Nyholm Lecture: Chemical education research: Facts, findings and consequences

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Chemical Education Research

Facts, Findings, and Consequences

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The 1960's saw the advent of a rash of curricular changes in chemistry in much of the English speaking world. CHEM Study and the Chemical Bond Approach appeared in the U.S.A., and Nuffield became the trend setter in England and Wales and was exported to several parts of the world. In Scotland, the Alternative Chemistry Syllabus appeared in 1962 and was rapidly adopted in all schools. Several curricular packages were tried, with varying success, in Australia and New Zealand and some of their new thinking found its way into Britain.

All of these changes have brought, in their wake, feelings of disquiet (*1*), and there have been attempts to revise them, to supercede them, and even to reverse them. Much of this retroactivity is taking place on emotive rather than rational grounds. "Back to Basics" has become a slogan no more meaningful, but no less potent than "Power to the People."

Ten years ago a research team was set up in Glasgow to examine the Scottish Alternative Syllabus and its effects upon schools, pupils, employers, and higher education. We were aware that all was not well and that measurement and research were necessary if things were to be put right. It was decided to begin the investigation with first-year undergraduates who had just come from school and to ask them for their subjective impression of the course they had just completed (*2*). Students were invited to choose, from the topics they had met in school, those with which they still had difficulty and would like to be retaught. The results obtained from different universities and over a period of two years showed an unmistakable constancy (Fig. 1). The frequency with which certain topics were mentioned is shown on the *y* axis against the topics on the *x* axis.

When similar questions were asked of pupils in their final year at school, we obtained peaks in the same places but in general they were more intense; presumably because we were dealing with a less able group than those who had become undergraduates. The main areas of discontent were balancing equations, net ionic equations, ion-electron half-equations, stoichiometry (especially in solution), conductivity interpretations of neutralizations, E^0 and cells, Hess's Law, condensation reactions, hydrolysis, saponification, esters, and carbonyl compounds.

Various members of the research team were then allocated an area, or group of topics, for further investigation. By a variety of techniques, most of these areas were examined for blockages to learning and large amounts of data were accumulated. However, no obvious common factor was apparent and we refused to ally ourselves with any one school of educational thought in our attempts to rationalize the outcomes.

When we came to investigate the organic areas our first hypothesis was that the orientation of a formula was important (*3*). To write an esterification equation, it was customary to present either the acid or the alcohol formula "backwards" to facilitate the "lasso operation" for the elimination of water. This hypothesis was shown to be untenable, but it gave us our

This article is an abbreviated form of a fuller text of the lecture which was published in *Chemical Society Reviews*, **9** (3), 365–380 (1980).

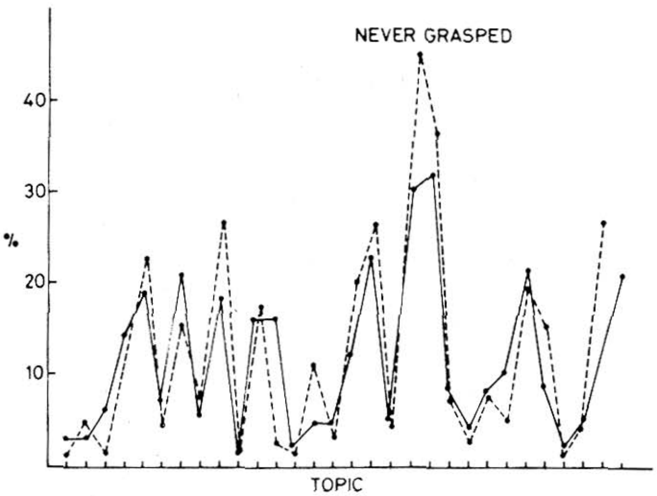
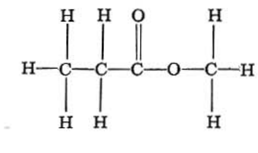


Figure 1. % Frequency with which topics were declared to be "never grasped".

first clue to the blockages in organic chemistry and eventually to the blockages in several other areas.

