TEACHING AND LEARNING PHYSICS SUCCESSFULLY

What does research evidence tell us?

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1 INTRODUCTION

Education in physics may serve three overlapping purposes:

- *To provide those qualified at the highest levels in physics to give leadership to the main strands of research as well as the many physics-based jobs;*
- *To provide those who will need physics for many other careers and occupations including medical sciences, other sciences as well as the communications industry;*
- *To educate a population who understand the main ideas of physics and can see its important place in any modern society: our future leaders, politicians, leaders in society as well as citizens and voters.*

The latter group is by far the largest and they must be seen as the main group to benefit from school education in physics. They are often neglected.

There is an enormous research literature describing empirical studies which offer clear evidence about what attracts students into physics, with some key research findings:

Interest develops early (by age 14): Courses at ages 12-14 are critical
Boys and girls are equally interested: But the interests are different
Things outside the school have almost no impact: Special events are NOT cost effective
There is a successful curriculum approach: The applications-led approach
School teachers are absolutely critical: Qualified, committed, rewarded as professionals
Integrated science courses are disasters: Loss of interest, simplistic, lacking commitment
Career potential must be perceived: Opportunity to make teachers aware

There were major curriculum changes in physics in schools in the early 1960s in many countries and students started to report difficulties in some topics in physics. Later studies identified the major difficulties in physics at school level and these have been summarised [1]. These included many areas in electricity (e.g. voltage, resistance, alternating current); the concept of energy and, especially, heat energy; radiation and ideas such as wavelength, frequency; and many ideas in mechanics and dynamics, especially issues related to forces and acceleration.

Although many studies were carried out to explore these areas of difficulty, the key thing is to find out *why* certain topics caused problems. Was it intrinsic to the nature of the physics or was it related to the way humans learn in highly conceptual areas? It turned out to be both [2, 3, 4]. Although these papers relate specifically to chemistry, it turns out that physics is very similar [1].

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2 INSIGHTS INTO LEARNING

Two other important findings occurred about the same time. The first one was the finding by Miller [5] that the capacity of an important part of the brain could be easily measured. This part is now known as the working memory and it is that part of the brain where we do our thinking, understanding and problem solving.

It was found that the capacity of the working memory grows with age (to about age 16) after which it was fixed. The capacity is determined genetically and cannot be modified. However, the efficient use of the space is open to development, largely through experience. The working memory capacity was found to be a rate-determining step in much learning [6]. The average adult capacity is 7 pieces of information and most adults possess a capacity between 6 and 8. Miller [5] described the capacity using the word 'chunk'. The size of a chunk of information will vary from person to person. It all depends on what the individual sees as a unit of information. The expert, by means of experience, can group ideas together so that they are seen as one chunk. The novice learner lacks such experience and tends to see these ideas separately. Therefore, much more working memory space is used to hold the ideas, leaving less for thinking and understanding.

A breakthrough came when Kellett [7] observed that all the topics causing difficulty were those where there was a high information load on the learner. Information load was defined as the number of pieces of information which the learner had to hold *at the same time* in order to perform the task successfully. Could it be that the limited capacity working memory was being overloaded with the topics which were proving difficult and that this was the source of the problem? A key paper brought the ideas together in a clear way and showed that this was the case [8].

It is relatively easy to measure working memory capacity [5] for students and working memory capacity correlates positively (ranging from 0.2 to 0.6) with performance. However, the relationships between working and performance are not a simple one: it was found that the relationship was not linear. When a task exceeds the working memory capacity, performance collapses quite spectacularly [9, 10]. Figure 1 show the kinds of graphs which are frequently obtained when questions of increasing working memory demand are asked of students.

However, further analysis gave an even more interesting picture (Figure 2). The sample in one experiment [9, 10] was divided into three groups by their measured working memory capacity. The point of collapse in performance corresponded approximately to one unit less than their measured working memory capacity.

The results of the experiment seem to be highly reproducible and are particularly marked for mathematics [11] but have been shown to occur in almost all school subjects [12] as well as university subjects However, it is possible to remove the effect completely simply be making sure that none of the questions asked overload the working memory [13]. This is nothing to do with trivialising the test questions and making them easy. In this specific case, the test (in mathematics with young children) was not easy and the marks were not good. Nonetheless, the performance did not relate to the working memory capacity of the students simply because of the way the questions were asked.

