
Research in Science & Technological Education

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/crst20

# Some strategies to improve performance in school chemistry, based on two cognitive factors

Eleni Danili [a] & Norman Reid [a]

[a] University of Glasgow , UK

Published online: 13 Oct 2010.

*Research in Science & Technological Education*
*Vol. 22, No. 2, November 2004*



# Some strategies to improve performance in school chemistry, based on two cognitive factors

Eleni Danili and Norman Reid*
*University of Glasgow, UK*



The background to this study are the difficulties facing the majority of Greek pupils in understanding chemistry concepts and, therefore, performing well in the National Examinations. The aim was to explore the problems and to suggest ways in which the situation might be improved. Working with 105 Greek pupils aged 15 to 16, the first stage of the enquiry confirmed that both working memory space and extent of field dependency were two psychological factors affecting performance. This is at least part of the nature of the problem. In the second stage, an attempt was made to explore how the problems might be reduced. New teaching materials were constructed to minimize any limitations to learning caused by working memory space and problems associated with being field dependent. The use of the new materials was compared to the normal teaching process working with 210 Greek pupils aged 15 to16. It was found that there was a significant difference in the average improvement of the experimental group and the control group, in favour of the experimental group. This result was independent of the effect of the teacher, and of the interaction of teaching method and teacher. It is suggested that approaches to learning must take into account cognitive factors in the learners in the context of information processing understandings of learning. If this is done, learning is much more effective.

## Introduction

In Greece, chemistry is taught for the first time as part of an integrated science course in the fifth and sixth year of primary school (ages 11–12) and, as a separate subject, in the second and third year of lower secondary school (12–15) and in all the years in upper secondary school (15–18). The majority of schools were not equipped with laboratories and it is only in recent years that, in many schools, teachers have started experimental work. In research related to chemical notation, atomic and molecular structure, chemical equations and simple stoichiometric calculations, Tsaparlis (1991, 1994) has already established that the chemistry understanding of the majority of pupils in secondary education is poor. Georgiadou and Tsaparlis (2000, p. 218) commented 'It is as if students come to upper

*Corresponding author: Centre for Science Education, St. Andrews Building, University of Glasgow, Glasgow, G3 6NH, Scotland. Email: N.Reid@mis.gla.ac.uk

ISSN 0263-5143 (print)/ISSN 1470-1138 (online)/04/020203-24 
DOI: 10.1080/0263514042000290903

secondary school, and their only knowledge from foreign language teaching is the alphabet; no vocabulary, no grammar, no structure of the language'.

This study seeks to explore two psychological factors which may influence performance in chemistry and to develop teaching strategies which minimize the effects of these limiting factors in allowing pupils to become more successful.

## Background to the study

It is possible that some of the causes of the high failure rates in Greece are that the material to be taught is not suitable for pupils at given ages. The abstractness of textbooks and an inadequate time allocation might also be factors. In addition, the lack of teacher training and appropriate theoretical support for educational development may contribute to the problem. It could be argued that we should view teaching in a systematic way and start looking into the pupils' minds and teaching them accordingly (Johnstone, 1991). Without training and support, this is far more difficult.

The problems observed in Greece are reflected in varying degrees in many other countries with different curricula and, although many studies have been carried out, those problems have not yet been solved. Studies on bonding misconceptions, misunderstanding about the nature of matter, equilibrium, free energy, molecules and intermolecular forces, acids and bases all reveal that students' conceptions are often inconsistent with the scientific concepts (Garnett *et al.*, 1995). Misconceptions and confusions from chemistry teachers occur as well, as is revealed from many studies (Nakhleh, 1992; Furio *et al.*, 2000).

Many studies in chemistry education are related to students' difficulties in learning and understanding chemistry concepts and their alternative conceptions in chemistry (e.g., Osborne & Cosgrove, 1983; Nurrenberg & Pickering, 1987; Anderson, 1990; Sawrey, 1990; Bodner, 1991; Gabel, 1993, 1999). However, fewer studies have looked at the effects of psychometric variables on student performance in chemistry (Niaz, 1988, 1989; Al-Naeme & Johnstone, 1991; Lee *et al.*, 2001).

When looking at the factors which might make chemistry understanding difficult for many school pupils, the following general observations can be made on the basis of past evidence.

### *The complex nature of the subject*

It has been suggested that the psychology of the formation of most of the concepts in chemistry is quite different from that of the everyday world (Johnstone, 1991, 2000). Johnstone suggests that we need three levels of thought when thinking within the discipline of chemistry:

(a) The macro and tangible: what can be seen, touched, smelled.
(b) The sub-micro: atoms, molecules, ions and structures.

(c) The representational: symbols, formulae, equations, mathematical manipulation and graphs.

While the trained chemist can move easily between these levels, the novice learner has great difficulty and can end up mentally overloaded.

*The language barrier*

Words, the meaning of which in everyday life might not be the same as their scientific meanings, create confusion in the learner's mind. Selepeng looked at the measurement of working memory when working in a second language, showing the effect on working memory space of less familiar language (Johnstone & Selepeng, 2001). In their study, Poollitt *et al.* (2000) addressed the problems related to language barriers which students face when they study in a language that is not their mother tongue. They concluded that the problems are linguistic, contextual and cultural. Sutherland (1992) discussed the problem of language in the context of information processing and quoted Oakhill (1988) who investigated why the use of negative comparisons (such as *'Ann is not as bad as Betty. Betty is not as bad as Carol. Who is the best?'*) can make it difficult for children to reason soundly. Oakhill's explanation is also based on the ideas of information processing.



*The curriculum programme*

The most common structure of teaching chemistry in many countries is based on a logical order. Thus, almost all textbooks start with atomic theory and bonding. These are best explained on the sub-microscopic level first, before presenting descriptive chemistry at the macroscopic level. For writers who are experienced academic chemists, this order is very logical. However, this may not make understanding easily accessible to the new learner. Reid (2000, p. 381) suggests that we might consider an 'application-led approach rather than an approach which is based on the traditional logic of the discipline'. According to this perspective, the chemistry curriculum may be designed starting with applications from life and not with the logic of the discipline of chemistry as perceived by the experienced chemist. Fleming (1998) holds similar ideas to Reid. Perhaps, overall, the curriculum design should take into account the psychology of the learner as well as logical and heuristic principles (Johnstone, 2000).

