Investigating students' success in solving and attitudes towards context-rich open-ended problems in chemistry

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Much research has been carried out on how students solve algorithmic and structured problems in chemistry. This study is concerned with how students solve open-ended, ill-defined problems in chemistry. Over 200 undergraduate chemistry students solved a number of open-ended problem in groups and individually. The three cognitive variables of working memory, M capacity and field dependence-independence were measured. A pre and post activity attitudes questionnaire was administered. The results show that there is a difference between the cognitive variables required for success in traditional algorithmic problems and open-ended problems. The context-rich open-ended problems significantly shifted students' attitudes towards problem solving.

Keywords: problem solving, open-ended problems, cognitive style, attitudes

Introduction

In current economic context the new graduate has to be equipped with the intellectual and personal skills needed to succeed in a rapidly changing professional and cultural environment. Employers have long been encouraging Higher Education to produce graduates with the ability to solve novel problems, to communicate effectively, work as part of a team, handle complex data, and many more personal skills (Mason, 1998). In a recent study, graduates two years after university identified that, whilst their chemical education had been comprehensive in terms of knowledge, they were ill-prepared for the world of work in terms of transferable skills (Hanson and Overton, 2010). Complex, open-ended problem solving activities, such as those tackled through problem-based learning have been demonstrated to develop this wide range of transferable skills (Duch *et al.*, 2001). There have been several successful implementations of such activities in chemistry (Belt *et al.*, 2002, 2005; Summerfield *et al*., 2003; Grant *et al*., 2006). However, these activities are usually carried out as group activities and individual students' abilities in tackling open-ended activities are seldom evaluated.

Much research has been undertaken into the factors that affect problem solving (Reid, 2002). Gabel and Bunce (1994) proposed that the factors affecting students' success in problem solving are threefold: the type of problem and the underlying concepts of the problem; the learner characteristics, including cognitive styles, developmental levels and knowledge base; and, learning environment factors, including problem solving strategies or methods, individual or group activity.

A model that has been used for many years in science education is the Information Processing Model, which has been described elsewhere (Atkinson and Shiffrin, 1968). The key feature of the Information Processing model, which is a recurring theme in research into cognitive styles, is working memory space (WMS), previously called short term memory. Baddeley and Hitch (1974) suggested that the working memory is a multi-component system comprising the central executive, which is responsible for integrating information, the phonological loop, which handles linguistic information, and the visuo-spatial sketchpad, which handles visual and spatial information. Working memory is thought to have a fixed capacity that can hold only a limited number of pieces of information. This was described as long ago as 1955 by Miller, who proposed that working memory can only hold seven plus or minus two pieces of information.

The working memory is where new information from the outside world and information retrieved from long term memory is held and processed. The size of the working memory is therefore a major determining factor in learning and problem solving (Kirschner *et al*., 2006). To reduce the part of working memory space used for holding information, and thus allow more space available for processing, the use of schema or chunking occurs. Schema (Anderson, 1977) is a term used in psychology to describe a mental framework that enables information to be organized and processed. In terms of problem solving, schema can be used to break down a complex problem into a number of smaller, familiar problem solving routines. Chunking (Miller, 1955) refers to a strategy used to make more efficient use of working memory. Chunking enables large amounts of information to be collapsed into a smaller number of chunks. For example, most people would not try to remember a mobile phone number (such as 07545688394) as eleven pieces of information but would break it down into smaller chunks (such as 075....456...etc). Chunking occurs with greater familiarity with the information such as an expert would have. As educators we chunk information constantly, whereas our students may not have yet learned the same strategies. Without the effective use of schemas or chunking, the working memory becomes

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overloaded and cognitive overload occurs. Academics can help avoid cognitive overload by careful design of teaching activities, such as problems. Strategies include presenting required prior knowledge before presenting the problem, removing 'noise' from the problem, by scaffolding learning, by breaking down the problem into smaller steps, and by using 'fading' which moves students gradually from worked examples to solving problems.(Paas *et al.*, 2003).

