

The effect of a structured problem solving strategy on performance in physics in disadvantaged South African schools

E. Gaigher¹ J.M. Rogan² and M.W.H. Braun¹

¹University of Pretoria, South Africa; ²University of KwaZulu-Natal, South Africa
egaigher@gk.up.ac.za

Abstract

A quasi-experimental study was undertaken to extend first-world research on physics problem solving into disadvantaged South African classrooms. Sixteen urban high schools, involving 189 learners, participated in the study, investigating the effect of a structured problem solving strategy on performance and conceptual understanding. This article focuses on the enhancement of problem solving performance in classroom tests and the midyear examination. The treatment group outperformed the control group by 8% in the midyear examination. Using ANOVA, this increased average score was statistically significant at the .001 level, indicating enhanced problem solving skills. Furthermore, it was demonstrated that the strategy was not transferred successfully to topics studied prior to implementation of the problem solving strategy. A theory is presented to explain the results in terms of the co-development of conceptual understanding and problem solving skill.

Introduction

South African learners performed worst among 38 countries participating in the Third International Science and Mathematics Study (Howie, 2001). The performance of Black learners in science and mathematics is of particular concern. In the national senior matriculation examination of 2002, Black students accounted for a mere 20% of those who passed Physical Science on the higher grade (Kahn, 2004).

More than ten years after South Africa's transition to democracy, most of the Black learners attend schools that are still at a disadvantage due to persisting effects of the apartheid school system (Pandor, 2006; Johnson, Monk & Hodges, 2000; Hartshorne, 1992). The ambitious curriculum reforms following the 1994 elections these have done little to improve the situation in poorly resourced classrooms (Jansen, 1999). Although many non-governmental organisations have been involved for almost thirty years to improve science education in secondary schools (Rogan & Gray, 1999), poorly trained teachers, teacher dominated approaches, student passivity and rote learning are still the norm (Hattingh, Rogan, Aldous, Howie & Venter, 2005; Arnott, Kubeka, Rice & Hall, 1997). In addition, most Black learners are at a disadvantage due to second language instruction (Pare, 2006; Howie, 2003; Prophet, 1990).

However, difficulties with learning science are not unique to South Africa. In first world countries, science educators are concerned with poor conceptual understanding of physics amongst university students, despite satisfactory achievement in traditional problems and examinations (Kim & Pak, 2002; Reif, 1995; Redish, 1994; van Heuvelen, 1991; McDermott, 1991; Hewitt, 1983). Various universities in the United States have undertaken programs to improve performance and conceptual understanding of physics. Structured problem solving is one avenue being explored to enhance performance and conceptual understanding (Maloney, 1994).

This article reports on a study (Gaigher, 2004) that extended first-world research on problem solving to disadvantaged South African classrooms, in an attempt to improve the teaching and learning of physics in these schools. The experiment was conducted in South African high schools in disadvantaged urban Black communities where most of the learners were at a disadvantage due to poor previous schooling, instruction in a second language, a shortage of qualified teachers, large classes, and poor facilities. The focus of the article is the effect of a structured problem solving strategy on performance in classroom tests and in the midyear examination. The type of problem in this context refers to the typical textbook and examination problems where physics principles are applied to determine a quantitative value of some parameter in a concrete situation described by the question. The larger study (Gaigher, 2004) showed improved performance as well as enhanced conceptual understanding. While this article reports on enhanced performance, the results on the development of conceptual understanding were presented elsewhere in a detailed discussion of qualitative data (Gaigher, Rogan & Braun, 2006).

Literature survey

Physics instructors and teachers generally accept that problem solving leads to an understanding of physics (Hobden, 1999; Maloney, 1994). However, success in calculating correct numerical answers does not necessarily imply a corresponding level of conceptual understanding (McDermott, 1991). In fact, instruction focusing on problem solving often ignores intellectual objectives and could encourage students to concentrate on algorithms instead of on physics. Poor conceptual understanding has been demonstrated by various studies (Kim & Pak, 2002; Pride, Vokos & McDermott, 1998; Schaffer & McDermott, 1992; McMillan & Swadener, 1991; Lawson & McDermott, 1987). These studies suggested that students learn to solve standard problems in physics without applying conceptual and interpretative knowledge.