## Cognitive structure

In recent years, science educators have attempted to take into account the educational psychology models of learning and students' cognitive structure. Cognitive approaches are concerned with the way in which information is processed in human beings. The differences which exist in cognitive structure and in psychological functioning enable individuals to have different cognitive styles. Individuals have

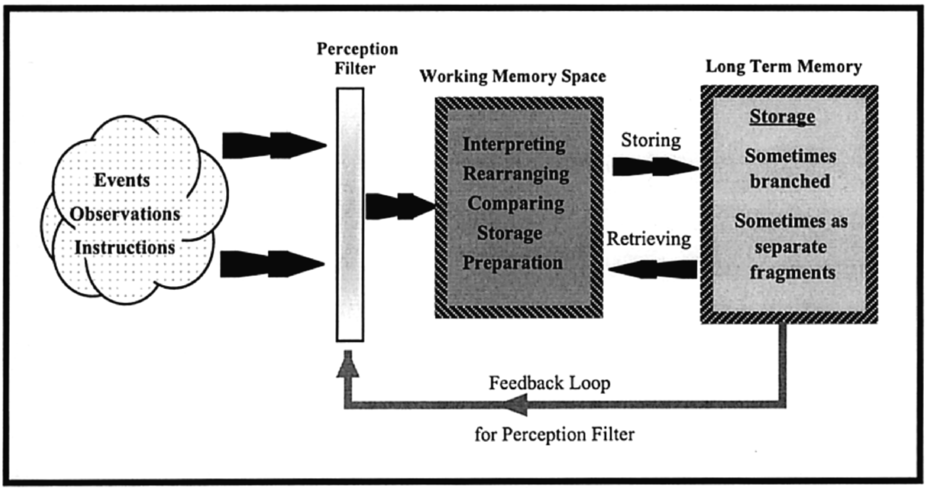



Figure 1. Information processing model

different ways of collecting and organizing information, depending upon their cognitive structure and what they already know (Messick, 1994). These approaches look at how we derive information from the environment. They investigate how we perceive, organize, store, retrieve and use information. They ask which are the criteria that drive us to select and influence our attention. Information processing models have offered considerable insights into the way learning takes place.

### *Information processing*

An Information Processing Model is used as a background to the work described here and this is an attempt to suggest a mechanism for learning arising from a number of psychological schools of thought. An understanding of the learning process may influence the way we teach and the way we react when the things not going well (Johnstone, 1997). The Information Processing approach studies the flow of information through the cognitive system. This flow process consists of an input, an output and a mental operation which occurs between input and output. These mental processes are similar in some ways to the working of a computer. There are many Information Processing Models in the literature based largely on the work of Atkinson and Schiffrin (1971). The model (Figure 1) proposed by Johnstone (1993) is based on a mechanism suggested by many researchers. This model focuses on learning and the learner. It suggests a simplified mechanism of the learning process and enables us to understand the limitations of learning.

When we attend to a stimulus it passes into short-term memory (Atkinson & Schiffrin, 1971; White, 1998) or working memory space (Baddeley, 1986). After various memory experiments, Miller (1956) found that the average capacity of the working memory is about seven plus or minus two ($7 \pm 2$) separate 'chunks'. Miller's idea of 'chunks' needs clarification. It is much more difficult, for example, to recall seven irrelevant letters than to recall seven letters that make a word. The term 'chunk' can be described as that which the observer perceives or recognizes as a unit; for example, a word, a letter or a digit. This is controlled by the student's previous knowledge, experience and acquired skills (Johnstone & El-Banna, 1986). 'Chunking' is the process through which the learner groups together pieces of information in a way that allows him to hold more information. According to White (1998), we 'chunk the world', that is we combine our sensations into a small number of patterns and so 'chunking' is a function of knowledge. As there are different ways of 'chunking,' there are differences between the knowledgeable person (e.g., teacher, adult, expert) and the novice (e.g., student, child, beginner) in the size and number of the information units perceived in a situation.

In recent years, the concept of short-term memory has been broadened into the idea of working memory space. It reflects better the notion that it is not only a space for storing information for a certain time but it is a space for processing and transforming information. It permits us to keep information long enough to make sense of sequences of words and directions to solve problems or to make decisions (Brunning *et al.*, 1995). Working memory is that part of the brain where we hold information, work on it, organize it and shape it, before storing it in the long-term memory for further use (Baddeley, 1986). Since working memory is limited and has to be shared for holding and operating processes, if we try to do too much at once we simply overload and learning falls.



### *Field dependency*

Another important cognitive characteristic is the field dependence of the individual. Witkin (1977) first investigated the personality in relation to the process of making contact with the environment through perception. Witkin and Goodenough (1981) defined the main characteristic of the field-dependent and field-independent cognitive styles in the following way. An individual who can easily 'break up' an organized perceptual field and separate readily an item from its context is a field-independent individual, whereas the individual who can insufficiently separate an item from its context and who readily accepts the dominating field or context would be defined as a field-dependent individual. This can be described as detecting the 'message' and separating it from the 'noise'.

Field-dependent persons have difficulty in separating an item from its context and are inclined to respond to the dominant properties of a field presented to them. Field-independent persons are capable of restructuring a field by breaking it up into separate items and to make a number of changes to the field or to 'go beyond the information given'. It was thought that there might be a relationship between the individual's 'disembedding ability' and their 'cognitive restructuring'. Thus, to determine an individual's level of field dependency, Witkin used what he called 'the embedded figure test'. In this test, the individual was required to recognize and identify a simple geometric shape within a complex pattern. The more shapes correctly found, the better the individual is at this process of separation and is said to be field-independent, and *vice versa* for field-dependent. The designation of field-dependent/independent does not imply two distinct categories. There is a continuum between these two classes and those of intermediate ability are classed as field-intermediate.

A very large number of papers have been published relating to the concept of field dependency. In their review, Tinajero and Paramo (1998) concluded that no matter what the nature of assessment is, field-independent students perform better than field-dependent students. They also reported the studies of Berger and Goldberger (1979) and Goodenough (1976) who believed that the differences in certain information processing components such as memory and attention between field-dependent and field-independent subjects might be affecting the ways in which children perform in the classroom.

Several researchers (e.g., Pascual-Leone, 1970) have considered the relationship between working memory capacity and the field-dependence/independence ability. Their results suggested that field-independent ability is a developmental characteristic and learners with this ability possess at the same time a highly effective working memory capacity. They may be described as high processors. Burton and Sinatra (1984) used audiovisual techniques to investigate vocabulary acquisition of preschool children. Their result was consistent with the above results: field-dependent subjects recalled fewer words than field-independent subjects in both modes of presentation.

Johnstone and El-Banna (1986) found a relationship between field dependency and performance in chemistry students. He found that among students with the same working memory capacity, their performance declined when the student was more field dependent. Al-Naeme and Johnstone (1991) found that there is a little difference in performance between low working memory capacity field-independent students and high working memory capacity field-dependent students.

## The first stage of the enquiry

The first stage of the research was conducted in Greece with 105 pupils of the first year of two upper secondary schools (*Lykeio*). It was decided to work with the pupils of the first year of *Lykeio* for two reasons. At that stage, pupils do not participate in national exams and teachers are more willing to be involved in research. Secondly, pupils at this stage are taught fundamental ideas of the chemistry discipline.

The two cognitive factors outlined above were examined in relation to pupils' performance in chemistry tests. For that purpose, the following measurements were made:

- The working memory capacity of the pupils;
- The field dependency of the pupils; and
- Pupils' performance in chemistry tests.

The measurement of each is now discussed in turn.

*Measurement of working memory capacity*

To determine an individual working memory capacity, the Digits Backwards Test was used (based on Jacobs, 1987). It consists of a set of digits, which are read out to individuals who were asked to recall and write them down in reverse order in a limited time. Thus, '2453' would return as '3542'. Students were not allowed to write backwards. The number of digits slowly increased to 8 digits and two chances were given for each level of testing. The highest number of digits that a student was able to recall correctly in order was considered to be the size of his/her working memory capacity. If the student fails to give the correct order of digits for the two attempts at a given level then the previous level is taken as the size of his/her working memory space. While the Digits Backwards Test is known to give good results, all that was sought here was to be able to place the pupils in order of their measured working memory space. Absolute measurement was not required.

