SYMBOLIC LANGUAGE IN CHEMISTRY – A NEW LOOK AT AN OLD PROBLEM

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ABSTRACT

When bridging students' decoding and encoding abilities in chemistry were assessed at the start of a South African Post Matric Program, it was clear that they experienced fewer difficulties in decoding than in encoding. Encoding from the names of chemical compounds to symbolic formulae caused considerable cognitive discomfort, with students resorting to creating their own chemical symbols and combining atoms or groups in a 1:1 ratio in molecules by default.

The strategies implemented during the course were successful to some extent. The post-test scores of the students were significantly different from the pre-test scores, both in decoding and encoding. The improvement in performance was more marked in tests where recall from memory also played a role. Decoding improved more than encoding and there was no correlation between the two improvements for individual students.

Certain aspects have been shown to be problematic. Distinction between atoms/groups with names that sound very similar remained unsatisfactory even at the end of the year. These atoms or groups include for example "sulfide", "sulfate" and "sulfite". At the end of the course, a significant number of students were still combining symbols and formulae in incorrect ratios, particularly in encoding compounds not usually encountered in curriculum-related activities.

Recommendations are made for future teaching strategies.

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1 INTRODUCTION

1.1 General Introduction

Chemistry and chemical symbols are inextricably linked, and therefore the learning of chemistry depends largely on a learner's ability to use the required symbolic language with some degree of comfort (Barke, 1982). The symbolic language required in the study of chemistry should be seen as a motivational factor rather than a limiting one and learners should appreciate the universality entailed in the abstract language of chemistry (Jones, 1981). Some learners regard the use of chemical symbols as an introduction to authentic science (Jones, 1981), while other learners find the use of chemical symbols extremely challenging (Barke, 1982).

In South Africa, high school learners experience the same problems in using chemical language as their counterparts world wide. The present study assessed the ability of students who had passed through the South African educational system, and who had succeeded in a National Senior Certificate Physical Science Examination, to use symbolic language in chemistry. The study was aimed at investigating the students' ability to decode symbolic chemical formulae to names of compounds and to encode names of compounds to symbolic formulae. By categorizing students' responses, data could be analyzed quantitatively and improvement in decoding and encoding in three different tests could be established. Results obtained in the study have identified particular difficulties students experience and have lead to the development of alternative teaching strategies to address these difficulties.

1.2 Objectives of the study

The present study was designed to investigate some cognitive skills involved in the use and understanding of chemical formulae.

The study focused on:

a) *Translation tasks*, for example translation of words into chemical formulae and vice versa and words into chemical equations and vice versa. Translation tasks focus on *decoding and encoding skills.*

b) Creation of chemical formulae and chemical equations. Creation tasks focus on *encoding skills.*

c) The relation between chemical formulae and chemical equations and the composition and structure of the entities in question. These tasks focus on *comprehension skills.*

The level of the bridging students' decoding and encoding skills was assessed by a series of pre-tests administered early in the course year. Based on the findings in the pre-tests, strategies to develop decoding, encoding and comprehension skills were selected and implemented during teaching of the chemistry course. Students' decoding and encoding skills were re-assessed at the end of the year. This study aimed to answer the following questions:

1. How do decoding and encoding skills of bridging students compare at the start of a bridging course, after they had written the South African Senior Certificate Examination as completion of the senior high school chemistry curriculum?
2. Can decoding and encoding skills of bridging students be improved within the framework of a bridging course and curriculum-related activities?
3. Will decoding and encoding skills of bridging students improve equally during the course?
4. What problematic areas in decoding and encoding can be identified?

1.3 The sample and research setting

The sample was a convenience sample, comprising 25 students (11 male, 14 female, of average age 18.62 years), who were selected from fourteen secondary schools in the Rustenburg area, North West Province, South Africa, to participate in a Post Matric Program. This program was funded by a mining company (Impala Platinum) operating in the area. During the year the students spent in the Post Matric Program (hereafter referred to as the "course"), the subjects received tuition in Mathematics and Physical Science with the aim of improving their performance to C symbols or higher when rewriting the South African Senior Certificate Examination on Higher Grade in those two subjects at the end of the course year.

All subjects were English second language speakers. Setswana was the home language of the majority of subjects (19) with Isizulu and Afrikaans being the home language of two subjects respectively. One subject indicated that he/she spoke both Setswana and English at home. The language background of three subjects was not established. With the exception of the Afrikaans-speaking subject, all subjects had previously been taught secondary high school Physical Science with English as the language of instruction. The language of instruction in the course was English.

The study was conducted using a single-group, pre-and post-test research design. The researcher was involved in the delivery of the Chemistry component of the course and had five days' contact with the subjects approximately once a month, starting in January 2005 and concluding in November of the same year. Pre- tests were conducted at the start of the course (January and February 2005) and post-testing was done approximately seven months later (August and September 2005).

2. LITERATURE REVIEW

A considerable amount of research has been undertaken in various aspects of chemistry education and the cognitive skills associated with the learning of chemistry. The following brief review of work by other researchers serves as theoretical background to the present study. Aspects considered will include:

i) cognitive skills associated with the learning of chemistry and the use of chemical formulae,
ii) problems learners experience with the writing of chemical formulae,
iii) the use of language in chemistry, with particular reference to symbolic language and English second language learners.

2.1 Cognitive skills associated with the learning of chemistry and the use of chemical formulae.

Comparison of the performance in chemistry between concrete-operational and formal-operational students and the study of cognitive factors such as memory demand, memory space and field-dependency/independency were features of the decade 1975 – 1985, with few subsequent publications being available. Researchers have focused on two areas, namely:

i the application of Piaget’s theories in the teaching of science, and
ii using an Information Processing approach to address difficulties in the learning of chemistry.

2.1.1 Piaget’s Theories and the teaching of chemistry.

The following researchers investigated the concrete-operational/formal-operational dichotomy with respect to science in general: Ausubel (1964), Beistel (1975), Herron (1975), Chiapetta (1976), Lawson and Blake (1976), Lawson and Wollman (1976), Karplus (1977), Herron (1978), Cantu and Herron (1978), Henry (1978), Gabel and Sherwood (1980), Ward and Herron (1980), Philips (1983), Abraham and Renner (1986), Chandran, Treagust and Tobin (1987) and Nurrenbern (2001). Very few of the studies by the above researchers dealt specifically with decoding or encoding in chemistry. Ausubel (1964) hypothesized that there is a combined influence of three concomitant and mutually supportive developmental trends that account for a transition from concrete-operational to formal-operational reasoning. Firstly, the individual who is developing on cognitive level will gradually acquire a working vocabulary of mediating terms that will lead to combination of different related abstractions. Secondly, a greater number of stable, higher order concepts will become available. Thirdly, after the individual has had some practice in meaningfully understanding and manipulating relationships with the aid of concrete props, progression will take place to a stage where mental operations can be done without concrete props.