A series of studies on experts and novices identified qualitative analysis and successive representations as characteristic of expert problem solving (Larkin, 1979, 1983; Larkin & Simon, 1987; Larkin, McDermott, Simon & Simon, 1980; Larkin & Reif, 1979). Dhillon (1998) observed that novice problem solvers had difficulty to relate quantities, and used symbols to infer connections. On the other hand, experts used the conceptual meaning of quantities to relate them. According to Maloney (1994), the most striking difference between the experts' and the novices' approaches was found in the experts' application of general principles of physics which were for the most part not found in the novices' solutions. The novices typically used means-end analyses, focusing on the gap between the required answer and the information, thus filling in steps to complete algebraic solutions.

Several authors commented on how classroom practices could be adjusted to ensure that students learn to understand physics. Hewitt (1983) proposed that conceptual reasoning should form part of examinations in order to encourage students to conceptualise. McDermott (1991) advocated that students should be intellectually engaged in the learning process in order to bring about significant conceptual change. She suggested that a deep mental engagement could be developed when students are required to explain their reasoning in their own words. According to Van Heuvelen (1991), students of physics tend to be passive observers while lecturers tend to demonstrate the algebraic aspects of solving problems. He suggested that students could learn to think like physicists when given opportunities to reason qualitatively and make use of translations from verbal, pictorial, and physics representations, before switching to the mathematical form of physics problems. Redish (1994) argued that physicists should learn from cognitive science, particularly the theories of constructivist learning and conceptual change, to improve their teaching. Students should be given opportunities to do

qualitative reasoning, to construct mental models, and to learn to apply their models. Duit, Roth, Komorek and Wilbers (1998) found that students' social interactions in science classrooms contribute to successful learning.

Concern with poor problem solving as well as with poor conceptual understanding that often accompanies successful algebraic problem solving led to the development of instructional strategies for the teaching of physics problem solving at various institutions. Enhancement of problem-solving performance has been reported for:

- Explicitly taught problem-solving strategies, which included qualitative analysis and multiple representations (Heller & Reif, 1984);
- Cooperative group problem solving (Heller, Keith & Anderson, 1992);
- Strategy writing, where students had to describe how they would solve given problems (Leonard, Dufresne & Mestre, 1996);
- Modelling instruction (Halloun & Hestenes, 1987; Hestenes, 1987);
- The technique of variation in problem solving (Fraser, Linder & Pang, 2004), and
- Familiarity with closely related problems (Alant, 2004).

While the strategies summarised above were all employed at universities, Huffman (1997) explored structured problem solving in high school physics. Huffman demonstrated that an explicit problem solving strategy improved problem solving performance as well as conceptual understanding.

The issue of students' problem solving without their understanding of the relation between algebraic solutions and reality was described as the 'insulation' of the symbolic world from the 'situated nature' of problems (Greeno, 1989). Greeno proposed a model for scientific problem solving and reasoning that provided an explanation to this question. The model is based on four domains of knowledge, namely:

1. Concrete domain (physical objects and events);
2. Model domain (models of reality and abstractions);
3. Abstract domain (concepts, laws and principles);
4. Symbolic domain (language and algebra).

This model explains the possibility that algebraic solutions can become disconnected from the concrete situation it represents: In the classroom, students manipulate symbols to solve problems, while the concrete problem situation is seldom present. This classroom reality can therefore lead to the belief that problems are about the symbols, rather than about the concrete situation represented by those symbols. The symbols are real marks on paper and the chalkboard, taking the place of the real objects described by the problem statement. Algebraic solutions can therefore amount to operations on knowledge located only in the domain of symbolic knowledge, without translation to the concrete, model or abstract domains. Such an approach can sometimes lead to correct equations and correct numerical answers, but it does not demonstrate or develop understanding of the meaning of algebraic solutions.