In group work, the group can take advantage of the availability of the individual working memory spaces of the members of the group. This can minimise the effect of limited working memory space (Reid, 2002). Many studies have concluded that co-operative problem solving has lead to greater success (Tingle and Good, 1990; Qin, 1995). Such group work can also help overcome misconceptions by sharing information, exchanging experiences and ideas (Basili, 1991). Tingle and Good studied 178 high school students in chemistry, and provided further evidence that students were able to teach each other by using models and analogies and asking questions during group discussion. Success in problem solving may increase as a result of this (Pascual-Leone, 1978).

M-Capacity is analogous to working memory and is defined as the mental-attentional energy available for a particular task (Pascual-Leone, 1978). It has also been termed M-power, the power of a person's mental concentration mechanism (Niaz, 1988). M-capacity can be broken down into structural M-capacity (Ms), the total available M-capacity and functional M-capacity (Mf), the amount of M-capacity that is actually used. For those with high processing capability Mf is said to be close to Ms and those with low processing capability Mf is much lower than Ms. As with the information processing model, the M-capacity of a person is a determining factor in problem solving.

Another cognitive style variable is field dependence/field independence (Witkin et al, 1977). It is sometimes referred to as global vs. analytical thinking. Field Dependence/Independence is a determining factor in academic achievement. A field dependent subject processes information globally, sees a problem as a whole and has difficulty analysing or deconstructing it and has difficulty separating relevant information from irrelevant information or 'signal from noise'. A field dependent student will be processing both signal and noise and will therefore be using more functional M-capacity (Mf) than a field independent student who will process only signal. A field independent subject is more analytical, can deconstruct information and is not influenced by the perceptual field or context. Field dependent subjects need more explicit instructions than field independent subjects when material is disorganized or instructions are not explicit (Frank and Davis, 1982).

Many studies have focused on the effect of these cognitive styles on academic achievement (Reid and Yang, 2002; Danili and Reid, 2006). Such studies have found students with higher working memory capacities and students who are field independent will perform better that those with lower working memory capacities and students who are field dependent, respectively. Tinajero and Paramo (1997) even found that students in subjects considered to be strong subjects for a field dependent style preformed worse than their field independent counterparts. There have been several studies that have investigated the influence of these cognitive styles on student success in algorithmic or structured problem solving in chemistry. Johnstone and El Banna (1986) reported a correlation between working memory capacity and scores in problem solving. Tsaparlis (2005) reported a correlation between functional M-capacity and non-algorithmic problem solving scores. He also found that the working memory model worked best for field independent subjects and that working memory overload was more marked in field dependent subjects. It would seem reasonable to assume that there is some relationship between working memory capacity and field dependence as field dependent subjects find it difficult to move from the global view and deconstruct information. Johnstone (1993) found such a relationship in a study of problem solving in physics.

Marton (1976) identified two types of information processing; deep and surface processing. Deep processing occurred when students understood the meaning of what they were learning, and was associated with high scores on tests. Surface processing occurred when students merely memorised what they were studying, and was associated with poor test scores. Coles (1990) identified elaborated learning as being even more effective than deep processing. Students who see the interconnections and links between different knowledge areas gained the highest scores in examinations that tested that knowledge, and were more able to retrieve and use the information they have learnt. Coles saw context as essential for elaborated learning. For elaborated learning to occur, students benefit from being able to relate what they need to know to past experiences and prior knowledge. Rogers (1960) said that context provides a motivating force through which the student develops a wish to know more (wants rather than needs to learn something).

Obviously, solving chemistry problems requires a good knowledge of chemistry (Frazer 1982). However, problem solving in many cases has been unsuccessful even when students possessed most of the requisite knowledge (Sumfleth, 1988, 1992; Adigwe, 1993; Lee *et al.*, 1996). Students with a basic knowledge of chemical terms did not recognize the relationships between concepts, and therefore were unable to apply their knowledge (Shaibu, 1992). In arguing the case for teaching chemistry in context, Hills (2003) identified the fact that most current scientific knowledge is explicit, *i.e.* factual precise data, presented in the form of machine-readable symbols, text and images. Epistemology classifies two types of knowledge, explicit knowledge and implicit knowledge. Hills called explicit knowledge the 'know-what' and implicit knowledge the 'know-how'. He claimed that implicit knowledge is generally ignored in science, and students are only examined on their explicit knowledge, yet 'know how' is clearly more important than 'know what'.