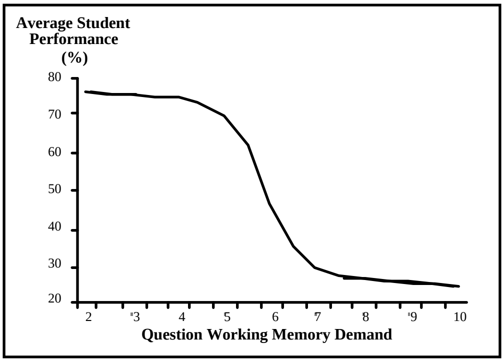

Figure 1 Performance collapse as information load increases.

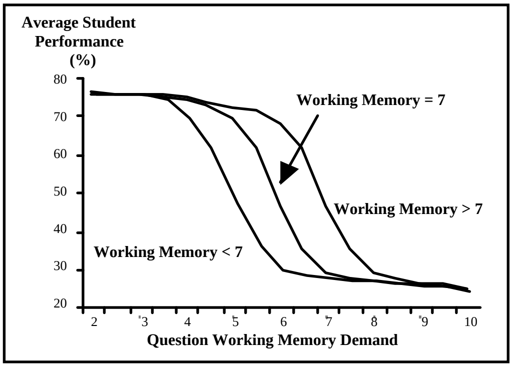

Figure 2 Performance collapse as information load increases.

3 INFORMATION PROCESSING

These experiments give a clear way forward in making the science subjects more accessible to learners. If neither the way of presentation nor the way of assessment requires the learner to hold more information than the capacity of their working memory, then their performance will relate to their knowledge and skill in the subject and not to their working memory capacity. However, it was not quite so simple. The working memory is where information is held temporarily, the information is worked on, rearranged, brought together, and understood. Extra information is drawn from long term memory and thinking and problem solving take place. It is now known that the capacity has to accommodate not only the items of information to be held at the same time but also to have space to carry out the necessary processing of that information [2]. The working memory grows by one unit for every two years of life, very approximately. This explains why some topics cannot be understood easily before a certain age. Understanding requires the young learner to hold too many ideas for their limited working memory.

The evidence from these experiments and much other work started to lead to a model of learning which is now widely accepted in much educational psychology (Figure 3).

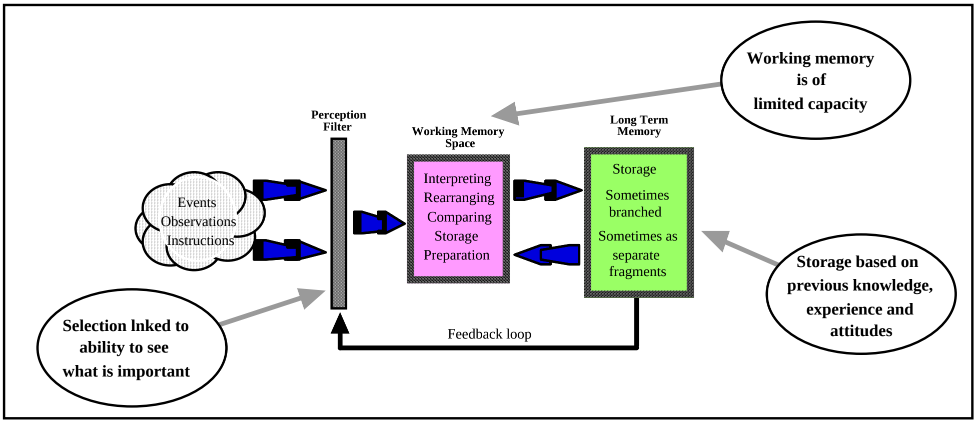

Figure 3 A Model of Information Processing [2].