Methodology

The structured problem solving strategy

The current study utilised the abovementioned successful practises reported in the literature to design a problem solving strategy that could be suitable in the disadvantaged South African classrooms. The steps of the strategy were designed to encourage the use of multiple representations. It was argued that if disadvantaged students could be guided to behave more like experts when solving problems, they could develop the thinking patterns associated with

expert behaviour. Qualitative aspects of problems were emphasised; algebra was part of a solution, not the entire solution. The successful approaches reported in the literature, and listed above, were combined and simplified into the following seven steps:

1. Draw a simple diagram to represent the system.
2. Write down the information at relevant positions on the diagram.
3. Identify the unknown variable, indicating it at the relevant position on the diagram.
4. Analyse the problem verbally and in writing to explain which physics principle is appropriate to the problem situation. When discussion is not possible, as in a test, only a written analysis should be done.
5. Write down the relevant equation(s).
6. Substitute numerical values and solve the equations algebraically.
7. Interpret numerical answers in words.

This strategy does not require separate 'real world' diagrams and 'physics' diagrams as used by the Heller group (Heller *et al.*, 1992). It was argued that separate diagrams could distract attention from the effort to learn to relate physics to reality. In fact, experienced problem solvers sometimes draw forces on top of objects in real world diagrams, thus making abstract physics concepts visible in their real world location (Larkin & Simon, 1987). In our strategy, the diagram becomes the focus of attention. While drawing the diagram, the student constructs a two dimensional model of the concrete situation described in the problem statement. Information and unknown quantities are grouped by location when these are superimposed on the diagram. In the analysis, these localised groupings guide the search for principles of physics applicable to different parts of the concrete situation. Links between different parts of the problem become visible as shared features between groupings on the diagram.

Although qualitative analysis has been associated with successful problem solving (Heller & Reif, 1984) and identified as one of fourteen fundamental activities in problem solving (Dhillon, 1998), it has not been prescribed as a step in the structured problem solving strategies reported in the literature. In our strategy, the step 'analysis' combines aspects of modelling (Halloun & Hestenes, 1987) and strategy writing (Leonard *et al.*, 1996), by including classroom discourse as well as written arguments to justify the selection of principles to solve the particular problem.

Regarding algebra, the strategy used in this study was also simplified. Students were encouraged to substitute numerical values before starting algebraic manipulation, the reason being that poor mathematical abilities could prevent many students from arriving at correct symbolic solutions. Here the current approach differed from others who preferred symbolic solutions before substitution (Huffman, 1997; Wright & Williams, 1986; Reif *et al.*, 1976). It was argued that emphasis on symbolic solutions could be counterproductive for disadvantaged students with poor mathematical skills. Incorrect symbolic solutions would not develop insight into the relevant physics relationships, and numeric substitutions into wrong symbolic solutions would be meaningless, adding to confusion.

In terms of Greeno's model, working through the steps required multiple translations between the four domains of knowledge, avoiding the trap of algebraic problem solving. First the written problem statement is translated to a structure in the concrete knowledge domain before being translated to the model domain to make a schematic representation of the concrete situation. Next, numerical data and abstract concepts are indicated at relevant locations on the diagram, requiring translations between the model, symbolic and abstract domains. The schematic representation is then translated to appropriate physics concepts, followed by translation to the symbolic-language domain when formulating the analysis. Then, the symbolic-language representation is translated to a symbolic-mathematical representation,

which is solved algebraically. Finally, the mathematical solution is translated back to the concrete and symbolic-language domains.

The steps encouraged intellectual engagement, prompting students to formulate arguments in classroom discussions and in writing their own solutions. The strategy therefore created opportunities for individual and social knowledge construction, to develop understanding of how physics concepts relate to concrete problem situations.

Research design

Two disadvantaged urban school districts, situated on opposite ends of town, respectively functioned as treatment and control group. Each group consisted of all the Grade 12 higher-grade physics students in the participating schools, with one participating teacher per school. The science teachers of the treatment group schools participated in four workshops on the problem solving strategy and were required to implement it in their classrooms. The control group teachers were not informed about a problem solving strategy being tested; they were required to continue teaching as always. Neither group was informed about the participation of the other. The decision to avoid random assigning of schools to the two groups was taken in a deliberate attempt to exclude diffusion, contamination and rivalry. This design is regarded as an improvement over studies where teachers had classes in both groups and where two groups were in close physical proximity (e.g. Huffmann, 1997). The lack of randomness in assigning schools to groups was compensated for by a pre-test that confirmed equivalence of the two groups.