The mean score of the Digits Backwards Test of 105 upper secondary schools pupils was 5.6 (minimum = 2, maximum = 8) and the standard deviation was 1.44. Although the analysis depended on looking at the correlation between working memory space and success in the chemistry test, it was convenient to divide the sample into three groups to illustrate the trends being observed. These groups were named 'low', 'intermediate' and 'high' working memory capacity.

- Low working memory capacity category: those who score $\leq 5$
- Intermediate working memory capacity category: those who score = 6
- High working memory capacity category: those who score $\geq 7$



*Measurement of field-dependence/field-independence*

Witkin *et al.* (1977) developed a group embedded figures test to determine an individual's degree of field dependency. It is called the Hidden Figure Test. Their test was modified very slightly in length and was made up of twenty complex figures plus two additional introductory figures that were used as examples. Students were required to recognize and identify one of the target shapes, which was embedded within each of the complex figures, by tracing its outline with a pen or a pencil. The main scoring scheme for the tests was to give one point for a correct simple shape embedded in a complex figure. The overall sum of the scores is the total mark which a student can gain. Thus, the possible maximum score that could be obtained was 20. A total of 20 minutes were given to complete the test.

The mean score of the Hidden Figure Test of 105 upper secondary schools pupils was 6.6 (minimum = 1, maximum = 17) and the standard deviation was 3.8. Again, correlation was the main method of analysis but, for illustrative purposes, the sample was divided into groups. Different studies have used different cut-offs to classify someone as field-dependent or field-independent (Kepner & Neimark, 1984; Liu & Reed, 1994; Luk, 1998). In this project, the sample will be divided into three groups according to the pupils' mean score and half the standard deviation. This

Table 1. Pearson correlations: cognitive variables and test scores

| Variable | Chemistry test scores |
|---|---|
| Digit Backward test scores | r = 0.31 (p = 0.001) |
| Hidden Figure test scores | r = 0.30 (p = 0.002) |

cut-off divides the whole cohort into three almost equal groups. The three groups were described as:

Field-Dependent (F.D.), Field-Intermediate (F.INT.), and Field-Independent (F.IND.).

- Field-Dependent (F.D.): those who scored less than 4.7
- Field-Intermediate (F.INT.): those who scored between 4.7 and 8.5
- Field-Independent (F.IND.): those who scored more than 8.5

The figures 4.7 and 8.5 are one half of one are standard deviation below and above the mean score respectively (see Appendix).

### *The test*

The same questions were administered to all the pupils. The test was given in four equivalent forms to avoid students' interaction in neighbouring seats. It was based on the mole unit. The time allowed was 45 minutes. The highest possible total marks for the test was 20 and marks were converted to percentages. The mean score of the chemistry test of 105 upper secondary schools pupils was 58.2% (minimum = 5%, maximum = 100%) and the standard deviation was 24.3. An example of part of the test is shown in the Appendix.

## Results

Table 1 presents the correlation between the Digits Backwards Test scores and Hidden Figure Test scores, and pupils' chemistry test scores. As can be seen, the variables correlate significantly with pupils' chemistry scores.

A One Way Analysis of Variance (ANOVA) was carried out to test whether there are differences in pupils' performances between the three working capacity groups. As can be seen from Table 2, there are significant differences in pupils performances between the three working capacity groups (F-ratio: 3.544, p = 0.033).

In addition, a One Way Analysis of Variance (ANOVA) was carried out to test whether there are differences in performance between the three field-dependent groups. As can be seen from Table 3, there are significant differences in pupils performances between the three field-dependent /field-independent groups (F-ratio: 5.031, p = 0.008).

Table 2. ANOVA statistics: working memory capacity and chemistry test performance (groups' performance in chemistry tests [N = 105])

| X-CAP | N | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|---|
| X-CAP ≤ 5 | 50 | 52.5 | 23.3 | 5 | 95 |
| X-CAP = 6 | 27 | 59.4 | 26.1 | 5 | 95 |
| X-CAP ≥ 7 | 28 | 67.3 | 22.2 | 20 | 100 |
| **ANOVA** | | | | | |
| *Chemistry scores* | | | | | |
| | **Sum of squares** | **df** | **Mean square** | **F** | **Sig** |
| Between groups | 3995.774 | 2 | 1997.887 | 3.544 | **0.033** |
| Within groups | 57503.274 | 102 | 563.758 | | |
| Total | 61499.048 | 104 | | | |



The sample of pupils was subdivided according to each pupil's working memory capacity (X-capacity) and field dependency cognitive style. Each group with the same X-capacity was subdivided into three groups by field dependency. It was thought that the field-independent pupils of high X-capacity might achieve better marks in the chemistry test than those who were field-dependent with low X-capacity. A table was constructed for comparison of the three variables: field dependency, working memory capacity and scores in the chemistry test (quoted as %). Table 4 and Figure 2 illustrate the differences between groups in the chemistry test.

Table 4 illustrates that a relationship exists between field dependency, working memory space capacity and the mean scores in the chemistry test. It demonstrates that the X ≤ 5 pupils have not achieved as well in the chemistry test as those considered to be X = 6 or X ≥ 7. There is a steady improvement in the pupils' marks, moving across the table from field-dependence in all X-space groups.

Table 3. ANOVA statistics: field dependency and chemistry test performance (groups' performance in chemistry tests [N = 105])

| FD-CAP | N | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|---|
| F.D. | 36 | 48.9 | 25.2 | 5 | 95 |
| F.INT. | 39 | 60.3 | 23.2 | 5 | 95 |
| F.IND | 30 | 66.8 | 21.5 | 20 | 100 |
| **ANOVA** | | | | | |
| *Chemistry scores* | | | | | |
| | **Sum of squares** | **df** | **Mean square** | **F** | **Sig** |
| Between groups | 5521.889 | 2 | 2760.945 | 5.031 | **0.008** |
| Within groups | 55977.158 | 102 | 548.796 | | |
| Total | 61499.048 | 104 | | | |

Table 4. Summary performance of the different groups

| Group | Field Dependent | | | Field Intermediate | | | Field Independent | | |
|---|---|---|---|---|---|---|---|---|---|
| Working Memory | N | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. |
| X ≤ 5 | 20 | 47 | 22.9 | 16 | 54 | 25.1 | 14 | 59 | 21.3 |
| X = 6 | 6 | 46 | 23.9 | 11 | 60 | 20.4 | 10 | 72 | 22.1 |
| X ≥ 7 | 10 | 59 | 24.5 | 12 | 69 | 22.1 | 6 | 78 | 15.1 |
| Total | 36 | 50 | 23.5 | 39 | 60 | 23.2 | 30 | 67 | 21.5 |



While greatest success in the test is shown for pupils with a high working memory space and high level of field dependence, it is interesting to note the very similar test performances (statistically, not significantly different) for the three groups along the shaded diagonal. It is reasonable to suggest that the field-independent students with Low Working Space have the ability to distinguish the essential information from the irrelevant and they can use their whole (but limited) working space. The field-dependent and High Working Space students do not have this ability and part of their working space is occupied by irrelevant information. Thus, the former and the latter have almost the same effective working memory capacity and therefore similar results in chemistry test. This is consistent with the kind of explanation proposed by Johnstone *et al.* (1993). A possible way to describe this is to suggest that the student's available working memory capacity is about the same for these three groups. This is illustrated in Figure 2.