Science instruction should be self-pacing to assist concrete-operational students (Chiapetta, 1976). In the teaching of chemistry, Chiapetta (1976) suggested that teachers have to be sensitive to the needs of the learners — if students require hands-on instruction, the appropriate time for such instruction should be provided. Chiapetta (1976) also proposed the use of concrete assessment methods.

Lawson and Blake (1976) suggested that students should have free interaction with concrete materials and Nurrenbern (2001) acknowledged the role concrete activities could play in the transition from concrete-operational to formal-operational reasoning, but expressed the view that such activities should best be seen as short-term intervention strategies.

2.1.2 Information Processing and the teaching of chemistry.

The flow of information through the cognitive system can be regarded as consisting of information input, output and mental operations which process information between input and output (Danili and Reid, 2004). Cognitive structures determine how information is perceived, organized, stored, retrieved and used. Danili and Reid (2004) suggested that the processes necessary for the understanding of chemistry are different from processes required to comprehend everyday events. They see chemical symbols, formulae and equations as the third of three levels of thought necessary in the learning of chemistry, the other two levels being, first, the macroscopic and tangible aspects, and, second, the microscopic aspects which would include concepts of atoms, molecules, ions and molecular structures. Danili and Reid (2004) studied the effects of working memory space and field-dependency on the learning of chemistry by Greek students. Learning not only of chemistry, but of all new information will fail if the working memory space is overloaded. This could occur if students are given too much information at once. Chunking, or grouping pieces of information can be used to reduce the demands on the amount of information to be held in the working memory. Chunking will be affected by students' prior knowledge, experience and skills in a particular subject. Since chunking is highly individualised, students should be given the opportunity to develop their own chunking techniques (Danili and Reid, 2004).

2.2 The problems learners experience with the writing of chemical formulae.

South African learners are gradually introduced to symbolic language in chemistry. In the intermediate and senior primary phases, learners use names of compounds in the classroom. In the junior high school phase, chemical formulae are given in classroom notes, but learners are encouraged to rote-learn the formulae rather than understand the underlying principles needed to create the formulae. Some Grade 9 learners experience frustration with this approach and problems also emerge in the writing of balanced chemical equations at this stage. Even at Grade 10 level, when Physical Science becomes an elective subject, learners who have chosen to study Physical Science have mixed reactions to chemical symbols. Experience gained in the present study and elsewhere indicates that most Grade 10 teachers in South Africa find it necessary to devote a considerable amount of time to the teaching of underlying principles necessary for the writing of chemical formulae

According to Savoy (1988) the understanding of valency, appreciation of concepts of polyatomic ions and molecules and ultimately the production of correct chemical formulae will depend on students' knowledge of bonding. Unfortunately concepts in chemical bonding are highly abstract and it appears that only the most able students will be in a position to apply their knowledge of bonding effectively to scaffold the writing of chemical formulae.

In a study investigating German learners' understanding of the combustion of magnesium, Barke (1982) tested 272 learners in Grades 8, 9 and 10. Only learners who had been taught the reaction between magnesium and oxygen, who knew the symbols for the reaction and who were familiar with the particulate model of matter were selected to participate in the study. Only 30% of the learners in the study by Barke who could write the symbolic equation for the reaction between magnesium and oxygen correctly could also represent the reaction correctly on microscopic level (Barke 1982). The remaining 70% of the learners relied on memorising the chemical formulae in the equation, but showed no understanding of microscopic changes taking place – and perhaps no understanding of chemical formulae. Barke (1982) ascribed the lack of understanding of microscopic changes to the inappropriate introduction of chemical symbols when learners were not yet able to reason on an abstract level. He also concluded that the use of chemical symbols in itself cannot help learners to explain chemical reactions adequately.

The prohibitive cost of modelling kits has led to the development of more affordable teaching aids to assist teachers in teaching the writing of chemical formulae. In two such publications, Jones (1981) and Ball (1981) proposed the use of interlocking cardboard cards to help learners write chemical formulae correctly. Learners are provided with visual cues to write down chemical formulae. The teacher will still have to explain the difference in writing 2Na and Na_2. Frequent use during the early stages of chemistry teaching is suggested (Jones, 1981). The models proposed by Jones (1981) suffer from certain limitations, namely over-simplification of bonding, with the cards being only suitable for representation of simple, ionic compounds, with difficulties experienced in the representation of diatomic molecules and in representation of molecules where the oxidation number of a particular atom changes.

In a paper linking cognitive aspects of learning in chemistry to the use of symbols in chemistry, Strauss and Levine (1986) mentioned that students operating at concrete operational level will appreciate the use of symbols with the more macroscopic, experiential aspects of chemistry. Students at formal operational level will be able to understand the non-observable meaning of symbols. According to Strauss and Levine (1986), students should be encouraged to chunk information that they do not understand completely to enable them to use such information effectively in the interim. Such "chunked information" can be used in situations where only certain features of the chunked information are of interest. Students can, for instance, chunk the name “nitrate” to a symbol “NO_3^-“ without necessarily understanding how the nitrogen and oxygen atoms are bonded together.

2.3 The use of language in chemistry, with particular reference to symbolic language and English Second Language learners.

The precision of language in chemistry is problematic (Bradley, Brand and Gerrans, 1987; Ver Beek and Louters, 1991, Herron, 1996) and if teachers for example use the terms atoms, molecules and ions indiscriminately misconceptions will, invariably, be the result. Difficulties in the learning of chemistry can be precipitated by a lack of chemistry language skills. (Ver Beek and Louters, 1991; Marais and Jordaan, 2000; Danili and Reid, 2004).

In their study investigating the ability of American students to solve problems in chemistry Ver Beek and Louters (1991) noticed a threshold response — students could solve problems of increasing difficulty until they had to work with one additional language item they did not understand. In single step problems the subjects in Ver Beek and Louters’ study could solve 91% of common language problems and 82% of chemical language problems. In three-step common language problems the success rate was 86%, but in three-step chemical language problems the success rate dropped to 32%. The authors recommended the following to address problems in chemical language (Ver Beek and Louters, 1991):

1) Students’ exposure to chemical language should be maximised.
2) Teachers should not assume that students are familiar with chemical terms and terms should be introduced carefully.