Many context-based courses have been evaluated, including those involving discipline-related activities (Bailey, 1997), discipline independent courses (Wyeth, 1997), and problem-based case studies in chemistry (Garratt *et al*., 1987, Pontin *et al*., 1993). More recently, studies within the sub-disciplines of chemistry: organic (Bennett, 2001), inorganic (Overton and Belt, 2005), and physical chemistry (Holman and Pilling, 2004; Belt, 2005) and subjects allied to chemistry, such as biochemistry (Cornely, 1998) and environmental science (Breslin *et al*., 2001) have also been described. Problem-based approaches in laboratory work are also gaining in popularity (McGarvey, 2004).

Hayes (1981) stated *"Whenever there is a gap between where you are now and where you want to be and you don't know how to find a way to cross that gap, you have a problem"*. Problem solving is something encountered in all aspects of life (Yang, 2002). It is a skill that, for many, is the defining graduate attribute, and we must ensure that graduates are well prepared for employment with sound problem solving skills. Developing problem solving skills has been the subject of much research into science education (AAAS, 1993; Zoller, 1999; NRC, 2003; Barak and Dori, 2005). The types of problems set in examinations or assessments in higher education chemistry are largely algorithmic (Bennett, 2004). Algorithmic problems use mainly lower order cognitive skills (LOCS), whereas more open ended problems call upon higher order cognitive skills (HOCS) (Zoller, 1999). Problems requiring the application of HOCS demand more than just knowledge to reach a solution. Knowledge or known theory must be applied in unfamiliar contexts using such skills as analysis, connection making, synthesis and critical thinking. Johnstone (1993) classified eight types of problem according to the amount of data given, familiarity of the methods and openness of the outcome. A problem of type 1 requires only the recall of algorithms and application of the problem to that algorithm. Type 8 problems are the most open ended and more like the types of problems that may be found in the workplace or academic research.

Inevitably, the introduction of problem solving as a new and unfamiliar way of learning will encounter resistance at first. This can be attributed to the problems of assimilation and accommodation identified by Piaget (1969, 1972). As Herron (1978) said *"everyone reverts to concrete operational thought when they encounter something new"*. In Perry's scheme for intellectual development (1970) the highest of the nine levels of development links challenges to commitment; when there are challenges to commitment, subjects retreat to a 'safer', lower position. Setting more challenging problems will enable the development of HOCS, and allow students to overcome those challenges and solve more open ended problems. This approach will help student's progression through the stages of intellectual development.

Berg (2005) stated *"If university teachers are asked, what is the most important student characteristic associated with successful studies, they usually mention traits such as attitude, motivation, and genuine interest."* Much of the work done in assessing student attitudes and motivation originates from Perry's work. Moore (1994) found that very few students reach the higher Perry levels concerned with elaboration of identity and commitment. Through pre and post course attitude questionnaires, Berg found that several students displayed significant changes in attitude towards learning chemistry, both positive and negative. In the Berg study the students with the largest shifts in attitude, positive and negative, were interviewed in order to determine the reasons behind these shifts. Interview questions explored the students' background, their experience of their first semester at university and any further thoughts on the discussion of those topics. The study found that students with a positive attitude shift displayed more motivated behaviour and students with a negative attitude displayed the opposite.

The aim of this study was to develop some context-rich, open-ended problems of the Johnstone Type 8 and to investigate whether the three cognitive variables, working memory capacity, M capacity and field dependence/independence, had any influence on student success in solving open-ended problems. Students' attitudes to open-ended *vs* algorithmic problems were also investigated.

Methodology

Problem solving

A number of context-based, open-ended problems were developed by the authors using real life contexts or engaging scenarios. It was intended that the problems would be of varying degrees of difficulty (Johnstone and El-Banna, 1986; Niaz , 1988), be designed to develop the higher order cognitive skills, such as critical reading, problem solving, critical thinking, decision making, evaluation, *etc*. (Overton, 2001), and begin with a real life context to provide greater motivation to reach a solution. (Rogers, 1960; Ramsden, 1984; Coles, 1990). The problems were designed to enable individuals or small groups to reach a solution in 20-30 minutes. Several problems were based on real industrial problems previously tackled by one of the authors. Care was taken to ensure that the context did not disadvantage or alienate particular groups of students. None of the problems provided students with all required data, and none of them led to a single correct answer. Students were expected to develop a strategy, make estimations, use judgement and be able to justify their answers. No access to calculators or the internet was allowed. Sample problems are shown below.