All the high schools from the two districts were invited to participate in the study. Twenty schools responded, eleven from the control group and nine from the treatment group. Four schools dropped out: one of the schools in the treatment group could not participate as all the students were doing physical science on the standard grade, while another three schools from the control group did not keep up with the schedule and were unable to take the tests on the prescribed dates. Students who were absent from any of the tests were not included in the sample, which consisted of 189 students: 80 from the 8 remaining schools in the treatment group and 109 from the 8 remaining schools in the control group.

The problem solving strategy was implemented by means of a cascading model: the researcher trained teachers while the teachers taught their students. During the teacher training workshops, problems taken from provincial final Grade 12 examination papers were discussed. The researcher provided no solutions. Instead, the teachers were given opportunity to interact and apply the strategy, thus participating in knowledge construction in a social context. Similarly, the students were expected to be active participants in problem solving in the classroom.

The study was designed to be non-disruptive. The only change from an ordinary school situation was the way in which problems was solved in the treatment group. The strategy was applied and practised while solving classroom and homework problems that would form part of the ordinary routine of learning physics by doing problems. The national Grade 12 syllabus and the schools' textbooks were used. No extra classes for students were required. Tests were structured like ordinary 30-minute classroom tests consisting of typical examination problems.

Data

Data were collected over a period of ten months, starting with the pre-test at the beginning of the academic year in January. The pre-test focused on two topics from the Grade 11 syllabus, covered during the previous year. These two topics, vectors and kinematics, are also examined in the departmental final Grade 12 examination. The pre-test scores would, therefore, be an

indication of knowledge and skills acquired during the previous year, while also being relevant to the coming final examination. The level of complexity of these Grade 11 topics is similar to that of the Grade 12 topics. The three post-tests were scheduled to follow soon after completing the relevant syllabus topics between February and May. The midyear examination in June covered the same content as the preliminary and final examinations: all Grade 12 topics as well as the two Grade 11 topics used for the pre-test.

The test and examination scripts were used as sources of quantitative and qualitative data. The researcher to ensure uniformity marked all scripts. The marked scripts were photocopied before being returned to the students. Quantitative and qualitative data were collected from the marked scripts. Videotaped problem solving and questionnaires contributed further to the qualitative data. The current article focuses on the effect of the strategy on performance, while the development of conceptual understanding is discussed elsewhere (Gaigher, Rogan & Braun, 2006; Gaigher, 2004). Average scores for the treatment and control groups were compared using single factor ANOVA to establish whether or not the groups performed similarly. Furthermore, two-factor ANOVA was applied to investigate possible interactions between the treatment and student achievement, teacher qualifications, school status and student gender.

Reliability and validity

The main threat to internal validity was the possibility that pre-existing group differences could influence results. The pre-test was taken to check for such differences. The results indicated equivalence of the two groups; the average percentages scored by the two groups differed by less than 0.2%. The distribution of scores remained practically unchanged throughout the study, with standard deviations between 14 and 15%. Another threat, performance enhancement resulting from a change in teaching strategy, could not be excluded in the design of this study. We assumed that the effect of change in itself would not produce a significant performance enhancement over a time of ten months.

The tests and midyear examination were all set and marked by the researcher to ensure a uniform standard, thus avoiding the issue of inter-rater reliability. It could be argued that the researcher would be biased, favouring the treatment group. To minimise bias, marking was done strictly in accordance with the departmental marking guidelines for physics, giving marks to correct formulae, substitutions and answers. The researcher has been involved for more than ten years in the marking of the departmental Grade 12 physics examinations, thereby assuming that the marking would be according to the standard. Furthermore, no additional credit was given for additional explanations or diagrams, ensuring that marks given to learners in both groups would reflect only on the appropriate formulae and algebra. Enhanced performance of the treatment group would thus reflect an improvement of their ability to select and apply the appropriate principles.

The reliability of the instruments was checked by comparing test results to the midyear examination results: For each student, the average score of the three post-tests was calculated and compared to his score in the midyear examination. A high degree of correlation was obtained; the correlation coefficient of 0.77 indicating agreement between the test and midyear examination results.