Herron (1996) indicated that one of the problems in the use of chemical language is that students do not reject incorrect or unacceptable chemical statements when they are processing chemical sentences superficially. Only if students understand the semantic meaning of chemical phrases and equations (in other words, if they clearly connect symbols to acceptable chemical practice) will they be able to reject unacceptable chemical statements or equations. The connections between symbolic representations and real-world knowledge of chemical processes are integrated for the expert and the expert relies on experience to interpret chemical symbols and equations meaningfully. The novice lacks the knowledge to assess his or her interpretation of chemical statements and the skill to understand and use chemical language will need to develop before the student has necessarily gained semantic knowledge.

Herron (1996) recommended the introduction of word games and word-attack skills during the teaching of chemistry. He also recommended that certain information should only be accessible by reading. Forcing learners to obtain information from reading would compel them to use chemical language (Herron, 1996). On the basis of experience, students should know when minor changes in symbolic meaning produce major changes in semantic meaning (Herron, 1996).

In a South African context, Marais and Jordaan (2000) tested the performance of 136 university first year chemistry students on the meaning of words and symbols describing chemical equilibrium. The study distinguished between letter symbols (e.g. Na, Ca, etc), iconic symbols (e.g. [ ] for concentration in mol dm^{-3}) and combinations of letter and iconic symbols (e.g. Na^+). The authors identified the cognitive steps necessary to interpret a simple chemical equation at equilibrium. Marais and Jordaan (2000) found that students experienced greater problems in interpreting symbols than words correctly. Based on their findings, Marais and Jordaan (2000) recommended that:

1) Students' understanding of symbols should be tested by including meaning items in content-related tests,
2) Students' should be discouraged from regarding chemical symbols as merely short-hand notations which could be adapted to suit the individual user,
3) Students' should be provided with a glossary of symbols, and
4) Students should be given group or individual exercises to supply correct symbolic notation.

In a second publication with a South African perspective, Rollnick (2000) discussed the second language learning of science. Some of the disadvantages the bridging students in this study may have suffered during their formal schooling are discussed briefly in the paper by Rollnick. Teachers in formerly disadvantaged schools, particularly in rural areas, are sometimes poorly qualified in both their scientific content knowledge and their command of English. Textbooks written in English are often the only resources for these teachers, but they are unable to mediate the text owing to their own poor background in the use of English. Science texts often present greater challenges to understanding than the texts students use for language instruction. Some problems will also exist in the verbal component if the language of instruction is not the home language. According to Danili and Reid (2004), if students study chemistry in a language other than their mother tongue, difficulties experienced in chemical language could be linguistic, contextual or cultural in nature. Rollnick (2000) recommended that second language science students need the opportunity to practice science in the presence of more capable peers and they need to be introduced overtly to the language requirements of the particular discipline.

3. DESIGN OF THE CHEMISTRY COURSE IN THE POST MATRIC PROGRAM

The design of the chemistry course for the Post Matric Program was based on considerations from the theoretical background, suggestions from the course coordinator and experiences gained during teaching of Senior High School Physical Science. The design considered four aspects:

i) Developing bridging students’ cognitive skills in chemistry;
ii) Addressing problems bridging students could be expected to experience in the writing of chemical formulae;
iii) Encouraging development of chemistry language; and
iv) Introducing bridging students to molecular modelling.

3.1 Design features of the chemistry course and intervention strategies aimed at a transition from concrete-operational to formal-operational reasoning.

3.1.1 Course notes

In the course, the writing of chemical formulae was addressed formally in the second contact week during one session of two hours. The intervention was introduced after pre-testing. The Course notes included notes on arrangement of electrons in atoms, trends in electronegativity and basic rules for establishing the valency of simple atoms. Course notes were extended to include notes on the use of Stock Notation and a comprehensive list of polyatomic ions commonly used in the Senior High School Chemistry Curriculum. Subjects were given the opportunity to practise the writing of chemical formulae during the session.

3.1.2. Addressing microscopic and macroscopic aspects in chemistry

To assist concrete-operational students who experience difficulty in visualising or conceptualising atoms and molecules, it is recommended in the literature that macroscopic properties are covered before an attempt is made to study microscopic properties (Beistel, 1975). In the present study, with its unique time constraints, this suggestion could be implemented to a limited extent. In the introductory week, for instance, some experiments were done and the microscopic properties the bridging students should have encountered in Grade 10 were reviewed.

3.1.3 Hands-on sessions and use of concrete materials

In a survey conducted during the course introduction it was established that many of the bridging students had little or no prior experience of practical work in chemistry. The bridging students in the present case were therefore given ample time during hands-on sessions, as suggested by Chiapetta

(1976). These sessions were either experimental in nature, with students doing their own microchemistry experiments, or consisted of opportunities for the learners to use molecular modelling kits. At the end of the course, the students were requested to comment on the chemistry course. From their responses, it was very clear that they experienced these hands-on sessions as helpful.

It has been suggested that students should have free interaction with concrete materials (Ausubel, 1964; Lawson and Blake, 1976; Gabel and Sherwood, 1980; Madden and Jones, 2002). This was one of the reasons why the bridging students were each provided with a set of cards to use in the writing of chemical formulae (Jones, 1981) and molecular modelling kits (Molymod® Inorganic and Organic Modelling Kits for Students, manufactured by Spiring Ltd, UK) were made available regularly. Course material in Week 3 dealt with the shapes of a limited number of molecules and models were used extensively in this section. In Week 4, particular attention was given to the differences between sulfur in elemental sulfur, sulfur in sulfide, sulfur in sulfur dioxide and sulfur in sulfur trioxide. Models could be built to illustrate the different valencies associated with sulfur in different compounds. In Week 5, models were used to illustrate the differences between nitrogen oxide, NO, and nitrogen dioxide, NO_2. Models of nitrogen and ammonia molecules were also constructed. Subjects were using the modelling kits extensively during the week dealing with Organic chemistry. Although the use of the modelling kits with organic chemistry might not contribute to any improvement in pen-and-paper decoding and encoding tests (which dealt only with inorganic compounds), it might contribute to better appreciation of the three-dimensional nature of molecules.

3.1.4 Assessment and level of tasks

Only two assessment tests dealt exclusively with rote-learning of chemical formulae. One of the items was administered on the second day of Week 7, the subjects being informed about it on the first day of that week. The test was marked and results were discussed with the subjects. Only a few subjects achieved a perfect score. The same test was written one day later and most subjects could now achieve a perfect score. A second test was administered on the last day of the same week. This test required subjects to distinguish between sulfide, sulfate and sulfite in one question and to match the correct chemical formula to chlorate, hypochlorite, chloride, perchlorate and chlorine. In assessment, incorrect spelling was noted and if it caused the meaning of a chemical sentence to be incorrect, no credit was given.

3.1.5 Whole-class and small group teaching

In accordance with a recommendation by Chandran, Treagust and Tobin (1987), the chemistry course was designed to provide both whole-class teaching situations and small-group teaching situations. Formal-operational students are expected to benefit from the former and concrete-operational students to benefit from the latter teaching methodology (Chandran, Treagust and Tobin, 1987).