The rivers and oceans contain levels of dissolved gold of between 5 and 50 ppt. Extraction of gold from seawater has been seriously considered many times. Approximately how many kg of gold are present in the world oceans.

Many commercial hair restorers claim to stimulate hair growth. If human hair is composed mainly of the protein a-keratin, estimate the rate of incorporation of amino acid units per follicle per second.

A shipment of Austrian Pumpkin Seed Oil arrives in the UK and upon inspection customs find suspended matter in a sample of the oil. You have been asked to ascertain the nature and origin of the foreign matter. How do you proceed?

Before presenting the students with the problems a set of guidelines for tutors for the sessions were drawn up along with suggested model answers. At the start of each problem solving session the aims of the session and guidelines were explained to the students. The problems were presented to the students and they were given about 20 minutes on each problem or until the majority of the class had reached a solution. Students tackled several problems in groups of four or five and then tackled several more problems individually. After each problem one group or individual presented their solution to the class. This was followed by a class discussion and reflection.

Open-ended problems are generally more difficult to mark than algorithmic or closed problems because the process is as important as the outcome. Marks have to given for the quality of the strategy and for the assumptions and estimations that are made. Each of the open-ended problems was marked out of ten with the marks being split according to the marking scheme in Table 1.

Students' ability in open-ended problem solving was compared with their ability to solve problems that were more algorithmic in nature, using their marks for individual algorithmic problems from past examination papers.

Table 1 Marking scheme for open-ended problems

Activity		Mark
Identifying data	Separating relevant from irrelevant	1.5
	Making estimations or assumption	1.5
Method	Applying known method	1.5
	Developing new method	1.5
Goals	Defining goal	1
	Working towards goal	1
	Reaching goal	1
	Checking goal	1

Cognitive styles

Assessing the students' individual cognitive style may enable correlations to be drawn against their performance in solving the problems (Danili and Reid, 2006). Three different cognitive styles were identified as significant factors affecting student performance. The tests were administered to students in their first year of study.

The tests administered to evaluate working memory capacity were the forwards and backwards digit span tests (Baddeley, 1992). The forward digit span test involves the tutor reading out progressively longer sequences of numbers that students record. The forwards test is then followed by the backwards digit span test where the sequences of numbers have to be mentally reversed by the students before being recorded. The tests can be administered and marked by a class of students in about 20 minutes. A student's working memory can then be categorised as high, medium or low.

The test for M-Capacity consists of the Figural Intersection Test (FIT) (Pascual-Leone, 1994). A typical task in the FIT is shown in Fig. 1. The task is to identify the common point of intersection in the complex figure on the left hand side of the shapes that appear on the right hand side. The FIT consists of 36 such tasks of varying degrees of difficulty. The number of correct items is then reduced to an M-capacity score.

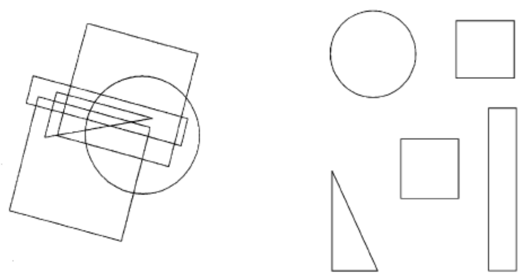

Fig. 1 FIT task.

The task for Field Dependence/Field Independence is the Group Embedded Figures Test (GEFT) (Witkin *et al.*, 1971). The GEFT consists of 20 sets of complex patterns. Embedded within each complex pattern is a simple figure. The task is to recognise the simple figure within the complex pattern. The scores can then be categorised as Field Dependent, Field Medium and Field Independent.