Care was taken to use test and examination problems that reflected the type of problems encountered in the typical departmental final examinations. However, problems were adapted to avoid students recognising 'old' problems. More than the normal time was allowed to prevent speed influencing the scores. The Departmental Preliminary Examination taken during

September was used as an independent external measurement to verify the validity of the test instruments. Students' scores in the midyear examination were compared to their scores in the September examination. A high degree of correlation, with a correlation coefficient equal to 0.84 was obtained, indicating that the results of the midyear examination were in agreement with that of the external examinations.

Attrition was checked by keeping track of all individuals participating in the study, and restricting the sample to the 189 learners who did not miss any of the tests or the examination. The correlations mentioned above referred to the students in the sample only.

Accurate measurement of the dependent variable, namely 'problem solving performance' was achieved as best as possible by restricting problems to 'typical examination problems' and marking it according to 'departmental examination standards'. To be fair towards the control group, no credit was given for steps of the strategy, or for any written explanations. Marks were allocated only for mathematical solutions in accordance with the standards used in the provincial and national final examinations as discussed above. This way of marking therefore did not explicitly encourage the use of the strategy, but it would indicate whether learning the strategy could be helpful to improve students' ability to use appropriate principles and algebra, which is the way, albeit imperfect, that 'problem solving performance' is measured in the departmental examinations.

All schools participating in the project received identical sets of homework problems as preparation for each test to ensure that all students and teachers have had sufficient exposure to problems on the topic. The researcher did not provide solutions, as the *teachers* were to interact with their students.

Since 16 schools participated, it was argued that having eight teachers in each group increased the likelihood of having 'good' and 'poor' teachers in both groups. Also, teacher qualifications in the two groups were similar: four teachers had teaching diplomas and four had degrees, although not one of the teachers with degrees had Physics as a major. Furthermore, since the same teachers were responsible for teaching the Grade 11 classes during the previous year, and the groups performed similarly on pre-test, it was assumed that the teachers' themselves would not be a factor to benefit one group.

Results

Test scores

The average pre-test scores of the two groups differed by merely 0.13%: the treatment group scored an average of 20.6% compared to 20.4% for the control group. Single factor ANOVA yielded $p = 0.940$ which indicated that no significant difference existed between the two groups prior to administering the treatment.

Average scores for the post-tests are summarised in table 1. For each test, the average scores of the two groups were compared by single factor ANOVA. For the sample, the critical value of F was $F(\text{crit}) = 3.89$ at $\alpha = 0.05$. In February, the difference was small (4.24%) and insignificant with $F = 2.61$, but the scores of the treatment group were significantly higher in March (9.64%) and May (9.5%) and with $F = 23.6$ and 16.7 respectively. Results of two-factor ANOVA indicated that no interactions existed between the treatment and student achievement, teacher qualifications, school status and student gender.

Table 1: Comparison of the average test and examination scores for the treatment and control groups

Test	Topics	Control group %	Treatment group %	Difference %	F	p
February	Newton's laws, Free fall	43.63	47.87	4.24	2.61	0.107
March	Momentum, Energy	41.73	51.37	9.64	23.06	3×10^{-6}
May	Electrostatics	42.97	52.47	9.50	16.70	7×10^{-5}
June examination	Problem section (All topics)	25.78	33.58	7.80	13.66	3×10^{-4}

The difference in performance between the two groups increased from only 4.24% in February to 9.64% in March. Two possible explanations are considered: Firstly, the school year started in mid-January, suggesting that the 'treatment' became more effective with time and with regular practise of the problem solving strategy. It is, therefore, possible that by February, the treatment group had not yet mastered the problem-solving strategy, thus having no advantage over the control group at that stage. By March, it would appear that the treatment group students mastered the strategy to such an extent that they became more successful than the control group. The second possible explanation of the trend involves the nature of the subject matter covered by these two tests. The February test dealt with Newton's laws and free falling bodies, for which quantitative problems can be solved successfully using well-known algorithms. On the other hand, the March test dealt with energy and momentum, and the May test with electrostatics for which general principles have to be interpreted and applied rather than using algorithms. It is possible that the treatment group were better equipped to apply such general physics principles, which enabled them to outperform the control group in the last two tests.