3.2 Designing the chemistry course to address problems bridging students could experience in the writing of chemical formulae- strategies used to teach chemical formulae

The three-step teaching strategy proposed by Newbury (1964) was broadly followed in the present study. Subjects were firstly given an exercise on elementary particles (atoms or molecules of elements and molecules of compounds) as part of a general introduction during the first week of the course. In subsequent writing of chemical formulae, subjects were given the opportunity to use word equations in a limited number of cases and to illustrate the easier equations with models. Thirdly, the use of models to illustrate valency, as suggested by Newbury (1964), could be implemented with the modelling kit used in the present study (the Molymod® Students' Kit for Inorganic and Organic Chemistry, manufactured by Spiring Ltd., UK). The extensive practice in the writing of chemical formulae recommended by Newbury could be offered in the present study in a single two-hour session in the second week of the course. The existence of ions such as HCO_3^-, SO_4^{2-} and NH_4^+ was also emphasised in the present study.

Alternative strategies were introduced to address difficulties bridging students experienced in the writing of chemical formulae. After careful consideration of the inherent limitations outlined earlier, it was decided to introduce the subjects in the present study to Jones cards (Jones, 1981) in a single session of thirty minutes in the second week of the chemistry course. Only simple ionic compounds were used. The limitations of the Jones cards were addressed during subsequent sessions of the course and subjects were also encouraged to use the three-dimensional modelling kit more extensively than the cards.

3.3 Designing the chemistry course to encourage development of chemistry language - chemistry for second language learners

Experience indicated that English second language speakers entering the Post Matric Program could have problems with words such as “produces”, “decomposes” or “representations” in spite of previously writing and passing an English Second Language Senior Certificate Examination. The textbooks used in the science course in the Post Matric Program (Brink and Jones, 1996) have a general glossary included at the end of each volume and definitions of concepts at the end of each chapter. Bridging students in the present study could refer to both sections freely during teaching and learning, but not during testing. It was found that in some cases, the language used in the particular textbook glossaries was not accessible to students. In verbal instruction during the course, particular attention was paid to differentiating between words that could sound very similar if not articulated properly, for example chlorine and chloride and sulfate and sulfite. Emphasis was placed on accuracy in spelling.

3.4 Introducing bridging students to molecular modelling

In a survey designed to assess bridging students' prior experience of molecular modelling, one subject indicated that he/she had seen the use of molecular models demonstrated. 22 subjects indicated that they had no experience of molecular modelling. The use of molecular modelling was recommended by Gabel and Sherwood (1980) to improve students' performance in chemistry and to promote the transition from concrete-operational to formal-operational reasoning. In the present study, two-dimensional representations of inorganic and organic molecules were related to three-dimensional models during teaching. Bridging students' modelling skills were assessed in the course, the findings of these investigations will be reported elsewhere.

4. TEST ITEMS AND ANALYSIS OF RESULTS

4.1 Test items

The same test items were used for pre- and post-testing. The tests were in pen-and-paper format and subjects answered individually. Responses were collected immediately afterwards and not discussed with the subjects at any stage. Tests 1 - 3 were administered early in the morning at the beginning of the various Chemistry contact weeks, with the decoding test item being placed before the encoding test item.

4.1.1 Test 1

Decoding

In Decoding Test 1, subjects were given symbolic representations (correct chemical formulae) of a number of familiar compounds and were required to write the name of the chemical compound represented by the formula in words. The test contained five items: four compounds comprised of electropositive metal atoms and simple electronegative atoms or groups, namely FeS, CuO, LiBr and KOH, and one compound contained both an electropositive and electronegative polyatomic group (NH_4NO_3). The test was in the form of a table, with the given chemical formulae in one column and corresponding spaces left in a second column. Subjects were only required to fill in the missing names represented by the chemical formulae. A trivial example was given at the start of the test. Subjects were also given a Periodic Table normally used during South African Senior Certificate Examinations. This version of the Periodic Table gives element symbols, atomic number, electronegativity and relative atomic mass, but no names or valencies of elements. Thus the Periodic Table subjects used in the study differed considerably from the approved IUPAC Periodic Table.

Encoding

In the first encoding test, subjects were given the names of familiar chemical compounds and were asked to write the chemical formulae in symbolic form. The test was again in the form of a table, with a trivial example given at the beginning. Subjects were required to complete the table by supplying the corresponding chemical formulae. In the first encoding test, only compounds the subjects should have encountered previously at school were used. Test items were selected to cover combination between the electropositive and electronegative portions of the molecules in ratios of 1:1 (sodium chloride), 1:2 (magnesium iodide), 1:2 (calcium hydroxide), 2:1 (potassium sulfide) and 1:3 (aluminium chloride).

4.1.2 Test 2

Decoding

In the second decoding test, subjects were given five balanced chemical equations in symbolic form and asked to write the equations in words. Five compounds, one from each equation, deemed similar in degree of difficulty and composition to those used in Test 1 were selected from the responses and analysed. Items analysed comprised KBr, $AgNO_3$, NaOH, Na_2SO_4 and $KClO_3$. A trivial example was given at the start of the test and spaces for subjects to write their responses were provided. Since the aim of the study was not to test subjects on their understanding of reaction stoichiometry, the example made no mention of the stoichiometric ratios of the reactants or the product and no aspects of referring to stoichiometric ratios in the chemical equations were analysed.

Encoding

After the second decoding pre-test, the subjects were given chemical equations written in words and were required to translate these into symbolic chemical equations. Although the symbolic equations should have been balanced, little emphasis was placed on the balancing by giving the subjects the instruction: “Write the following chemical equations by using chemical formulae” and using as example an equation in words which did not require any balancing when translated into a symbolic equation.

Compounds in the chemical equations that were considered comparable to compounds used in the first encoding test were analysed, namely potassium hydroxide, ammonia, zinc chloride, calcium sulfate and nitrogen dioxide.

4.1.3. Test 3

Decoding

Since an aim of the pre-testing was to try and establish whether subjects were using the correct mental processes during decoding, and not relying on recalling either the names of compounds or the formulae from memory, the third test contained five items of compounds not usually encountered in the study of Senior High Physical Science. Information was therefore supplied to the subjects as part of the test item. The information contained the names, symbols and valencies of the chemical species used in both Decoding Test 3 and Encoding Test 3. The compounds used in decoding included AgCNS (decoded to silver thiocyanate), $Rb_2S_2O_6$ (decoded to rubidium dithionate), $Sr(ClO_4)_2$ (decoded to strontium perchlorate), $Co_2P_2O_7$ (decoded to cobalt pyrophosphate) and $FeHPO_4$ (decoded to iron hydrogenphosphate).