It was clear that the problem lay somewhere in the students' perception of organic structural formulas. To probe this, it was decided to use the students' short term memory (*4*). When most people are presented with a short sequence of six letters, such as AVPSNQ, and given 10 sec to memorize them, they can recall them in the next 10 sec with ease. However, if the sequence is increased to twelve letters, such as AVPSNQZBKLWR, few people can recall them. Another twelve-letter sequence can be easily recalled if it is of the form, BOYCATPINLAW, because English speakers perceive it as four short words. This fits in with the psychological observation that most people can store up to about seven pieces of information in their short term memory. The size of each piece of information depends upon the way it is perceived by the person. This technique was used to examine students' perception of organic structures. For example



could be "seen" as 27 pieces, if each letter and each bond were to be memorized by a total novice. This would be well outside his short term memory capacity. Someone more sophisticated might "see" the structure as a methyl group, a methylene, a carbonyl, an oxygen atom, and a methyl group and would be straining at the upper end of her memory capacity. The most sophisticated would see it as *one* piece, methyl propanoate, and would be able to store this plus several other similar structures simultaneously.

By this method we were able to establish that only 13% of those entering undergraduate study were perceiving all of the following groupings:

$-CH_3$, $-C_2H_5$, $-C{\scriptstyle\begin{matrix}\diagup O\\ \diagdown OH\end{matrix}}$, $-NH_2$, $-OH$, $-C{=}O$

It is little wonder that they were having trouble with esterification, hydrolysis, and saponification.

This research technique led to a consideration of the part the short term memory (and its associated working memory) might play in the other areas of the syllabus about which students were complaining. The working memory is thought to be the area where new and recalled information interacts, is linked and sequenced ready for a response or for storage.

In the area of stoichiometry we had observed that students could cope quite adequately with many kinds of problems involving the mole, but, as soon as materials were placed in solution, performance in the problems dropped from about 80% success to nearer 30% success (*5*). A similar drop in performance was noted if students were asked to provide an equation, balance it, and then use it to solve a problem of reacting masses (about 30% success). If the equation were supplied and balanced, the success rate was around 70%.

What is clear, is that when the pupil is being asked to recall more information and, at the same time, sequence it and use it, he is more likely to get the wrong answer. It was often noticeable that, even if he balanced the equation correctly, he did the calculation as if the stoichiometric ratio were 1:1 regardless. Could it have been that the form of his perception of the total problem just overloaded his short term and working memory?

The problem of substances in solution raised the additional phenomena of intensive and extensive properties. Any confusion here would be disastrous. A question of this form gave poor results.

Which one of the following sodium chloride solutions is most concentrated?

A. 1000 ml of 2 *M*
B. 800 ml of 3 *M*
C. 500 ml of 4 *M*
D. 200 ml of 5 *M*

More than half of the pupils at age 16+ chose B.

Seventeen year olds, when offered a choice of equation to express the reaction between aqueous solutions of barium chloride and sodium sulfate, chose the "molecular" equation rather than the net ionic equation (*6*).

$$BaCl_2 + Na_2SO_4 \rightarrow BaSO_4 + 2NaCl$$

rather than

$$Ba^{2+}(aq) + SO_4{}^{2-}(aq) \rightarrow BaSO_4(s)$$

At first sight this would seem to indicate a choice for the more complex, but this would only be the case for someone who had a very adequate perception of the reaction; who knew what was soluble and insoluble; who, therefore, knew what to declare redundant. To recall the formulas in the first place and to balance the equation if necessary may have pressed close to the limit. Going through the next and most complex stage to get to the net equation may have saturated the working memory.

Using a working hypothesis like this one can begin to make sense of a number of well-known phenomena. It is a common observation in laboratories that students, working from a manual, do so line by line as for a recipe. If a student is questioned by a demonstrator about what she is doing, the student is often unable to say more than, "I am about to add the 10 ml of HCl." The plethora of instructions in a laboratory manual far exceed what she can hold in her short term memory so that she is unable to group the information, declare parts of it redundant, and see the whole purpose of the experiment. This is a phenomenon similar to that seen in young children who can read every word of a sentence correctly, but have no idea of the total meaning of the sentence. All their working memories are occupied with the mechanics of reading and the early part of the sentence has passed out of the memories before the latter part has entered. Often an experiment makes sense only after it is over and the student is writing a report.

It was shown some years ago (*7*) that undergraduates who were given clear objectives for their laboratory work responded more favorably than their colleagues who were "kept in the dark." This simple strategy helped students to focus on the important and to place less emphasis on the preliminary and relatively unimportant. In so doing the students were seeing the wood and not being blinded by their close proximity to the bark of the tree.

A similar observation was made when, periodically, students were asked to plan their own experiments working in a small group of four (*8*). The preliminary discussion among the students was concerned mainly with decisions about what mattered and what did not and about the sequence of operations. Hence, the students' perceptions of the whole task were being grouped and ordered.

Students confronted with a complicated calculation confess that they do not know where to start, whereas the teacher is in a position to plan a strategy because his perception of the problem is different. The teacher knows what to do first and what to leave till later. His sub-conclusions are reached before his main conclusions so that his working memory is never flooded.