Student attitudes

An attitude questionnaire was designed to assess the students' attitude to chemistry in general, to problem solving and to the use of context. The questionnaire used statement pairs (Perry, 1970). The questionnaires consisted of paired statements representing opposing viewpoints of the attitude object. For example, *"I am good at problem solving"* would be opposed by *"I am poor at problem solving"* or *"It is useful to solve problems similar to those that are found in the workplace"* paired with *"There is no advantage in solving problems similar to those that are found in the workplace"*. The responses to these questions would be Strongly Agree, Agree, Undecided, Agree, Strongly Agree. Such questionnaires avoid the potential ambiguity that can arise from Likert-type questionnaires where, for example, a statement like *"Learning all the material covered in lectures should be enough to pass the course"* could prompt the response disagree from two students holding very different views: *"I strongly disagree since you should know much more"* and *"I strongly disagree since it is enough to know part of what has been covered in lectures."* The questionnaire was administered before and after the problem solving sessions; An extract from it is shown in Fig. 2.

Twelve students were interviewed following the problem solving sessions. Their responses to the question 'How did the problems compare to others that you have done on your course' were analysed and main themes identified.

11	I find problem solving interesting.	**SA**	**A**	**N**	**A**	**SA**	I find problem solving tedious.
12	I find problem solving too demanding.	**SA**	**A**	**N**	**A**	**SA**	I find problem solving too easy.
13	It is important that chemistry problems relate to real life contexts.	**SA**	**A**	**N**	**A**	**SA**	There is no advantage in chemistry problems that relate to real life contexts.
14	I find chemistry problems that relate to real life contexts enjoyable.	**SA**	**A**	**N**	**A**	**SA**	I don't find chemistry problems that relate to real life contexts enjoyable.

Fig. 2 An extract from the attitudes questionnaire.

Table 2 Pearson r correlations

	N	Working memory capacity	M Capacity	Field independence	Degree class	Open-ended problem solving score
Open-ended problem solving score	205	0.18	0.30**	0.27**	0.23**	
Algorithmic problem solving	40	0.18	0.37**	0.25	0.81**	0.17

** Correlations are significant at 0.01 level for 2-tailed test.

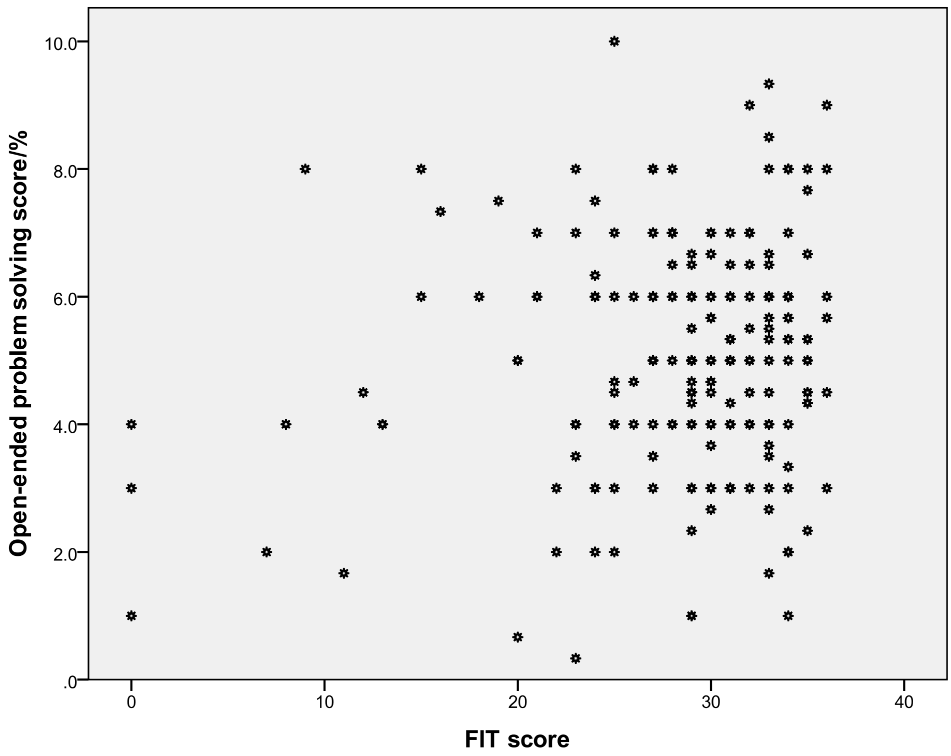

Fig. 3 Scatter plot for FIT score (M capacity) *vs* scores for open-ended problem solving.