The two explanations can be further explored by comparing scores in different questions in the midyear examination, shown in Table 2. For the first three questions, the differences between the groups' scores were small (less than 3%) and insignificant with F-values below the critical value of $F(\text{crit}) = 3.89$. For the last three questions the treatment group scored significantly higher than the control group (more than 10%) with F-values well above the critical value. Questions 4, 5 and 6 covered the topics studied later (March-May) in the grade 12 year. This supports the notion that using the problem-solving strategy seemed to become advantageous as the year progressed, when the volume of work and the likelihood for confusion increased. In addition, the topics of questions 4 (momentum and energy) and 5 (electrostatics) were also covered by the March and May tests, with similar favourable results for the treatment group.

Table 2: Comparison of average scores obtained by the two groups for separate questions in the June examination

Question Number	Topic	Control group %	Treatment Group %	Difference %	F	p
1	Multiple-choice (All topics)	30.5	32.7	2.2	0.32	0.323
2	Kinematics	13.6	16.3	2.7	1.79	0.182
3	Newton's laws	37.7	39.7	2.0	0.46	0.499
4	Momentum, Energy	24.2	37.5	13.3	17.8	4×10^{-5}
5	Electrostatics	29.8	40.0	10.2	8.48	0.004
6	Electric Current	28.3	40.0	11.7	10.7	0.001

Both groups performed very poorly in question 2, which dealt with uniformly accelerated motion, a topic studied during the previous year; the same topic was included in the pre-test where both groups performed equally poorly. It seemed that the learners in the treatment group were unable to transfer the problem solving strategy to a topic studied prior to learning the strategy. The success of the strategy thus appeared to be rooted in its application while learning new content.

Both groups did relatively well in question 3, which dealt with Newton's laws, giving an insignificant difference in performance. This result is in agreement with the results of the February test, which also covered Newton's second law. Why would the problem-solving strategy not equip the treatment group to outperform the control group on this particular topic? Most textbooks offer a step-by-step explanation on how to apply the second law: draw a force diagram, resolve the forces into components, substitute the components in the famous second law equation and solve. Assuming that the control group teachers and students used this typical textbook strategy, the control group would be equipped with an algorithm for this topic, thereby keeping up with the treatment group. This result was in agreement with Huffman's (1997) conclusion that 'textbook' and 'explicit' strategies yielded similar results.

Question 1, the multiple-choice section, covered all topics and showed an insignificant difference between the average scores of the two groups. This result indicates that although the strategy enhanced problem-solving performance of the treatment group, it did not enhance the skill to choose correctly in multiple-choice questions. (The very poor performance in this question may be a consequence of second language instruction, however this is a topic not discussed here.)

Discussion

The quantitative results reported in this article show an overall significant improvement of scores, which is interpreted as evidence of enhanced problem solving skills. The performance enhancement was not uniform throughout the different tests and examination questions, indicating that improved performance resulted if the strategy was applied while learning new content. Specifically, the strategy was:

- not particularly valuable for topics for which well known problem solving algorithms are available;
- not transferred successfully to topics studied prior to the introduction of the problem solving strategy, and
- most successful for topics studied towards the end of the course.

In order to explain the three results, it is proposed here that using the problem solving strategy resulted in the co-development of problem solving skill and conceptual understanding. When algebraic problem solvers learn to use the strategy, the prescribed steps prompt unfamiliar actions, which can be described as translations between Greeno's knowledge domains. Regular use of the problem solving strategy results in repeated translations between the four knowledge domains, creating links between concrete situations, models, concepts and algebra. For a particular problem, using the strategy creates links between a particular concrete situation and particular physics principles. For a collection of problems on a topic, a particular physics principle is linked to different concrete situations. During the course of time, a particular concrete situation becomes linked to different physics principles. Eventually, a broad conceptual understanding develops as a network of links between concrete situations and physics principles, while at the same time, problem solving skill develops as the ability to link a particular concrete situation with appropriate physics principles. The network of concepts and the skill to link concepts to concrete situations develop simultaneously, from linking

simple concepts and solving simple problems to a broader conceptual understanding and skilful problem solving. Such development of problem solving skill resonates with Alant's (2004) notion of familiarity as a means of learning physics through problem solving.