This thinking led us to a model (Fig. 2) in which there was an interdependence of three factors

(a) the size of the information content
(b) the degree of development of the perception of the concept or task, and
(c) the difficulty perceived by the student

This can be looked at another way (see Fig. 3.)

There are eight possible routes from the top to the bottom of the table and, of these, two are most unlikely (numbers (3) and (6)). When the information content is low, the working memory can cope and this is further helped by an already highly developed level of concept understanding. Under these circumstances the perceived difficulty will not be high. By similar reasoning we can eliminate (3). Two other routes are possible, but not very likely (2) and (8). Despite the large amount of information, the high development of the concept will enable the student to group and sequence the material and so his perceived difficulty is unlikely to be high (8). The diagram now reduces to the form shown in Figure 4.

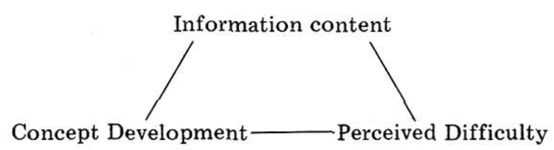


Figure 2. Interrelation among the factors influencing how a problem is perceived.

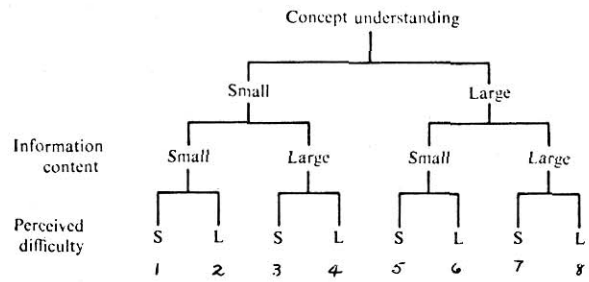


Figure 3. Possible combinations of the factors, concept understanding information content, and perceived difficulty.

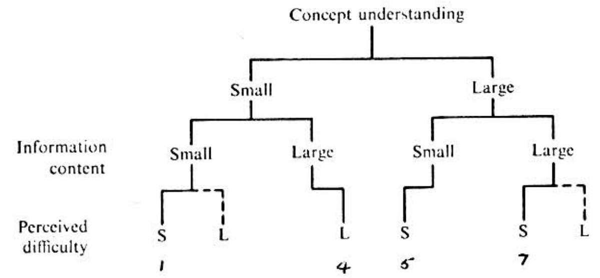


Figure 4. The most probable combination of factors leading to perceived difficulty.

Of the most likely routes, (1), (4), (5) and (7), only one of them leads to high perceived difficulty, that is, a *high load* of information, given to a student while her grasp of the *concept is low*, is perceived as *difficult*.

This may be self-evident, but why is it that we have allowed this to occur in so many areas of our new (and old) chemistry curricula? Each area we examined following the students' complaints of difficulty showed all the signs of information overload, while the students' conceptual framework was still primitive. This also was observed in topics in physics and biology.

There are two possible sources of overload both of which can be remedied. The first of these is that teachers unwittingly make a wrong estimate of their pupils. Experimental evidence (*6*) showed this to be true on several occasions. For example, teachers were invited to examine a set of tests on ionic equations and to estimate which topics would prove difficult for their pupils. The test was then administered and the test results along with the teachers' estimates are shown in Figure 5. The sad pattern which emerged was that the *easier* teachers thought ionic equations were, the *poorer* their pupils performed. There is a salutary lesson in this for all of us who teach, and especially for those who teach in higher education. It is so easy to become competent in an area of knowledge and forget what it is like to be a first-time learner. Teachers have built up, over the years, an interlinked cognitive structure which makes the elementary ideas look trivial, but for the novice, the trivial may be incomprehensible because he has no conceptual framework to which he can attach the new ideas. There may even be grounds for suggesting that the specialist is not the best man or woman to do the elementary teaching. The basic tenet of teaching is to lead the learner *from where she is* into new areas of knowledge and understanding. It behooves us all as teachers to establish clearly where our students are and to lay the ground carefully for the next step. There is no use in expecting to obtain good learning by starting with a statement like, "You will remember from last year . . ." or "I assume Dr. X taught you this last term . . ."