Results

Statistical analysis

Comparison of performance in algorithmic and open-ended problem solving and correlations with the cognitive variables were analysed using SSPS. Results are shown in Table 2. Positive correlation was found between algorithmic problem solving scores and M capacity. Scores in open-ended problem solving correlated with both M capacity and field independence. This is in agreement with the findings of Tsaparlis (2005) in his work on problems that were non-algorithmic but closed in style The lack of correlation between problem solving scores and working memory capacity may be an artefact of the difficulty of scoring the working memory test and the ease with which subjects can 'cheat'. The scatter plots for these results give additional insight (Figs. 3 and 4). Fig. 3 shows that very few students with a FIT score below 20 scored as much as 40% on the problem solving activities, indicating a threshold effect for M capacity in solving these open problems. There was no apparent correlation between algorithmic problem solving and open-ended problem solving scores, although the sample size was small for algorithmic scores (N = 40). Both

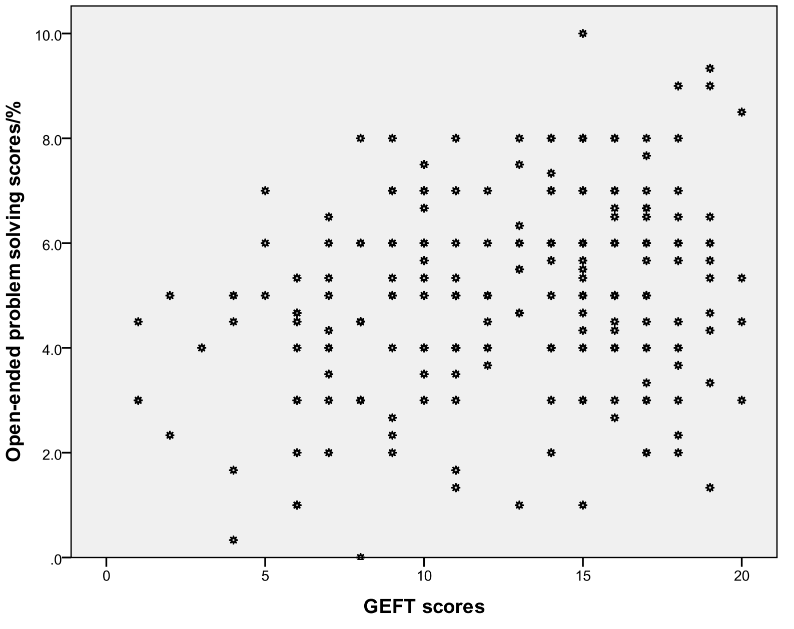

Fig. 4 Scatter plot for GEFT score (field independence) *vs* scores for open-ended problem solving.