Encoding

Subjects were given the names of unfamiliar chemical compounds and were required to translate the names to symbolic formulae. Additional information on the formulae, names and valencies of chemical species was given. The compounds used in encoding included gallium selenide (encoded to Ga_2Se_3), uranyl sulfate (encoded to UO_2SO_4), ferric oxalate (encoded to $Fe_2(C_2O_4)_3$), tin(IV) cyanide (encoded to $Sn(CN)_4$) and tantalum pentoxide (encoded to Ta_2O_5).

4.2 Analysis of data

4.2.1 Analysis of decoding data

Coding of decoding data, Decoding Tests 1 – 3.

Responses obtained in Decoding Tests 1 – 3 were coded as follows for both pre- and post-tests:

Type 1:	the name of the compound was written entirely correctly.
Type 2:	the electropositive portion of the compound was decoded correctly, but the electronegative portion of the compound was decoded incorrectly.
Type 3:	the electropositive portion of the compound was decoded incorrectly, but the electronegative portion was decoded correctly.
Type 4:	decoding of the chemical formula was incorrect for both electropositive and electronegative portions of the compound.
Type 5:	no answer was attempted or subjects indicated that they didn't know or couldn't recall the correct response.

Responses for each individual subject were first coded using the proposed coding scheme. Thereafter the data were entered on a spreadsheet, assigning a numerical value of 1 to the type of answer for each test item. For each subject, the spreadsheet allowed calculation of the total number of Type 1 answers, the total number of Type 2 answers, etc. for all five test items. The number of Type 1, 2, 3, 4 and 5 responses obtained from all subjects could be expressed as a percentage of the total number of responses in a particular decoding test.

Responses were awarded marks as follows: Type 1 responses: 2 marks; Types 2 and 3 responses: 1 mark each and Type 4 and 5 responses: 0 marks. The maximum score a subject could therefore obtain in a single decoding test would be 10 if all five test items led to a Type 1 answer. If totals from all the decoding pre-tests were added, the maximum possible score for a subject would be 30. A similar maximum score for decoding in post-tests would also be 30.

A Facility Index was calculated for each item using the total number of Type 1 responses recorded for the particular item (Savoy, 1988).

4.2.2 Analysis of encoding data

Coding of encoding data, Encoding Tests 1 - 3

Responses obtained in Encoding Tests 1 – 3 were coded as follows for both pre- and post-tests:

Type A:	all the chemical symbols are correct, and the molecular formula is correct with respect to the combination ratio between atoms or groups, for example NaCl for sodium chloride.
Type B:	all the chemical symbols are correct, but the molecular formula is incorrect with respect to the combination ratio between atoms/groups, for instance $NaCl_2$ for sodium chloride.
Type C:	one or both of the chemical symbols are incorrect, but the molecular formula is correct with respect to the combination ratio between atoms/groups, SCl for sodium chloride, for example.
Type D:	one or both of the chemical symbols are incorrect and the molecular formula is incorrect with respect to the combination ratio between atoms/groups, for instance SCl_2 for sodium chloride.
Type E:	the molecular formula was not attempted, the subject “did not know” or “did not remember” the answer.

Responses for each individual subject were first coded using the proposed coding scheme. Thereafter the data were entered on a spreadsheet, assigning a numerical value of 1 to the type of answer for each test item. For each subject, the spreadsheet allowed calculation of the total number of Type A answers, the total number of Type B answers and so on for all five test items. The number of Type A, B, C, D and E responses obtained from all subjects could be expressed as a percentage of the total number of responses in a particular encoding test.

Type A answers were awarded 2 marks, Type B and C answers 1 mark each and Type D and E answers 0 marks. The maximum score a subject could therefore obtain in a single encoding test would be 10, if all five test items led to a Type A answer. If totals from all the encoding pre-tests are added, the maximum possible score for a subject would be 30. The maximum score for encoding in post-tests would also be 30.

A Facility Index was calculated for each item using the total number of Type A responses recorded for the particular item (Savoy, 1988).

4.2.3. Comparison of Pre- and Post-test performances

Paired, two-tailed t-tests were conducted to establish whether decoding pre-test scores for individual subjects differed significantly from their post-test scores. If the two-tailed, paired t-tests indicated that differences were significant, one-tailed, paired t-tests were conducted to establish whether the differences were due to improvement (Lemmer, 2006). Similar t-tests were conducted for encoding.

Using Hake’s Fraction of Possible Gain to quantify improvement in performances between pre- and post-testing

Quantifying general trends in results

In order to quantify improvement between pre- and post-testing, an average Hake’s Fraction of Possible Gain for each decoding or encoding test can be calculated as follows (Redish, Saul and Steinberg, 1997; Joyner and Larkin, 2002):

$$h = \text{(actual gain)/ maximum possible gain)}$$

$$= \frac{\text{(average post score, \% – average pre score,\%)}}{\text{(100 – average pre-score, \%)}}$$

For decoding the formula would become:

$$h = \frac{\text{(\% of Type 1 answers in Post-test - \% of Type 1 answers in Pre-test)}}{\text{(100 - \% of Type 1 answers in pre-test)}}$$

For encoding the formula would become:

$$h = \frac{\text{(\% of Type A answers in Post-test - \% Type A answers in Pre-test)}}{\text{(100 - \% of Type A answers in pre-test)}}$$

This statistical tool shows improvement based on pre-test performance, so even if the percentage of correct answers in two pre-tests differed, an equally high Hake’s Fraction can be calculated for both tests, depending on the post-test scores. A high average Hake’s Fraction of Possible Gain indicates that scores improved considerably between pre- and post-testing in the particular test. An average Hake’s Fraction of Possible Gain equal to 1.00 implies that performance between pre- and post-testing improved as much as possible. A negative average Hake’s Fraction of Possible Gain indicates that performance in post-testing was inferior to performance in pre-testing. The proposed equation to calculate Hake’s Fractions of Possible Gain cannot be used if the pre-test score was 100%.

Quantifying improvement between pre- and post-testing for individual subjects

The total pre-test and post-test scores for individual subjects in decoding (or encoding) could also be used to calculate the Hake's Fraction of Possible Gain for each subject for either decoding or encoding. These figures are potentially useful, since they would indicate whether subjects' performances in decoding and encoding improved to the same extent.