There are some very straightforward predictions from the model:

- *If working memory is overloaded, learning will more or cease*
- *If the perception filter works efficiently, overload is less likely*
- *The filtration is controlled by what you know already*
- *If knowledge is stored in linked fashion, it will be more easily recalled*

The consequences of overloading the working memory have been demonstrated again and again: success becomes elusive. The effect of the selection of information by means of the perception filter can also be shown easily. Different people have different abilities to select what is important for a particular task from all the information which is presented [14] and this ability can be measured easily. The key is that *everyone learns in essentially the same way* although there may be important variations in the details.

There are many variants of the information processing model of learning in the literature but they all offer the same kind of picture [15, 16, 17, and 18]. Through our senses, we take in information from our environment, we select what is of importance and relevant to us at a particular moment, we process it in some way and then, perhaps, we store what we have found. Overload of the working memory can be reduced if the perception filter selects more efficiently. This is controlled by what is already known and stored in long term memory. The idea of pre-learning follows naturally from this.

4 PRE-LEARNING

In a large university first year class (size varied from 160 to 220 from year to year), students were given pre-learning experiences in the first two years, these being discontinued in the next three and then, finally, pre-learning was re-introduced in a paper form. 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 key observation is that the experiences known as pre-learning had the greatest benefit for those in the class who were *least* well qualified. 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 [19].

Table 1 The Effects of Pre-learning.

Year	Pre-learning	Average Examination Marks		Difference in Averages	Significance
		Better qualified group	Poorer qualified group		
1993-94	Pre-lectures used	50.9	48.8	2.1	not significant
1994-95	Pre-lectures used	49.2	49.0	0.2	not significant
1995-96	No pre-learning	46.9	38.7	8.2	Significantly different
1996-97	No pre-learning	48.2	42.0	6.2	Significantly different
1997-98	No pre-learning	46.7	41.3	5.4	Significantly different
1998-99	pre-learning (paper)	49.8	47.7	2.1	not significant

Pre-learning has a very large effect in making laboratory learning much more effective. In one large experiment [20], students undertook four experiments, two with pre-learning experiences and two without. The sample was a large first year university class. The pre-labs were sets of very short exercises which the student undertook before the laboratory. These might involve revising background ideas from the past, revising calculation techniques, being prepared for the equipment they were to meet, thinking through what they were looking for in the experiment and so on. Tests for understanding were applied afterwards and, on average, the performance in these rose by 11% as a result of the pre-laboratory experiences.

5 REDUCING DEMAND ON WORKING MEMORY

Of course, re-organising teaching to reduce the overload on working memory directly is always possible. There are several examples of large experiments where this prediction has been tested and found to generate *very marked* improved performance in tests of understanding. Of course, it is easy to get better examination marks if we make the examinations easier. It is easy to get students to pass examinations if we trivialise what is to be taught! However, students soon see through such deception. This offers no way forward.

The prediction from the Information Processing Model is that, if we reduce the demand on the working memory, then learning (seen in terms of understanding) will improve. The content to be taught is *not* changed. The time allowed for learning is *not* changed. Difficult themes are *not* avoided. Re-training of teachers is *not* envisaged. In the various experiments, what was done was to change the teaching order, modifying speed and sequencing, breaking down complex areas into smaller parts and allowing the learning to fit the human psychology outlined in the information processing model. This was achieved by thinking through each difficult theme and then making sure that it is presented in a step by step way, thus reducing the load on working memory.

The key thing to note is 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, by using dialogue boxes carefully and skilful use of graphics, the working memory is not faced with too much at the same time. It is predicted that learning will increase.

One major experiment is described here to illustrate what is possible. In this experiment, several areas of a school syllabus were re-organised. With a total sample of 800, students in two year groups towards the end of their studies in school experienced being taught by new materials covering major sections of the school syllabus. Each student undertook one topic using the new approach. The new materials were designed with several factors in mind: they 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 being discussed here.

The remarkable thing is that, with large samples and large areas of the curriculum, the average performance rose for the four areas by an average of 13%. This completely transformed the examination performance of these students. This work involved no contact at all with the many teachers involved.

What was even more remarkable, were the outcomes from the attitude measurements. It was shown that large negative attitudes toward most aspects of the school experience had been converted into strong positive perspectives. As with the examination performance, attitudes had been *transformed* simply by applying the ideas predicted from the Information Processing Model.