It is a matter of concern that performance in a chemistry test is so strongly related to certain psychological parameters, control over which is outside of the individual pupil. This observation has been confirmed for tests in biology (Bahar & Hansell, 2000), mathematics (Christou, 2001) and, more recently, in physics (Chen, 2004).

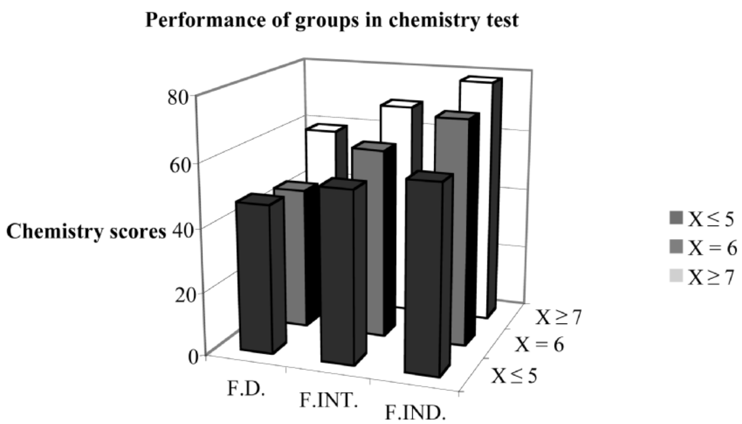



Figure 2. Summary performance of the different groups

## The second stage of the enquiry

The first stage demonstrated that pupil performance is related to their working memory space and extent of field dependency. The purpose of the second stage was to develop an instructional approach to improve students' conceptual understanding of two difficult areas of the syllabus: atomic and bonding theory. The aim in designing this new instructional approach was to minimize learning situations where a high working memory was demanded, thus making the chemistry more accessible for all pupils, irrespective of their working memory space.

The original intention was to repeat the psychological tests with the pupils involved at this stage, but access to these pupils proved difficult, given the over-crowded nature of their curriculum. As a result, it proved impossible to run these tests.

In this study, 211 first year *Lykeio* pupils (aged 15–16 years) were involved. The sample was divided to give a control and an experimental group with each teacher. Three teaching units were developed (covering atomic theory, periodic table and bonding theory). The pupils were tested at the start to define their starting levels of knowledge—this is described later. After the units had been used with the experimental group, the pupils were all tested to look for any significant differences in progress between experimental and control groups. The control groups followed the syllabus in the normal way.

The normal teaching approach in Greek schools is very much based on the use of the prescribed textbook and the use of the blackboard. With the control groups, this procedure was followed as normal. The teaching of the experimental groups was very different, using the new materials with their emphasis on minimizing working memory demand.

### *Features of the new teaching approach*

The new materials employed several features in seeking to make the material more accessible to those with lower working memory spaces. Of course, learning can be made easier if less is taught and less is demanded. This was not done but the material was taught in a more stepwise fashion, with less wordiness, using small workbooks as guides. The aim was to reduce the working memory demand by reducing the amount of material which had to be processed by pupils at the same time. The aim was also to reduce the peripheral information that would act as 'noise' for those who were field-dependent.

The new materials had the following features:

(a) The working memory demand was reduced by presenting the material in a more stepwise fashion;
(b) Dialogue boxes were used to encourage pupils to focus on the essential 'message';
(c) Pictures, analogies and diagrams were introduced carefully, always seeking to reduce information load and to reduce 'noise';

(d) Models were used so that pupils were able to use both verbal and imaginal coding and encourage them to link the symbolic and representation aspects of the teaching material;
(e) The order of presentation of the material was changed in some cases. This was only done when it offered a reduction in working memory demand;
(f) Great care was taken to ensure that the demand on working memory space was kept low by careful structuring of the material with reference to previous knowledge;
(g) Although chunking is difficult to teach as individuals chunk information in idiosyncratic ways, where appropriate, suggestions were offered to enable the learners to bring together information into what might be meaningful units;
(h) Teaching in Greece tends to be lecture orientated, with pupils taking notes. By offering pupils well organized learning materials, the aim was to reduce the need for note-taking, allowing more attention to be paid to the new material. By reducing note-taking, pressure on working memory space was being reduced;
(i) Great care was taken to build on prior knowledge and to allow opportunities for pupils to link new material to material already grasped.

In all of this, the aim was to encourage active learning where the pupils would interact with the material, drawing conclusions, answering questions and completing simple calculations. The aim was to gain understanding and to enable this to happen by minimizing the effects of limited working memory space. These features are now described in turn with reference to examples from the actual teaching units.

As the curriculum programme in Greece is spiral (i.e. the same themes are taught at successive stages, with increasing depth), when students come to upper secondary education, they have already been taught basic concepts such as atomic theory, and the periodic table. Hence it was decided not to repeat the teaching and an active learning approach was designed in the first and second booklet for the topics of atomic theory and periodic table. Thus, in the first booklet students were asked to work in groups and to find out with the help of their textbooks how to connect concepts related to atomic theory. The second booklet was distributed to the students accompanied by a copy of the periodic table showing the usage of each element. Students were asked to answer questions. All of this sought to encourage an active learning approach. Of course, it could be argued that the use of group work is not parallel to normal teaching approaches although group work can be used in these. However, group work was chosen deliberately as it can reduce the problems arising from limited working memory space. In a small group, pupils are using the working memory spaces of all members, thus reducing the dependence on the working memory space of an individual (Reid & Yang, 2002). Another major feature was the use of models as analogies, particularly in developing the ideas of atomic structure and bonding. Some examples of these 'simple' models are described below.

(a) In order to explain how electrons surround the nucleus of an atom, an analogy of multi-storey flats was used, borrowed from Johnstone and Morrison (1966).

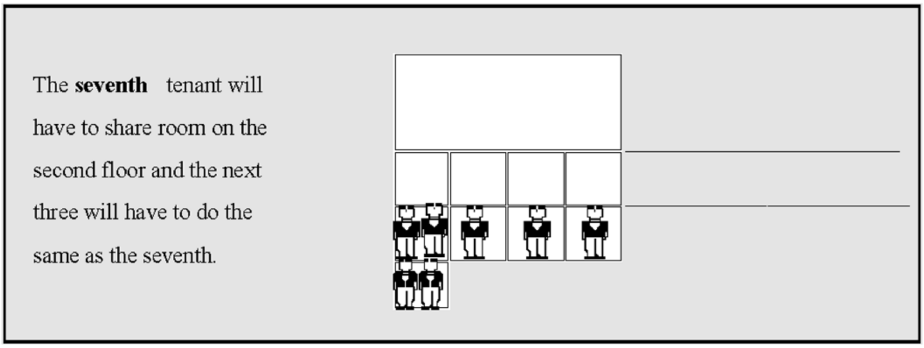



Figure 3. An example using multi-storey analogy to show how electrons surround the nucleus of an atom



This idea is shown in Figure 3. The idea of compartments that look sausage-shaped was used to explain the electron pair clouds and consequently the idea of the orbital.