Implications

Teachers should take care not to regard the problem solving strategy as a final goal in problem solving. If it is prescribed as a rigid structure, it could become another algorithm, lacking the experts' holistic approach to problem solving. However, in the larger study, it was found that the treatment group students tended to adopt a conceptual approach rather than adhering to the steps, suggesting that learning the strategy induced a shift towards expert-like problem solving (Gaigher, Rogan & Braun, 2006; Gaigher, 2004).

The implementation of the problem-solving strategy in the eight treatment group schools was a relatively small intervention, which produced significant gains in students' performance. The low cost associated with such an intervention makes it particularly suitable to implement in the developing world. Furthermore, it is a promising vehicle for in-service professional development of teachers in disadvantaged schools.

Acknowledgements

A substantial part of this project was completed at the University of Wisconsin-Madison, during a study visit sponsored by a collaboration project of the National Research Foundation (South Africa) and the National Science Foundation (USA).

References

- Alant, B. (2004). Researching problem solving in introductory physics: Towards a new understanding of familiarity. *African Journal of Research in Mathematics, Science and Technology Education*, 8, 29-40.
- Arnott, A., Kubeka, Z., Rice, M. & Hall, G. (1997). *Mathematics and science teachers: Demand, utilization, supply and training in South Africa*. Johannesburg: Edusource.
- Dhillon, A.S. (1998). Individual differences within problem-solving strategies used in physics. *Science Education*, 82, 379- 404.
- Duit, R., Roth, W.M., Komorek, M. & Wilbers, J. (1998). Conceptual change cum discourse analysis to understand cognition in a unit on chaotic systems: towards an integrative perspective on learning in science. *International Journal of Science Education*, 20, 1059-1073.
- Fraser, D., Linder, C. & Pang, M.F. (2004). Learning through variation, part 1: a pedagogical tool. Proceedings of the 12th Annual Meeting of the Southern African Association for Research in Mathematics, Science and Technology Education. Cape Town.
- Gaigher, E., Rogan, J.M. & Braun, M.W.H. (2006). Exploring the development of conceptual understanding through structured problem solving in physics. Accepted for publication in *International Journal of Science Education*, 28 July 2006.
- Gaigher, E. (2004). *The effect of a structured problem solving strategy on performance and conceptual understanding of physics: a study in disadvantaged South African schools*. PhD thesis, University of Pretoria, Pretoria. <http://upetd.up.ac.za/thesis/available/etd-02022006-160908/>
- Greeno, J.G. (1989). Situations, Mental Models, and Generative Knowledge. In D. Klahr, and K. Kotovsky (Eds.). *Complex Information Processing: The Impact of Herbert A. Simon*, (pp.285-318), Hillsdale, NJ: Lawrence Erlbaum Associates.
- Halloun, I.A. & Hestenes, D. (1987). Modeling instruction in mechanics. *American Journal of Physics*, 55, 455-462.