The evidence from these experiments is that, by simply applying the predictions of the Information Processing model, performance and attitudes can be enhanced enormously. Similar effects have been found consistently with other experiments.

Table 2 Improvement in Performance [21].

N = 800	Mean (%)	Gain	t-test	Probability
Topic 1				
Experimental Group	79.2	18.2	26.2	$p < 0.001$
Control Group	61.0			
Topic 2				
Experimental Group	80.2	9.2	9.7	$p < 0.001$
Control Group	71.0			
Topic 3				
Experimental Group	71.0	14.0	19.7	$p < 0.001$
Control Group	57.0			
Topic 4				
Experimental Group	75.0	10.7	15.1	$p < 0.001$
Control Group	64.3			

6 ATTITUDES

This leads on to attitudes. The literature is full of papers noting declining attitudes towards studies in physics at school level. Some key work was carried out by Skryabina in Scotland [22, 23]. Looking at large samples of school pupils and university students, she found that attitudes towards physics did *not* decline with age as found in most studies in other countries.

Attitudes were fairly positive at later primary stages (where the pupils had met little physics) but very rapidly declined in the early stages of secondary school where physics was part of an integrated science course. This confirmed work done may years before by Hadden [24, 25, and 26]. Nonetheless, good numbers chose to take the physics course in the middle secondary years, reflecting the very high status of physics in Scottish Education. Attitudes towards their studies rose steadily and rapidly through this two year course (which was an applications-led course) and, by the end, 90% of both boys and girls expressed a wish to continue studies in physics, a remarkable reflection on the power of an applications-led course to attract and stimulate. Students performed extremely well in the upper stages of secondary physics, again showing that the previous applications-led course had laid good foundations for further study.

An applications-led course can be described as one where the physics to be taught and its teaching order is determined by focussing on the learners - their needs, what is perceived by them to be related to their context and lifestyle. In the end, the same physics as in traditional courses can be covered but the approach, order and emphasis may be very different [27].

It is important to note that there very little university physics departments can do directly to attract students towards physics. The evidence shows very clearly that attitudes are formed at an early age. However, if the way courses at school are constructed and are taught makes physics attractive to the learners, then many will be attracted to stay with physics into colleges and universities. However, university physics departments can support school teachers with resources and career information as well as encouraging some of the best students to consider a career as secondary school teachers.

7 SOME CONCLUSIONS

Physicists seek to act scientifically in their own areas of specialisation. However, we can be just as scientific with regard to our teaching. Very often, curriculum construction, textbook writing and teaching approaches are based on assertion and opinion. No scientist ever works that way in their own science areas! Science is developed on the basis of evidence and that evidence is mainly gained by means of carefully conducted experiments.

This paper has gathered the outcomes from many carefully conducted experiments conducted in many countries with learners of diverse ages and backgrounds. The actual fundamental process of learning is the same for everyone. Through our senses,

- *We take in information from our environment;*
- *We select what is of importance and relevance to us at a particular moment;*
- *We process it in some way;*
- *We store, perhaps, what we have found.*

By taking the outcomes from the experiments described in the literature, it is possible to improve all of these markedly, with a vast improvement in the outcomes for the learners. This is seen not only in better examination results but also in the way much more positive attitudes are developed. In this way, as teachers, we have a great opportunity to excite our pupils and students so that they too can be stimulated to make sense of the physical world, thus becoming more informed citizens and, perhaps even the scientists of the future.

8 RECOMMENDATIONS

On the basis of clear research evidence, it is recommended that:

- *Conceptual physics should not be taught to young learners too early and never be attempted at the primary stages of education;*
- *Physics should be taught at all levels of school only by those who have a qualification in physics and are committed to it;*
- *Physics curricula, especially at all school stages, should be redesigned in line with an applications-led structure;*
- *The presentation of physics (teaching, laboratory work, problem solving, and developing text books and other teaching materials) should take into account the established understandings of the way the human mind works when learning, especially limited working memory capacity;*
- *It is critical that assessment should match the aims of understanding and applying ideas in real-life.*

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