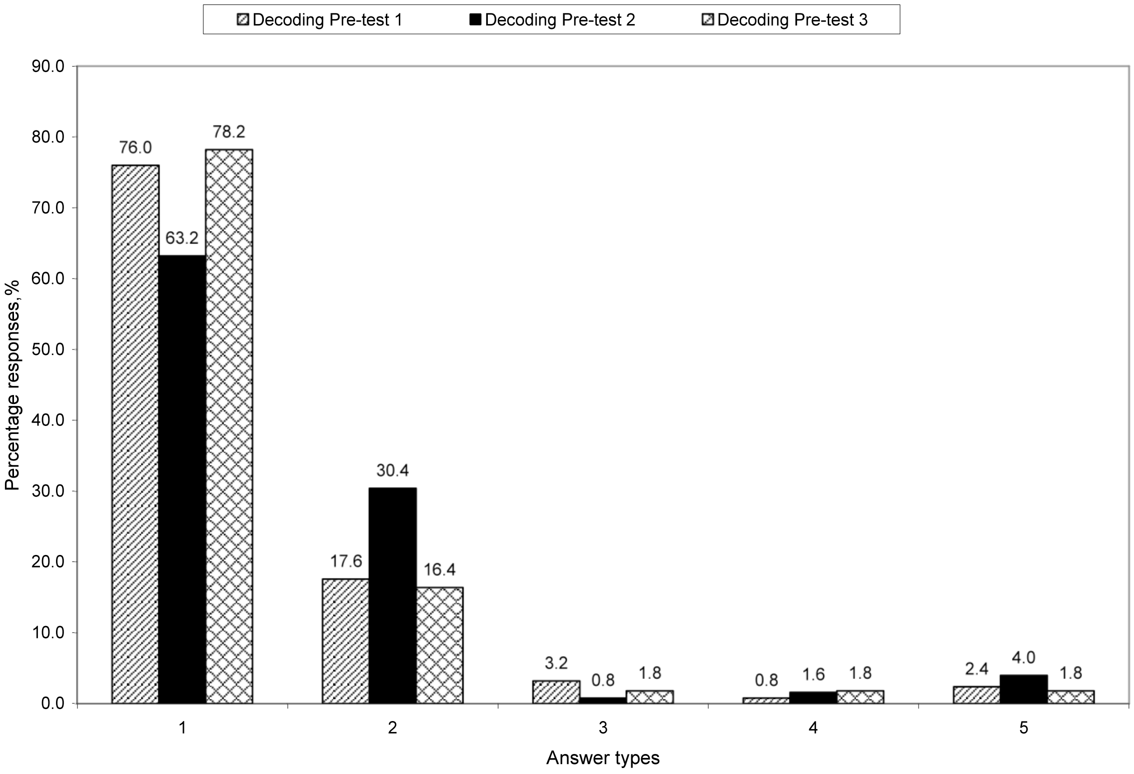
5. RESULTS AND DISCUSSION

5.1 Decoding results

The results obtained in Decoding Pre-tests 1, 2 and 3 are given in Figure 1.

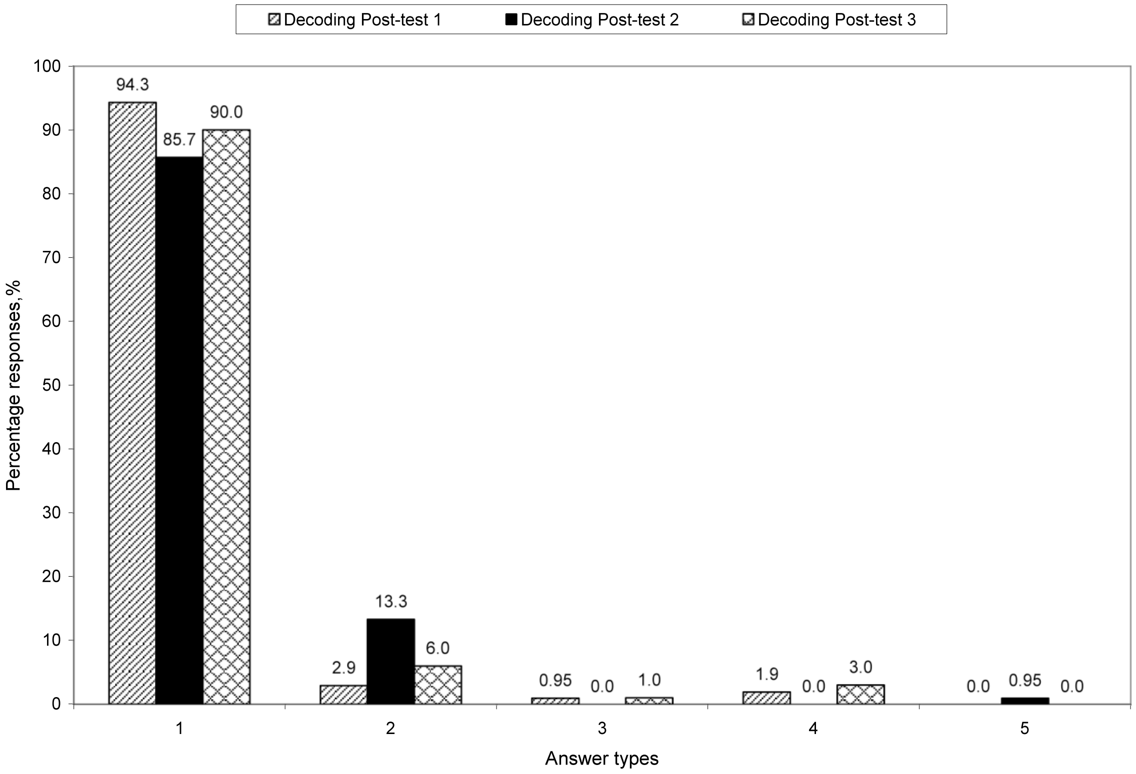
The results obtained in Decoding Pre-tests 1, 2 and 3 indicate that subjects could decode symbolic chemical formulae to names of compounds with a reasonable level of competency, with percentages of Type 1 answers of 76.0%, 63.2% and 78.2% obtained for Decoding Pre-tests 1, 2 and 3 respectively. Only Type 2 answers, in which the electronegative portions of molecules were decoded incorrectly, were significant. Very low percentages of Type 3, 4 and 5 responses were recorded.

Figure 1 Comparison of results obtained in Decoding Pre-tests 1, 2 and 3



The results obtained in Decoding Post-tests 1, 2 and 3 are given in Figure 2.

Figure 2 Comparison of results obtained in Decoding Post-tests1, 2 and 3



Subjects could improve their decoding skills during the course to the extent that the percentage correct responses (Type 1 answers) increased for all three tests. The number of Type 2 answers (correct decoding of the electropositive portion, but incorrect decoding of the electronegative portion) decreased during post-testing.