- Hartshorne, K. (1992). *Crisis and challenge: Black education 1910-1990*. Cape Town, South Africa: Oxford University Press.
- Hattingh, A., Rogan, J.M., Aldous, C., Howie, S. & Venter, E. (2005). Assessing the attainment of learner outcomes in Natural Science of the new South African curriculum. *African Journal of Research in Mathematics, Science and Technology Education*, 9, 13-24.
- Heller, J.I. & Reif, F. (1984). Describing effective human problem solving processes: Problem description in physics. *Cognition and Instruction*, 1, 177-216.
- Heller, P., Keith, R. & Anderson, S. (1992). Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving. *American Journal of Physics*, 60, 627-636.
- Hestenes, D. (1987). Toward a modeling theory of instruction. *American Journal of Physics*, 55, 440-454.
- Hewitt, P.G. (1983). Millikan Lecture 1982: The missing essential – a conceptual understanding of physics. *American Journal of Physics* 51, 305-311.
- Hobden, P.A. (1999). *The context of problem tasks in school physical science*. Doctoral dissertation, University of Natal, Durban.
- Howie, S.J. (2001). *Mathematics and science performance in gr.8 in South-Africa*, 1998/9. Pretoria: HSRC.
- Howie, S.J. (2003). Language and other background factors affecting secondary pupils' performance in mathematics in South Africa. *African Journal of Research in Science, Mathematics and Technology Education*, 7, 1-20.
- Huffman, D. (1997). Effect of explicit problem solving instruction on high school students' problem-solving performance and conceptual understanding of physics. *Journal of Research in Science Teaching*, 34, 551-570.
- Jansen, J.D. (1999). Why outcomes-based education will fail: an elaboration. In Jansen, J. & Christie, P. (Eds.), *Changing curriculum: Studies on outcomes-based education in South Africa* (pp. 145-155). Cape Town: Juta..
- Johnson, S., Monk, M. & Hodges, M. (2000). Teacher development and change in South Africa: a critique of the appropriateness of transfer of northern/western practice. *Compare*, 30, 180-192.
- Kahn, M. (2004). For whom the school bell tolls: Disparities in performance in senior certificate mathematics and physical science. *Perspectives in Education*, 22, 149-156.
- Kim, E. & Pak, S. (2002). Students do not overcome conceptual difficulties after solving 1000 traditional problems. *American Journal of Physics*, 70, 759-765.
- Larkin, J.H. (1979). Processing information for effective problems solving. *Engineering Education*, 285-288.
- Larkin, J.H. (1983). The role of problem representation in physics. In D. Gentner & A.L. Stevens (Eds.), *Mental Models* (pp.75-98). Hillsdale, NJ: Lawrence Erlbaum.
- Larkin, J.H., McDermott, L., Simon, D.P. & Simon, H.A. (1980). Expert and novice performance in solving physics problems. *Science*, 208, 1335-1342.
- Larkin, J.H. & Reif, F. (1979). Understanding and teaching problem solving in physics. *European journal of science education*, 1, 191-203.
- Larkin, J.H. & Simon, H.A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11, 65-99.

- Lawson, R.A. & Mc Dermott, L. (1987). Student understanding of the work-energy and impulse-momentum theorems. *American Journal of Physics*, 55, 811-817.
- Leonard, W.J., Dufresne, R.J. & Mestre, J.P. (1996). Using qualitative problem-solving strategies to highlight the role of conceptual knowledge in solving problems. *American Journal of Physics*, 64, 1495-1503.
- Maloney, D.P. (1994). Research on problem solving: Physics. In D.L. Gabel (Ed.), *Handbook of Research in Science Teaching and Learning* (pp. 327-354). New York: Macmillan.
- McDermott, L.C. (1991), Millikan Lecture 1990: What we teach and what is learned – closing the gap, *American Journal of Physics*, 59, 301-315.
- McMillan C. & Swadener, M. (1991). Novice use of qualitative versus quantitative problem solving in electrostatics. *Journal of Research in Science Teaching*, 28, 661-670.
- Pandor, N. (2006). Introducing the Debate on the Education Budget, Vote 15, National Assembly. <http://www.pmg.org.za/briefings/briefings.php?id=267>.
- Pare, P. (2006). Proceedings of the 14th annual meeting of the Southern African Association for Research in Mathematics, Science and technology Education, Pretoria.
- Pride, T., Vokos, S. & McDermott, L. (1998). The challenge of matching learning assessments to teaching goals: An example from the work-energy and impulse-momentum theorems. *American Journal of Physics*, 66, 147-157.
- Prophet, R. B. (1990). Rhetoric and reality in science curriculum development in Botswana. *International Journal of Science Education*, 12, 13-23.
- Redish, E.F. (1994). Implications of cognitive studies for teaching physics. *American Journal of Physics*, 62, 796-803.
- Reif, F. (1995). Millikan Lecture 1994: Understanding and teaching important scientific thought processes. *American Journal of Physics*, 63, 16-32.
- Reif, F., Larkin, J. H. & Brackett, G.C. (1976). Teaching general learning and problem solving skills. *American Journal of Physics*, 44, 212-217.
- Rogan, J.M. & Gray, B.V. (1999). Science Education as South Africa's Trojan Horse. *Journal of Research in Science Teaching*, 36, 373-385.
- Shaffer, P.S. & McDermott, L.C. (1992): Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies. *American Journal of Physics*, 60, 1003-1013.
- Van Heuvelen, A. (1991). Learning to think like a physicist: A review of research based instructional strategies. *American Journal of Physics*, 59, 891-897.
- Wright, D.S. & Williams, C.D. (1986). A WISE strategy for introductory physics. *The Physics Teacher*, 24, 211-216.