(b) To illustrate how atoms join together so that their single electrons share a cloud and form molecules in the covalent bond, a demonstration with balloons is suggested. An example of this demonstration showing how nitrogen atoms combine to form molecules is shown in Figure 4.

(c) To explain the ideal geometries for two to six electron pairs, and to find out how electron pair clouds surrounding the central atom are oriented with respect to one another, teachers are instructed to carry out a demonstration with balloons as shown in Figure 5, following an idea borrowed from Masterton and Hurley (1989). Here the position taken naturally by two to six balloons tied together at the centre is shown. The balloons, like the electron pair clouds they represent, arrange themselves so that they are as far from one another as possible.

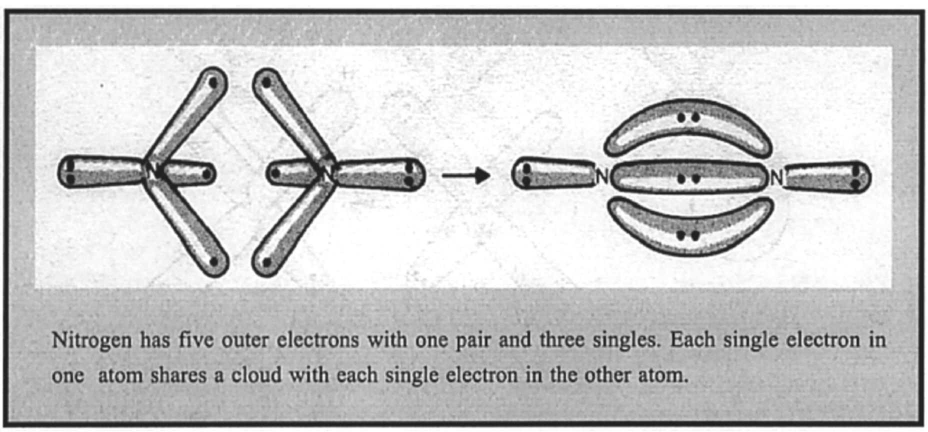



Figure 4. An example using balloon analogy to show how nitrogen atoms combine to form molecules

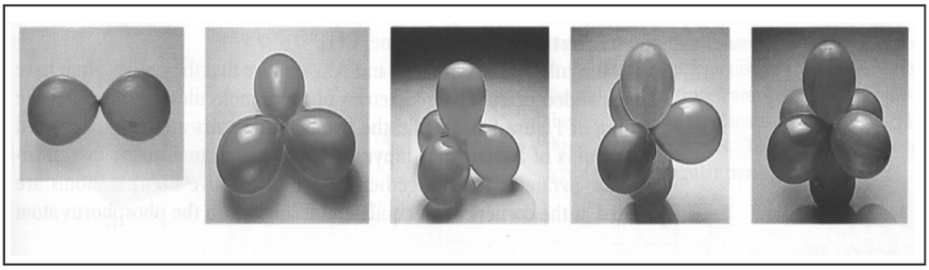


Figure 5. An example using balloons to show the geometry of the electron pairs

In most textbooks in secondary education, bonding theory starts first with the ionic bond and then the covalent bond. In the new teaching material, this syllabus order was changed. Time was spent at the start to represent and explain the way that the outer shell's electrons might position themselves around the nucleus: two electrons moving as far apart as possible, three at the corners of a triangle, four at the corners of a tetrahedron and so on. Balloon models were used to illustrate this (an example can be seen in Figure 5). In this, no abstract ideas were invoked but the shape of covalently bonded molecules was shown to arise simply from the way geometry works and the repulsion of electrons on each other. Covalent bonds were then shown to arise naturally as a pair of electrons was attracted to two adjacent nuclei. The pupils were then taken through examples using balloon illustrations and then gently introduced to the use of lines and pairs of dots to represent bonds between atoms. In turn, this was shown to lead to molecular formulae. Hydrogen was shown first, then oxygen and nitrogen.

At that stage, the idea of the electrons held between two nuclei not being attracted equally by the two nuclei was introduced. This was related to the first row of eight elements of the periodic table, showing why there is an increase in electron attraction moving across the period. Simple molecules with polar covalent bonds were then used to illustrate the idea, using balloon models and ball and stick models. Only at this stage was the idea introduced that there is a possibility of the electron sharing being so unequal that ions might form. This description illustrates the way the ideas were introduced in such a way that working memory demand was minimized.

The first stage of the enquiry showed that working memory space is a critical factor. Because of this, the new materials were carefully designed to enable the learners to work within the limitations of working memory space. The aim was to see whether it was possible to improve performance if the teaching approach deliberately tried to avoid working memory overload.

## *Experimental design*

Four chemistry teachers in four different schools of the first year in upper secondary schools (*Lykeio*) participated in this study. They were all from typical high schools

Table 5. Pupils' performance in pretest and post-test in chemistry

| Groups | Pretest | | Post-test | | Improvement in performance |
|---|---|---|---|---|---|
| | *Mean* | *Standard Deviation* | *Mean* | *Standard Deviation* | |
| Control | 7.8 | 3.9 | 10.4 | 4.5 | 13% |
| Experimental | 6.1 | 3.3 | 10.5 | 4.3 | 22% |

located in urban areas. In these schools, students are from families representing a broad range of socio-economic backgrounds. There were 11 classes involved, with a control group of 112 pupils (six classes) and an experimental group of 99 (five classes). The same teachers taught control and experimental groups.

At the start, a pretest was applied to check whether there were many differences between control and experimental groups based on previous learning, before the teaching procedure commenced. This pretest was based on the material taught in previous years when simple ideas had been established relating to atoms, molecules, the periodic table and bonding. After the units had been used with the experimental group, the pupils were all tested (based on questions normally used by the schools) to look for any significant differences in progress between experimental and control groups. The control groups followed the syllabus in the normal way (lecture, chalk-and-talk, note-taking) while the experimental groups only completed the new units. For both tests, the highest possible total was 20.

It was important to see whether there was any significant difference in the *improvement* between the two groups, where improvement is defined as the difference between post-test and pretest. This is shown in Table 5.

Of course, it is possible that the difference might be due to the effect of the teacher. To check this, the follow comparisons were made:

- Average improvement related to teaching method;
- Average improvement related to teacher;
- Average improvement related to teaching method, teacher and the interaction effect between method and teacher; and
- Average improvement related to teaching method and teacher, without the interaction effect between method and teacher.

## Statistical analyses

A One Way Analysis of Variance (ANOVA) was carried out and it was found that there was a significant difference in the improvement between the experimental and control group in favour of the experimental group ($p = 0.002$). This is shown in Table 6.