A second source of overload may be in the very nature of the chemistry itself. Teaching must never do violence to the discipline being communicated. If teaching is seen as a series of diminishing deceptions, the simplification at the beginning must not lay up problems for future stages. If pupils are at the beginning of an area of work and have as yet no grasp of the concept and if the nature of the topic is complex and full of information, some strategy must be found to resolve the dilemma. The student is not in a position to group and sequence the information for himself and yet he must interact with the information to allow his conceptual understanding to grow. Somehow the teaching itself must provide a grouping and sequencing strategy. We used to call these strategies rules of thumb, mnemonics, or even formulas.

So many of them were swept away when the new curricula appeared and the banners were raised against rote learning and for "no learning without understanding." Almost all the problems in the area of the mole came when normality went and molarity arrived. The $V_1N_1 = V_2N_2$ crutch was removed

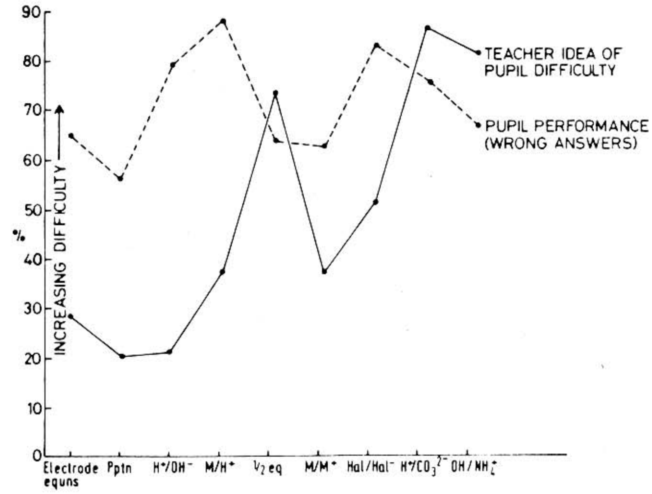


Figure 5. Teacher estimate of difficulty and actual pupil performance on a test over ionic equations.

and little or nothing was put in its place. Although it was possible to use this relationship blindly, it served the important function of allowing a student to build confidence so that when his concept had developed, he would be in a position to understand and, if need be, abandon the crutch. There are ways by which molarity calculations can be given a structure which can be applied using reason. For example, a student can be convinced that the following statements are reasonable.

The number of moles of hydrogen ions in an acid must depend upon three factors: (a) the volume (in liters), (b) the molarity, and (c) the number of hydrogen ions in the acid's formula.

A similar argument can be raised for the number of moles of hydroxide ions in a solution of a base. At neutralization, the number of moles of H^+ = number of moles of OH^-.

Most volumetric problems consist of six pieces of information, five known and one unknown. The problem is sequenced as: find the number of moles of H^+ in the acid (3 pieces become 1); then the number of moles of OH^- in the base (3 pieces become 1). They must be equal at neutralization and so the unknown can be found.

This strategy does not involve the additional writing and balancing of the equation which can make the load on the working memory into an overload. Once mastered, this simple method can be expanded to take in masses as well as volumes and also redox situations.

Whenever the chemistry is complex, but necessary, similar devices can be found. This applies to chemistry at all levels because the evidence is that the capacity of the short-term working memory of students does not change materially. What does expand is the size of what constitutes a unit and this expansion depends upon the student's concept understanding. The idea of "stretching" a student really amounts to encouraging her to expand the size of the units which she can handle as one. This involves the provision of a good interlinked framework into which new information is incorporated. It is not unusual to find students half way through a chemistry degree course who have never seen any linkage between the concepts of base, nucleophile, and ligand.

A final word must be said about concept growth. Although a teacher may carefully structure and sequence the learning to make the material accessible to the pupil, there are factors which may be beyond his control. The first of these is the pupil's ability or intelligence. The second is probably developmental in nature. This does not necessarily imply a Piagetian interpretation in terms of stages related to age (or mental age). It may be explicable by a consideration of the previous experience, background, and knowledge of the pupil. A third factor comes under the loose term motivation or attitude.

In conclusion, an apparently trivial idea has emerged from our research. To present a student with a large amount of information while his concept is as yet primitive, prevents him from grouping and handling the very information he needs to make the concept grow. Each area which students deem to be difficult, which we have analyzed, bears the hallmarks of this overload process. This impasse can be overcome by sympathetic teaching which reduces the load or by providing strategies to enable the load to be grouped and sequenced.

The fact that chemistry comes high in the league of pupil estimates of difficulty (*9*) allegedly has led to the move away from the subject. These ideas of overload, although not providing all the answers, should help us to think more clearly about the transmission of our subject. It may provide a reasonable framework for an examination of chemistry teaching and give direction to any new moves in the chemistry curriculum at all levels.

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