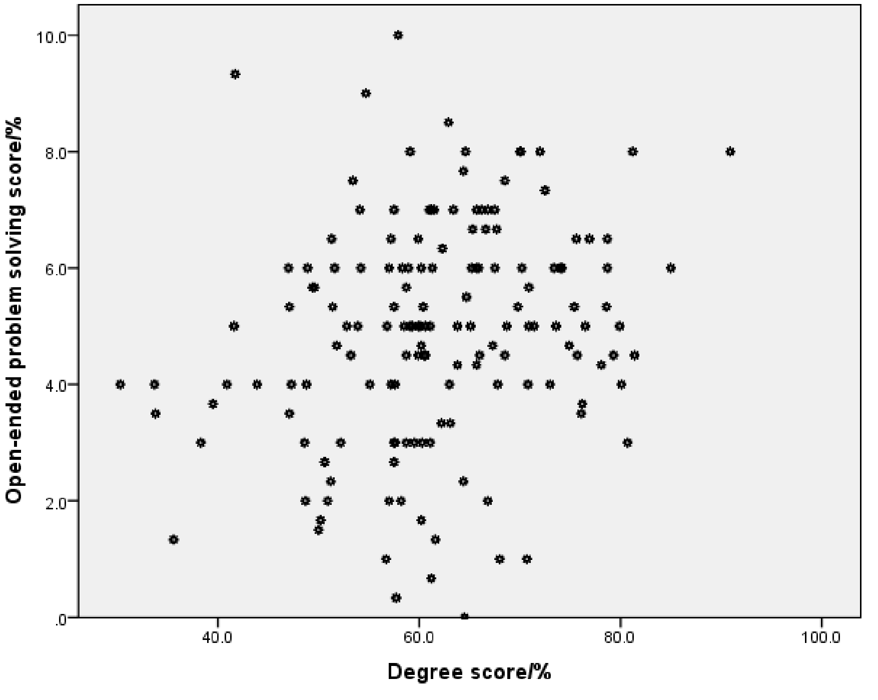

Fig. 5 Scatter plot for degree score *vs* scores in open-ended problem solving.

problem solving scores correlate with final degree results, although this seems to be more striking for algorithmic problems (Fig.s 5 and 6).

Student attitudes

The questions on the attitudes questionnaires were designed to indicate positive or negative attitudes to problem solving. The number of responses that demonstrated positive attitudes (by a strongly agree or agree response to a positive statement) or negative attitudes (by a strongly agree or agree response to a negative statement) to problem solving for each student were collated and plotted for the cohort. This is shown in Fig. 7, and shows a significant shift in students' attitudes toward the positive responses.

The open response question 'Please tell us how the problem solving activities you have tackled over the past

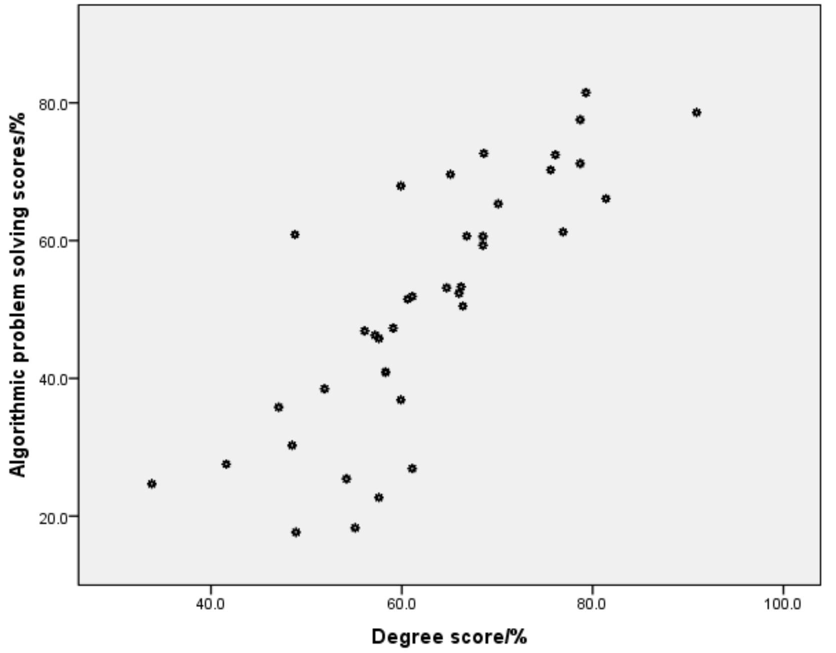

Fig. 6 Scatter plot for degree score *vs* scores in algorithmic problem solving.