A One Way Analysis of Variance was carried out to examine whether there was any significant difference in the improvement in each school due to a teacher effect.

Table 6. ANOVA results for the improvement versus teaching methods

**One-Way Analysis of Variance**

Analysis of variance on improvement

| **Source** | **Df** | **SS** | **MS** | **F** | **p** |
|---|---|---|---|---|---|
| Treatment | 1 | 157.4 | 157.4 | 9.87 | **0.002** |
| Error | 209 | 3331.2 | 15.9 | | |
| Total | 210 | 3488.6 | | | |

| **Level** | **N** | **Mean** | **StDev** |
|---|---|---|---|
| 1 | 112 | 2.686 | 3.671 |
| 2 | 99 | 4.416 | 4.328 |

It was found that there was significant difference in the improvement between each school due to different teachers (p = 0.007), shown in Table 7.

Since the above analysis shows that there was significant difference in the improvement between each school due to different teacher, another statistical analysis was carried out to examine whether there was any significant difference in the improvement for each group (experimental and control) due to the interaction effect between teacher and teaching method. To check these, a General Linear Model Analysis was carried out. (This model was carried out because the size of the sample of each group is not the same.)

From the results of the General Linear Model Analysis, it was found that there was no interaction between teaching method and teacher (not significant, p = 0.063) but there was significant difference in the average improvement between the experimental and the control group without the effect of the teacher (p = 0.011). The full analysis is shown in the Appendix.

Table 7. ANOVA results for the improvement versus teachers

**One-Way Analysis of Variance**

Analysis of variance on improvement

| **Source** | **DF** | **SS** | **MS** | **F** | **p** |
|---|---|---|---|---|---|
| Teacher | 3 | 199.3 | 66.4 | 4.18 | **0.007** |
| Error | 207 | 3289.3 | 15.9 | | |
| Total | 210 | 3488.6 | | | |

| **Level** | **N** | **Mean** | **StDev** |
|---|---|---|---|
| 3 | 88 | 3.877 | 4.489 |
| 4 | 52 | 4.588 | 3.048 |
| 5 | 30 | 2.673 | 2.743 |
| 6 | 41 | 1.902 | 4.594 |

Thus, the results of the second stage of this study reveal that the average improvement in learning of the experimental group was better than the average improvement of the control group. This was not being caused by an interaction between the materials and the teachers involved. It is likely that the changes made to the teaching material had this impact.

## Findings and general conclusions

Looking at the enquiry overall, the following conclusions may be drawn:

1. A relationship exists between working memory capacity and pupils' performance. This was shown in terms of a statistically highly significant correlation ($r = 0.31$). It was illustrated by looking at three groups of pupils: thus, high working memory capacity pupils performed better in the chemistry test than intermediate working space memory capacity pupils, and intermediate working space memory capacity pupils performed better in chemistry test than low working space memory capacity counterparts. When a test question makes a demand (in terms of information which has to be handled at the same time) greater than a pupil's working memory capacity, performance drops markedly.
2. A relationship exists between extent of field dependency and chemistry scores. This was also shown by a highly significant correlation ($r = 0.30$). Performance in the chemistry test improved as the pupils went from being field-dependent to field-independent and this was illustrated by looking at three groups of pupils. If field dependency is a measure of the ability to separate the 'message' from the 'noise', then pupils who are field-independent (high in this ability) have an advantage in not overloading their working memory with excessive information.
3. It is possible to bring working memory and field dependency measurements together. The first offers a measure of working memory capacity while the latter offers a measure of efficiency in using that working memory space. High working space memory capacity and field-independent pupils scored better in the chemistry than those who were field-dependent and of low working space memory capacity. However, there was no difference between low working space memory capacity/field-independent pupils, intermediate working space memory capacity/field-intermediate pupils and high working memory capacity/field-dependent pupils. It is possible to interpret this in terms of efficient use of working memory being able to compensate for low capacity.
4. It is postulated that the size of the *available* working memory space is a critical factor in success in learning chemistry at this stage. If a working memory is cluttered with excessive (and unnecessary) information, then ability to cope with chemical questions is diminished.
5. Using teaching materials which were specifically designed to minimize the impact of limitations in working memory space increased pupil performance. These materials were designed in the light of predictions suggested by an information processing model and every feature sought to minimize the demands on working

memory. This was done firstly by re-designing learning situations so that the actual demand on working memory was lessened. It is important to note that this is not the same as making things easy. The chemistry to be taught was *not* altered; the *way* it was to be taught was re-structured. Secondly, strategies were adopted to encourage the learners to focus on the essentials without being overloaded with excessive (and unnecessary) information. The aim was to enable pupils to use their working memory efficiently.

6. When the re-designed materials were used in several topics, it was found that they enhanced pupil performance significantly and the impact of the new materials did not depend on any teacher effects.

This work has shown that certain psychological factors (working memory space and extent of field dependency) are related to performance in chemistry. It has also shown that re-designing some curriculum materials and teaching strategy in line with the predictions about learning derived from an information processing model improves performance. The key is to think in terms of psychological factors for pupils learning chemistry.

Chemistry is, by its very nature, highly conceptual. To grasp concepts frequently requires the holding and use of quite large amounts of information. This places the working memory, with its fixed capacity, under some strain. Assessment which demands the handling of information in this way will always favour those with a high working memory capacity.

In looking at teaching and learning, if learners are to cope with many of the high information themes in chemistry (like atomic theory, bonding, periodic table, the mole, organic, polymerization and so on), it is essential that the material is presented in such a way that working memory demand is minimized and learners are enabled to focus on the essentials without being overloaded with the peripheral.

In light of these results, it is recommended that the design and delivery of school chemistry courses should take into account the predictions from information processing models derived from the psychology of learning and that such changes will bring about improved performance. This may involve changing the order of presentation and method of presentation. It may involve the careful use of appropriate analogy and models (remembering that not all analogies or models will bring about information reduction). It may mean a more careful linking of new material to previous knowledge and a deliberate effort in flagging up what is important and what is peripheral.

Of course, the ideas used here in re-structuring the teaching presentation are not in themselves new. They were gleaned from many sources. What is new is the choice of teaching presentation specifically to reduce working memory demand and to focus strongly on essentials. Performance has been shown to improve. This offers one basis for deciding predictively whether a particular teaching presentation is likely to be helpful.

If assessment is to be fair for all pupils, it should not unnecessarily penalize those who happen to have lower working memory spaces and those who tend to be field-dependent. Working memory space is fixed for an individual although there is some evidence that extent of field independency can be enhanced. This can be achieved by a small group of 'experts' looking at questions and assessing the working memory demand. Again, it has to be stressed that this is not the same as difficulty. However, if assessment is to be fair, it must not require working memory capacities that favour some learners more than others.

Further work needs to be carried out to explore whether the benefits of the approach adopted here bring specific benefits to those with lower working memory spaces and those who are more field-dependent. It had been the intention of this research to check if this was so, but access to the pupils in the second part of the work to measure working memory space proved impossible. That experiment is an exciting one waiting to be completed.



## References

Al-Naeme, F. & Johnstone, A. H. (1991) Room for scientific thought? *International Journal of Science Education*, 13, 187–192.

