Zaman (Zaman, 1998) Al-Shuaili (Al-Shuaili, 2001), began to design laboratory experiences with pre-lab preparation. This involved the students in thinking through the purpose of a laboratory, in planning some part of the experiment and, in so doing, activating the Long Term Memory in readiness to 'make sense' of the laboratory which followed. With the LTM thus primed, the students were in a position to distinguish 'noise' from 'signal' in the laboratory and to disregard the 'noise' as irrelevant and release space for thinking about the meaning of what they were doing. There was also an added bonus in an improvement in student attitude to laboratory work. How this developed, is reported in a recent paper in this journal (Al-Shuaili , 2001).

Multi-level learning

It was recognised that overload could occur at the early stages of learning chemistry because of the very nature of the subject (Johnstone, 1982 and 1991). Pre-1960, the atomic and molecular aspects of chemistry were not as evident at the early stages of learning the subject as they are now. Atomic and molecular structure and the nature of bonding tended to be kept until the later years in school. However, we now have a situation where the particulate nature of matter (the atomic and molecular development of this) and the introduction of ions and bonding are found early in introductory chemistry. Pupils are now confronted with the simultaneous introduction of unfamiliar substances on the bench, a description of them in molecular terms and a representation of them by symbols and formulae (Figure 6).

Figure 6.The three conceptual levels of chemistry



This figure is semi-quantitative in that any corner of the triangle indicates 100% treatment of the subject in that medium. For example, a totally macro approach would be represented by the macro corner. However, when the teacher introduces an experience on the bench interpreted by an equation, the treatment is somewhere along the right side of the triangle depending upon the emphasis given. Similar considerations would apply to the other two sides.

In many lessons, there is a blend of all three experiences simultaneously, represented by a point within the triangle, its position being determined by the relative proportion of the three components. Inside the triangle lies the potential for gross overload of Working Memory Space.

Teachers, and other chemists, flit around and inside the triangle with ease, giving us a powerful way of thinking about our discipline, but can early learners follow us inside the triangle without the onset of overload or with 'rationalisations' which lead to Alternative Frameworks? We might have to rethink our curricula to begin with a treatment of one corner only followed by the use of a side, before we lead the students into the middle of the triangle.

This idea is now appearing widely in the literature, often quoted, but little of the consequences followed up. A notable exception can be seen in the work of Tasker (Tasker, 2002) who has devoted much study and ingenuity to tackling this problem.

This triangular aspect of the nature of chemistry also gets in the way of laboratory learning and partially explains the lack of conceptual development in the laboratory.

Assessment of learning

We have almost come full cycle to El-Banna's work (El-Banna, 1986). He showed that, as we increase the complexity of test questions, there is, for most students, a rapid fall in performance when their Working Memory Space is exceeded. Another way of looking at this could be that, provided the task is within the Working Memory Space, we are testing mainly chemistry, but when the task exceeds the Working Memory Space, we are measuring a psychological artifact; the Working Memory Space. But a minority of students seem to succeed beyond this limit, by chunking. They have been taught, or have devised for themselves, strategies for breaking the over-size problem into smaller sub-tasks (or chunks) which are well within their Working Memory Space and sequencing them in such a way as to arrive at the solution. In a class situation, where such strategies have been taught, it is probably fair to set problems, which, on their face value, would appear to have a complexity greater than Working Memory Space. There is a danger, however, that teaching such chunking strategies reduces problems to algorithms which may not warrant the description, 'problem'. Before the advent of the mole and molarity, we settled for 'normality' and were able to use the relationship $V_1N_1 = V_2N_2$ to solve volumetric problems. There was no need to write formulae, balanced equations, mole ratios and so on. Volumetric normality questions come well within Working Memory Space whereas Mole questions almost inevitably come well outside Working Memory Space, and so we see in the literature a plethora of papers lamenting students' inability to solve them. The answer may be staring us in the face.

One line taken by some workers is to abandon such data-loaded questions and settle for multiple choice. This might be a partial solution (in reducing apparent load), but does multiple choice really measure the skills we think we are testing? Friel (Friel, 1979a and b) , Ambusaidi (Ambusaidi, 2000 and 2001), Johnstone (Johnstone, 2004) and Danili (Danili, 2005) have cast doubts upon multiple choice by exposing very serious problems.