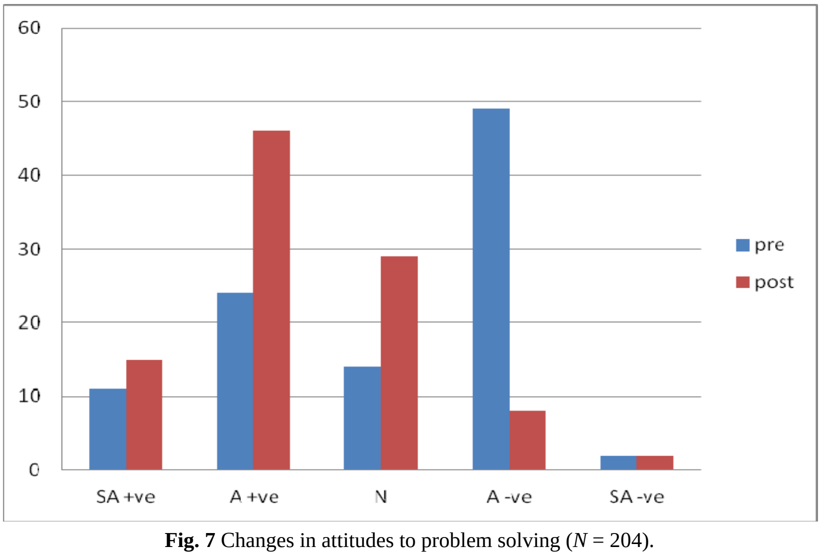

Fig. 7 Changes in attitudes to problem solving (N = 204).

two weeks has compared to problem solving you have done previously' and drew a variety of responses. Typical responses are listed here:

Far more difficult. The lack of information hindered progress and, while it was useful for making assumptions, it often led to some panic.

More interesting and challenging.

The problem solving activities I tackled over the past two weeks, some of them I did similar on other modules but some not. Some of them were difficult for me but the others were ok.

Never did problem like these before.

Easier in terms of knowledge required. Harder because had to assume a lot of stuff.

Much more difficult and complicated than anything I have done previously.

More difficult as there was far too much to assume.

More interesting as they related to the outside world.

In my opinion, this type of problem solving is more enjoyable than other done before. And also, I think they are closer to what we will find in the future workplace.

Analysis of the transcripts of the student interviews identified several major types of response. All these students interviewed made comments related to the following:

- The ability to take different routes to solve the problem

- The motivation provided by the real-life context
- The fact that there is not a single correct answer
- The challenging nature of the problems
- The perception that the activity would be useful in future employment
- The enjoyable nature of the activity.

The majority of students reported enjoying these activities. However, this was not universal, and one student commented *"I didn't really enjoy this as it made me feel stupid and like I didn't know anything. However, I do understand that it is good to learn this skill."*

Discussion

This investigation demonstrated that there is a positive correlation between M capacity and both algorithmic and open-ended problem solving. However, M capacity appears to demonstrate a threshold effect, with only students with relatively high scores being able to succeed in open-ended problem solving. The sample number for algorithmic problem solving was too small to enable any similar pattern to be observed. The factors that appear to affect a student's ability to solve these context-rich, open-ended problems differ from those for algorithmic problems in that field independence is crucial for success. This is not entirely surprising, as the context which is used to motivate learners also requires them to extract the relevant information from a problem that contains more 'noise' than a more traditional, algorithmic problem.

Perhaps not surprisingly, both types of problem solving activities show correlations with final degree score. Problem solving is a major component of any chemistry programme and should be well recognised within the assessment scheme. However, the correlation between algorithmic problem solving and degree score is striking. This must indicate that algorithmic problem solving constitutes a significant part of a student's assessment portfolio and that open-ended problem solving is not assessed to as great an extent. This aligns with the findings of Bennett (2004) whose study of examination papers from university chemistry departments in the UK and Australia showed that 95% of problems on examination papers were of the Johnstone Type 1, which are algorithmic.

Investigation of student attitudes to context-rich, open-ended problems indicated that the real-life context was motivating, but did make the problems more challenging, perhaps because of the correlation with field dependence and M capacity. There was a shift to more positive attitudes to problem solving following the problem solving activities. Students recognised that they were developing skills that would be useful in future employment.

Conclusions

Open-ended problem solving requires different cognitive skills from algorithmic problem solving. This could have implications for the growing use of problem-based learning in teaching chemistry. Tutors should be aware that some students will be hindered in such activities by their inherent field dependence. Using context-rich, open-ended problems motivates and enthuses learners and produced more positive attitudes towards problem solving. The only way to enable undergraduates to develop open-ended problem solving skills is to allow them to practise in an unthreatening environment. If academics value these skills, they must be properly addressed within the curriculum and rewarded within the assessment schemes.

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