Anderson, B. R. (1990) Pupils' conceptions of matter and its transformation on classroom activities (age 12–16), *Studies in Science Education*, 18, 53–85.

Atkinson, R. & Schiffrin, R. (1971) The control of short-term memory, *Scientific American*, 225, 82–90.

Baddeley, A. D. (1986) *Working memory* (Oxford, Oxford University Press).

Bahar, M. & Hansell, M. (2000) The relationship between some psychological factors and their effects on the performance of Grid Questions and Word Association Tests, *Educational Psychology: An International Journal of Experimental Educational Psychology*, 20, 349–363.

Berger, E. & Golberger, L. (1979) Field dependence and short-term memory, *Perceptual and Motor Skills*, 49, 87–96.

Bodner, G. M. (1991) I have found you an argument, *Journal of Chemical Education*, 68(5), 385–388.

Brunning, R. H., Schraw, G. J. & Ronning, R. R. (1995) *Cognitive psychology and instruction* (2nd edn) (Upper Saddle River, NJ, Prentice-Hall).

Burton, E. & Sinatra, R. (1984) Relationship of cognitive style and word type for beginning readers, *Reading World*, 24, 65–67.

Chen, W-C. (2004) *An analysis of pupil difficulties in physics in relation to working memory space*, M.Sc. Thesis, University of Glasgow, UK.

Christou, K. (2001) *Difficulties in solving algebra story problems with secondary pupils*, M.Sc. Thesis, University of Glasgow, UK.

Fleming, A. (1998) National Curriculum review— what future for chemistry to age 16? *The School Science Review*, 291, 29–33.

Furio, C., Azcona, R., Guisasola Z. & Ratcliffe M. (2000) Difficulties in teaching the concepts of amount of substance and mole, *International Journal of Science Education*, 22(12), 1285–1304.

Gabel, D. (1993) Use of the particle nature of matter in developing conceptual understanding, *Journal of Chemical Education*, 70(3), 193–194.

Gabel, D. (1999) Improving teaching and learning through chemistry education research: a look to the future, *Journal of Chemical Education*, 76(4), 548–553.

Garnett, P. J., Garnett, P. J. & Hackling, M. W. (1995) Students' alternative conceptions in chemistry: a review of research and implications for teaching and learning, *Studies in Science Education*, 25, 69–95.

Georgiadou, A. & Tsaparlis, G. (2000) Chemistry teaching in lower secondary school with methods based on: a) psychological theories; b) the macro, representational, and submicro levels of chemistry, *Chemistry Education: Research and Practice in Europe*, 1(2), 217–226.
Goodenough, D. R. (1976) The role of individual differences in field dependence as a factor in learning and memory, *Psychological Bulletin*, 83, 675–694.
Jacobs, J. (1987) Experiments in prehension, *Mind*, 12, 75–79.
Johnstone, A. H. (1991) Why science is difficult to learn? Things are seldom what they seem, *Journal of Computer Assisted Learning*, 7, 75–83.
Johnstone, A. H. (1993) The development of chemistry teaching: a changing response to changing demand, *Journal of Chemical Education*, 70(9), 701–705.
Johnstone, A. H. (1997) And some fell on good ground, *University Chemistry Education*, 1(1), 8–13.
Johnstone, A. H. (1999) The nature of chemistry, *Education in Chemistry*, 36(2), 45–48.
Johnstone, A. H. (2000) Teaching of chemistry—logical or psychological? *Chemistry Education: Research and Practice in Europe*, 1(1), 9–15.
Johnstone, A. H. & El-Banna, H. (1986) Capacities, demands and processes: a predictive model for science education, *Education in Chemistry*, 23(3), 80–84.
Johnstone, A. H. & Morrison, T. I. (1966) *Chemistry takes shape, Book 1* (London, Heinemann Education Books).
Johnstone, A. H. & Selepeng, D. (2001) A language problem revisited, *Chemistry Education: Research and Practice in Europe*, 2(1), 19–29.
Kepner, M. D. & Neimark, E. D. (1984) Test-retest reliability and differential patterns of score change on the group embedded figures test, *Journal of Personality and Social Psychology*, 46(6), 1405–1413.
Lee, K.-W., Tang, W.-U., Goh, N.-K. & Chia L.-S. (2001) The predicting role of cognitive variables in problem solving in mole concept, *Chemistry Education: Research and Practice in Europe*, 2(3), 285–301.
Liu, M. & Reed, W. M. (1994) The relationship between the learning strategies and learning styles in a hypermedia environment, *Computers in Human Behavior*, 10(4), 419–439.
Luk, S. C. (1998) The relationship between cognitive style and academic achievement, *British Journal of Educational Psychology*, 29(2), 137–147.
Masterton, W. L. & Hurley, C. N. (1989) *Chemistry: principles and reactions, International Edition* (Florida, Saunders College Publishing).
Messick, S. (1994) The matter of style: manifestations of personality in cognition, learning, and teaching, *Educational Psychologist*, 29, 121–136.
Miller, G. D. (1956) The magical number seven plus or minus two: some limits on our capacity for processing information, *Psychological Review*, 63, 81–97.
Nakhleh, M. B. (1992) Why some students don't learn chemistry, *Journal of Chemical Education*, 69(3), 191–196.
Niaz, M. (1988) The information-processing demand of chemistry problems and its relation to Pascual-Leone's functional M-space, *International Journal of Science Education*, 10(2), 231–238.
Niaz, M. (1989) Relation between Pascual-Leone's structural and functional M-space and its effect on problem solving in chemistry, *International Journal of Science Education*, 11(1), 93–99.
Nurrenberg, S. & Pickering, M. (1987) Concept learning versus problem solving: is there a difference? *Journal of Chemical Education*, 64, 508–510.
Oakhill, J. (1988) The development of children's reasoning ability: information processing approaches, in: K. Richardson & S. Sheldon (Eds) *Cognitive development to adolescence* (London, Lawrence Erlbaum Associates in association with the Open University).
Osborne, R. J. & Cosgrove, M. M. (1983) Children's conceptions of the changes of state of water, *Journal of Research in Science Teaching*, 20(9), 825–838.

Pascual-Leone, J. (1970) A mathematical model for the transition rule in Piaget's Development Stages, *Acta Psychological*, 32, 301–345.

Poollitt, A., Marriott, C. & Ahmed, A. (2000) *Language, contextual and cultural constraints on examination performance*, paper presented at the International Association for Educational Assessment, Jerusalem, Israel. Available online at: http://www.ucles-red.cam.ac.uk/conferencepapers.htm (accessed 11 October 2004).

Reid, N. (2000) The presentation of chemistry—logically driven or applications-led? *Chemistry Education: Research and Practice in Europe*, 3, 381–392.

Reid, N. & Yang, M-J. (2002) Open-ended problem solving in school chemistry: a preliminary investigation, *International Journal of Science Education*, 24(12), 1213–1332.

Sawrey, B. A. (1990) Concept learning problem solving: revisited, *Journal of Chemical Education*, 67(3), 253–254.

Sutherland, P. (1992) *Cognitive development today: Piaget and his critics* (London, Paul Chapman Publishing Ltd).