5.2 Comparison of Pre- and Post-test Decoding results

When the graphs depicting the results for the three decoding pre-tests in Figure 1 are compared to the graphs for the three decoding post-tests in Figure 2, it can be seen that there were improvements in all three tests. An average Hake's Fraction of Possible Gain for each decoding test can be calculated as outlined above. The results are summarized in Table 1.

Table 1 Average Hake's Fractions of Possible Gain for Decoding Tests 1, 2 and 3

Decoding test Number	Average Hake's Fraction of Possible Gain
1	0.76
2	0.61
3	0.54

The average Hake's Fractions of Possible Gain calculated for improvement in decoding in the present study are pleasing when compared to values of 0.23 and 0.48 obtained in studies investigating students' improvement in Physics (Redish, Saul and Steinberg, 1997; Joyner and Larkin, 2002). The results of Decoding Test 3, a test which entailed the decoding of unfamiliar chemical formulae to the names of the compounds, showed the least possible gain. This is also the test that would rely the least on recall, since these compounds were never used in the period between pre- and post-testing. It would be reasonable to assume that the average Hake's Fraction of 0.54 is indicative of an improvement in the decoding ability of the subjects if recall plays very little part. In both Decoding Tests 1 and 2 some effects of recall could have played a role, leading to higher average Hake's Fractions. The test items used in Decoding Test 1 comprised items often referred to during the chemistry course. The test items used in Decoding Test 2 consisted of balanced symbolic chemical equations. Subjects would have used four of these equations during the chemistry course. In the fifth test item the particular equation did not form part of the curriculum.

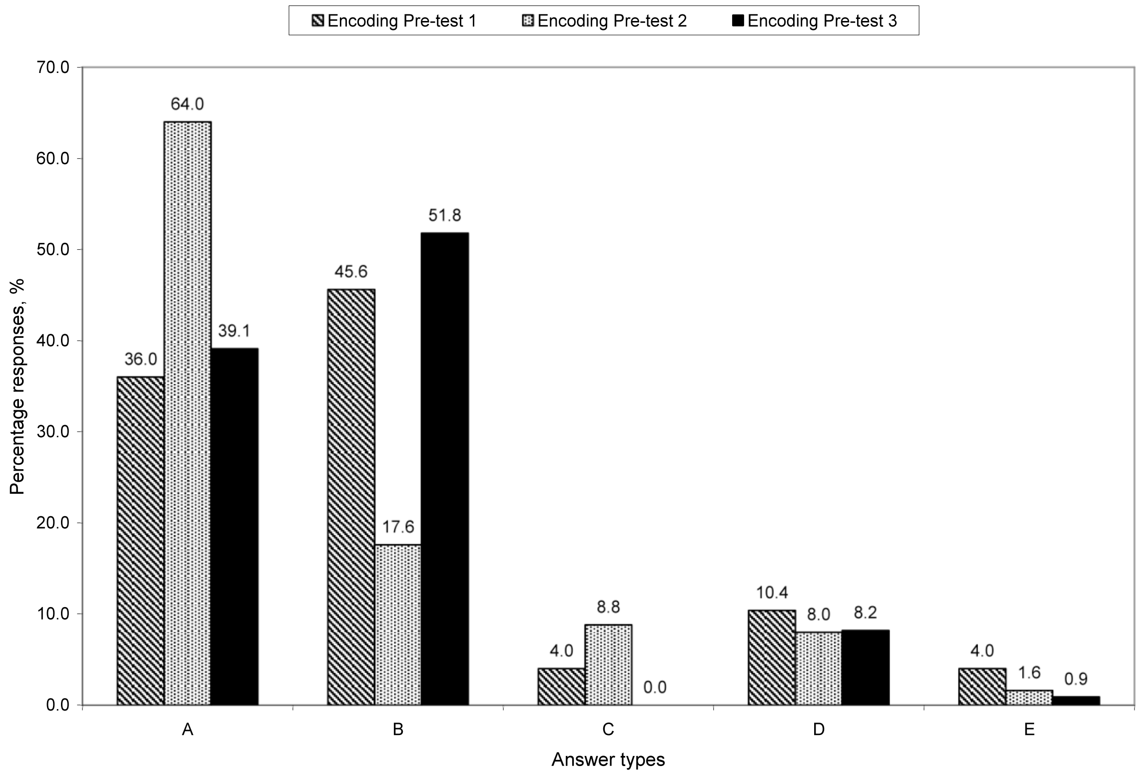
A two-tailed, paired t-test indicated that the differences between decoding pre- and post-test results were significant ($p = 0.000357$). A subsequent one-tailed, paired t-test indicated that the difference between pre- and post-test results could be ascribed to improvement in decoding ($p = 0.000178$).

5.3 Encoding results

The results obtained in Encoding Pre-tests 1, 2 and 3 are given in Figure 3.

These results clearly show that subjects found encoding considerably more difficult than decoding. The percentage correct answers amounted to only 36.0%, 64.0% and 39.1% for Encoding Pre-tests 1, 2 and 3 respectively. Most of the errors could be ascribed to Type B answers in which the symbols were encoded correctly, but the ratio in which atoms/groups were combined in the formula were incorrect.

Figure 3. Comparison of results obtained in Encoding Pre-tests 1, 2 and 3



The results obtained in Encoding Post-tests 1, 2 and 3 are given in Figure 4. The number of correct responses increased significantly in the Encoding Post-tests and the number of Type B answers decreased.

Twenty four of the errors recorded in Encoding Post-test 1 led to Type B answers in which the correct chemical symbols were used, but the ratio in which the atoms or groups of atoms in the compound were combined was incorrect. Instances of subjects' assuming a 1:1 combination ratio predominated and were recorded a total of eighteen times.

5.4 Comparison of Pre- and Post-test Encoding results

Upon comparing the graphs depicting the results for the three pre-tests to the graphs for the three post-tests, it can be noted that improvements occurred in all tests.

An average Hake's Fraction of Possible Gain for each encoding test can be calculated, using the equation proposed before.