This area of assessment needs much work to be done on it, taking into account the psychology involved alongside the massive efforts being made to design more clever computer programs to reduce the scoring load on teachers. 'Recall' has to be distinguished from 'recognition'; 'free and creative reasoning' has to be recognised as different from 'algorithm'; 'clever programming' must not be confused with 'better assessment'.

Problem solving

This is almost a corollary from the section above, but there are further considerations to be made. Reid (Reid, 1979), Hadden (Hadden, 1989), Wood (Wood, 1993), Yang (Yang, 2002) and Tsaparlis (Tsaparlis, 2001), have all shown that problem solving, well above the level of algorithms, is possible for pupils at middle secondary school as well as for undergraduate university students.

Using Johnstone's classification of problems (Johnstone, 2001), (Table 1) involving the information given, the methodology and the goals, these workers have exploited all eight types of problem to stimulate learning, to enhance interpersonal discussion skills, and to show chemistry to be a subject that is not remote from everyday living. Students are exposed to a large variety of different problems. Some are entirely pencil and paper, while others are conducted in the laboratory. Hadden's work (Hadden, 1989) has breathed new life into otherwise dull, routine verification laboratories in schools. Other examples can be found in some of the papers in this issue of the journal. The kinds of problems in this section are not algorithmic. Where they are complex, there is structuring to avoid overload. In some cases there are pre-problems to activate the stored information required to tackle the 'real' problem. All this development has stemmed from the clear theoretical base provided by the Information Processing Model.

Table 1. Categories of problems

Type	Data	Method	Goal
1	Complete	Familiar	Clear
2	Complete	Unfamiliar	Clear
3	Incomplete	Familiar	Clear
4	Complete	Familiar	Unclear
5	Incomplete	Unfamiliar	Clear
6	Complete	Unfamiliar	Clear
7	Incomplete	Familiar	Unclear
8	Incomplete	Unfamiliar	Unclear

Overview

This paper is really a history of a large group tackling problems of Chemical Education on a broad front and in an integrated way. It has told the story of how we have moved from data gathering to hypothesis construction. A working hypothesis has been tested and then used to influence other research leading to better teaching and learning. The Information Processing Model, which could be dismissed as sterile and soul-less, has been shown to embrace and bring together the 'schools' of Piaget, Ausubel and Novak; along with the students of Alternative Frameworks and the practitioners of Constructivism. The Model has been shown to have predictive as well as explanatory power. Like all models, it will continue to be useful only if it continues to explain the sources of the problems of the present and to point to ways of solving them for the benefit of future students.

The other papers in this issue show how things have moved on in Glasgow and elsewhere through the work of those whom I have come to regard as valued colleagues and friends. It has been impossible to discuss fully the research of the eighty workers who have been in the group and to show how each one has contributed pieces, both big and small, to the construction of a rich corpus of work.

Attitudes

Much of what appears above deals with cognitive issues, but on the way along it has been indicated that attitudes to chemistry and the development of attitudes through chemistry are of major importance. So much of the gloom, which exists at present about the future of chemistry in schools and universities, is due to negative attitudes to the subject and these must be related directly to bad experiences which pupils and students have had in chemistry lessons. The curricular changes in the 1960s and since, have, by their very structure, overloaded young people with an indigestible diet of conceptual overload. The mixture of abstraction, symbolism and formal laboratory experience (often mediated through mind-deadening worksheets) has been a huge turn-off for many. The seminal work of Reid (Reid, 1981) and his students in Glasgow has attempted to study the factors underlying attitude change and to apply them to the teaching of chemistry. His work is complementary to the cognitive work described briefly in this paper and together, these two strands of work provide a strong basis for the rethinking of the chemistry curriculum in schools and universities. Perhaps it is time for the 30 years of science education research to break out from its introspectiveness and repetitiveness and be applied to making the learning of chemistry an enjoyable and exciting experience for all young people.

Nothing that has been said in this paper denies or denigrates the valuable work of many researchers in many parts of the world, but, to keep the size of the paper within bounds it has been confined to the 'Glasgow School', the subject of this issue of CERP.

I am grateful to the editors and the editorial board of this journal for affording us the opportunity to present a very large corpus of work in a coherent way, to show how it has arisen, how it has fitted together and how a powerful set of tools has been fashioned to allow Chemical Education to meet the needs of our students and ultimately contribute to the needs and well-being of society. I am also indebted to my colleagues and former students who have contributed so generously to this issue of CERP. I commend their papers to the reader's attention, illumination and enjoyment.

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