Tinajero, C. & Paramo, F. M. (1998) Field dependence-independence cognitive style and academic achievement: a review of research and theory, *European Journal of Psychology of Education*, 13(2), 227–251.

Tsaparlis, G. (1991) S.O.S. from lower secondary chemistry (in Greek), *Chemica Chronica (General Edition)*, 53(4), 111.

Tsaparlis, G. (1994) S.O.S. from lower secondary chemistry (in Greek), in: *Proceeding of the 4th Greece-Cyprus Conference* (Ioannina, Association of Greece Chemists), 135–140.

White, R. (1998) *Learning science* (Oxford, Basil Blackwell).

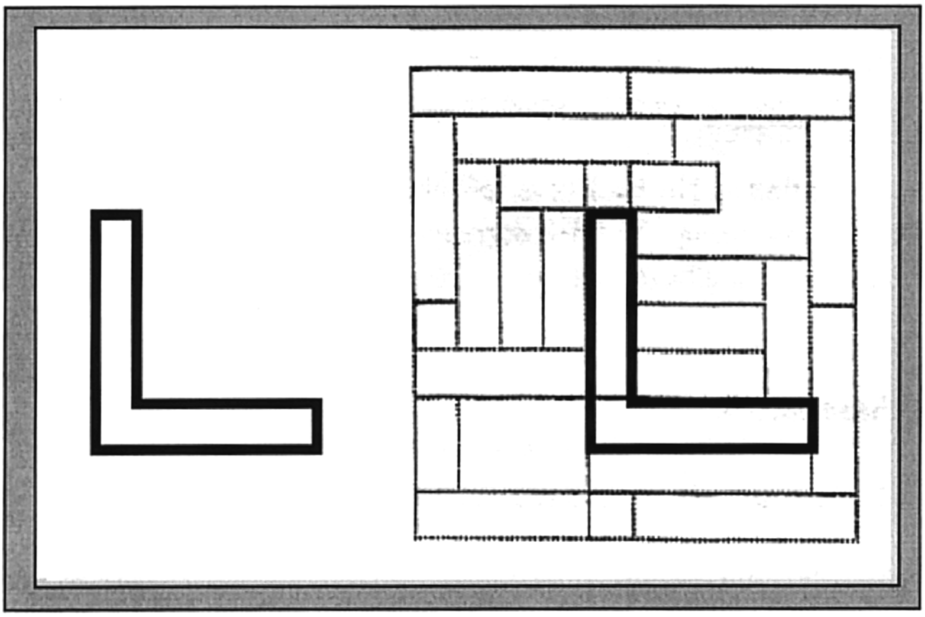
Witkin, H. A. (1977) *Cognitive styles in personal and cultural adaptation* (Worcester, MA, Clark University Press).

Witkin, H. A., Goodenough, D. R., Moore, C. A. & Cox, P. W. (1977) Field-dependent and field-independent cognitive styles and their educational implications, *Review of Educational Research*, 47(1), 1–64.

Witkin, H. A. & Goodenough, D. R. (1981) *Cognitive styles: essence and origins field dependence and field independence* (New York, International University Press).

## Appendix

(1) Example of an item from the Hidden Figure Test



(2) Typical question from the Chemistry Test

Each box contains either an acid or an alkali.

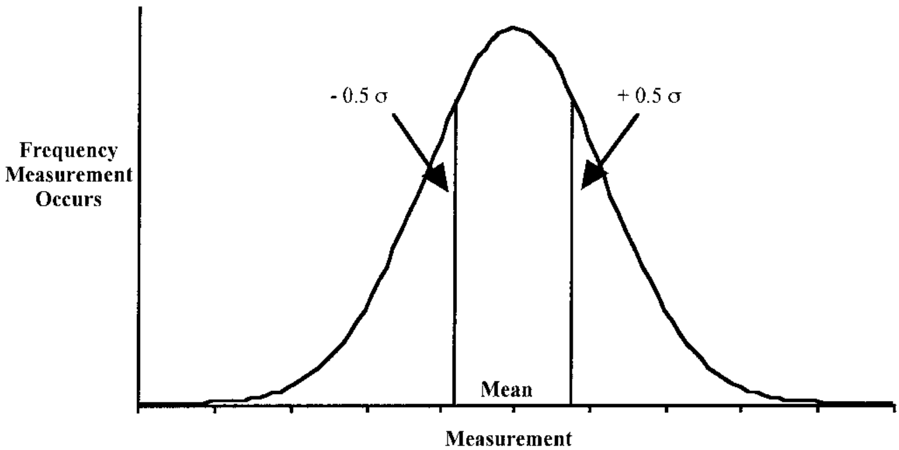
| | | |
|---|---|---|
| 20g NaOH<br>**A** | 2 moles $HNO_3$ in 2L of solution<br>**B** | 80g NaOH<br>**C** |
| 250 mL $H_2SO_4$<br>**D** | 500 mL of 1M NaOH solution<br>**E** | 500 mL of 2M NaOH solution<br>**E** |

1. What is the molarity of the acid in box B.
2. Calculate the number of moles of each acid or alkali present in each box.
3. Pick out the boxes where the substance would exactly neutralize the contents of box C.

Relative atomic masses of the elements are:

Na = 23 O = 16 H = 1 S = 32

(3) Dividing a sample into three roughly equal parts




The area under a typical normal distribution is divided into three:

Those above Mean + 0.5 standard deviation
Those between Mean + 0.5 standard deviation and Mean − 0.5 standard deviation
Those below Mean − 0.5 standard deviation

The three areas in a perfect normal distribution are approximately each one third of the total area under the curve.
This offers a convenient way to divide a normally distributed sample into three roughly equal parts.

(4) General Linear Model
Average improvement versus method; teacher; and interaction between method and teacher.

| Factor | Type | Levels | Values |
|---|---|---|---|
| Group | fixed | 2 | C E |
| Teacher | fixed | 4 | 1 2 3 4 |

Analysis of variance for improvement, using adjusted SS for tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | p |
|---|---|---|---|---|---|---|
| Group | 1 | 157.36 | 51.15 | 51.15 | 3.38 | **0.068** |
| Teacher | 3 | 144.83 | 215.23 | 71.74 | 4.74 | **0.003** |
| Group*Teacher | 3 | 112.31 | 112.31 | 37.44 | 2.47 | **0.063** |
| Error | 203 | 3074.09 | 3074.09 | 15.14 | | |
| Total | 210 | 3488.59 | | | | |

General Linear Model: average improvement versus method and teacher without the interaction effect

| Factor | Levels | Values |
|---|---|---|
| Method | 2 | 1 2 |
| Teacher | 4 | 3 4 5 6 |

Analysis of variance for improvement

| Source | DF | Seq SS | Adj SS | Adj MS | F | p |
|---|---|---|---|---|---|---|
| Method | 1 | 157.36 | 102.91 | 102.91 | 6.65 | **0.011** |
| Teacher | 3 | 144.83 | 144.83 | 48.28 | 3.12 | **0.027** |
| Error | 206 | 3186.40 | 3186.40 | 15.47 | | |
| Total | 210 | 3488.59 | | | | |