Figure 4 Comparison of results obtained in Encoding Post-tests 1 , 2 and 3

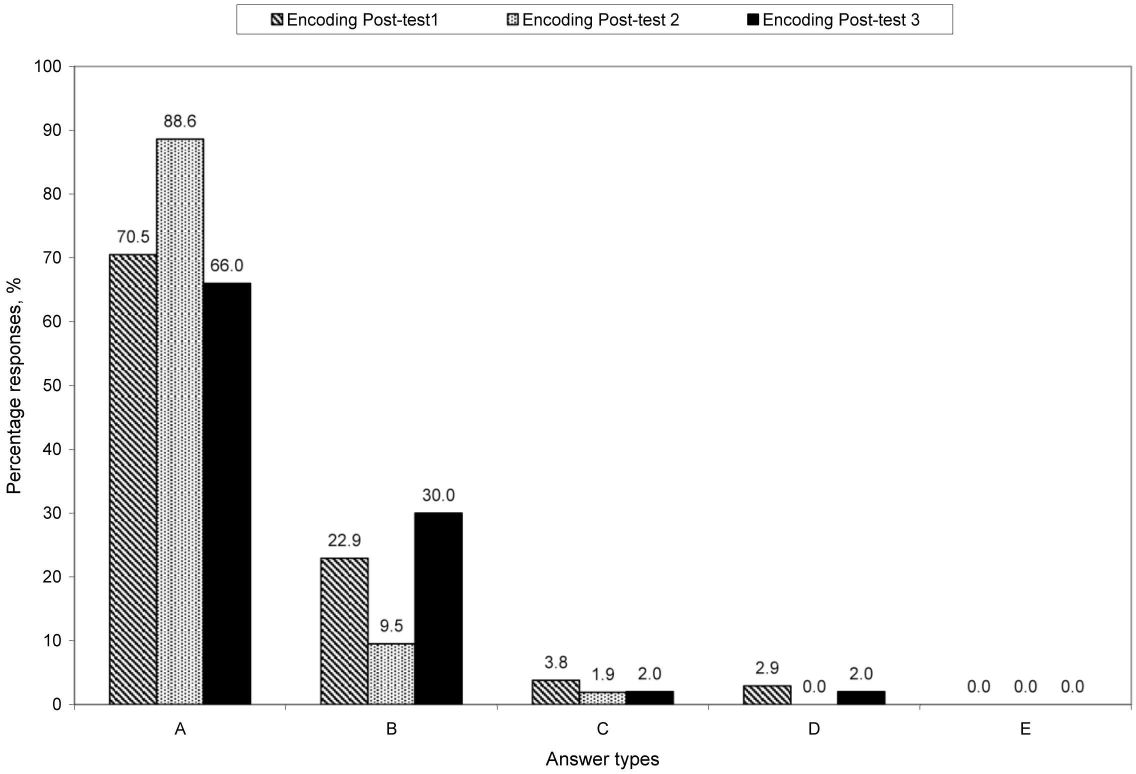


Table 2 Average Hake's Fractions of Possible Gain for Encoding

Encoding test Number	Average Hake's Fraction of Possible Gain
1	0.54
2	0.68
3	0.44

The results of Encoding Test 3, the encoding from the names of unfamiliar compounds to the chemical formulae, showed the least possible gain. This is however the test that would rely the least on recall, since these compounds were never used in the period between pre-testing and post-testing. It would therefore be reasonable to assume that the average Hake's Fraction of 0.44 is indicative of an improvement in the encoding ability of the subjects. In both Encoding Tests 1 and 2 some effects of recall could also have played a role in achieving the higher average Hake's Fractions (a similar observation was made for decoding). The test items used in Encoding Test 1 consisted of items often referred to during the chemistry course. The test items used in Encoding Test 2 consisted of balanced symbolic chemical equations. Subjects would have used all five of these equations during the chemistry course and it is possible that both the effects of recall and the context in which encoding had to be done contributed to the high average Hake's Fraction of Possible Gain.

A two-tailed, paired t-test indicated that the differences in encoding pre- and post-test scores were significant at all levels ($p = 2.1 \times 10^{-6}$). A subsequent one-tailed, paired t-test indicated that the differences in encoding test scores were due to improvement ($p = 1.04 \times 10^{-6}$).

The results obtained in the study allowed the calculation of a Hake's Fraction of Possible Gain in decoding and encoding for each individual subject. Calculation of a Spearman's Rank Correlation Coefficient indicated that there was no significant correlation between individual subjects' improvement in decoding and encoding, $R = 0.00559$, $p = 0.82$ (Lemmer, 2006).

5.5 The significance of results obtained in Decoding and Encoding Test 3

It is remarkable that Test 3 parallels Test 1 and 2 in both decoding and encoding. The percentage correct answers in Test 3 is very similar to the percentage correct answers obtained in Test 1, and the principal errors recorded in decoding comprise Type 2 answers in Test 1 and 3, and Type B errors in encoding. Since all the required information was given in Test 3, the result is recall-free. The results in Decoding Test 3 clearly indicate that the recognition of polyatomic groups in a formula is problematic.

Writing the polyatomic group in a bracket (required for strontium perchlorate), did not appear to lessen the problem – the decoding of $Sr(ClO_4)_2$ did not improve as much as the decoding of $FeHPO_4$ (Steenberg, 2006).

From Encoding Test 3 it is apparent that deriving stoichiometric ratios from valencies is problematic. This is not particularly surprising, but it is disappointing that 30% of the subjects still failed this task on post-testing. The results suggest that strategies designed to address this issue were not very effective.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In conclusion, it should be considered whether the overall aims of the Post Matric Course were achieved and the extent to which the present study was successful in answering the research questions. Some recommendations for future research and strategies to develop students' decoding and encoding skills will be proposed.

It should be noted that the sample used in the present study was a convenience sample comprising less than thirty subjects. In addition, the sample was located in a particular South African geographical and cultural setting. Results discussed below would refer to the present sample and generalizations to other populations should be tentative.

6.1 Research question 1: How did decoding and encoding skills of bridging students compare at the start of the course?

Results obtained in decoding pre-tests showed that bridging students in the Post Matric Program had moderate to fair skills in decoding at the start of the course. In Decoding Pre-tests 1, 2 and 3, correct answers amounted to 76.0%, 63.2% and 78.2% of the total number of responses respectively. Bridging students could therefore translate symbolic chemical formulae into names with some success. The results clearly show that Type 2 answers, or responses in which the electropositive atoms in compounds could be named correctly, but electronegative atoms were named incorrectly were the most common incorrect answers. Levels of Type 2 answers amounting to 17.6%, 30.4% and 16.4% of the total number of responses were obtained in Decoding Pre-tests 1, 2 and 3 respectively.

Results obtained in Encoding Pre-tests indicated that bridging students did not have the same level of encoding competence at the start of the course. In Encoding Pre-tests 1, 2 and 3, correct answers amounted to 36.0%, 64.0% and 39.1% of the total number of responses respectively. Type B responses, in which the correct chemical symbols were used but the ratio in which the atoms/groups were combined incorrectly in the compounds accounted for most of the errors. Type B answers amounting to 45.6%, 17.6% and 51.8% of the total number of responses were obtained in Encoding Pre-tests 1, 2 and 3 respectively.

One can therefore conclude that bridging students had better skills in decoding than encoding at the start of the Course. As these students had recently completed their high school curriculum, one may also conclude that this reflects the relative success in the teaching and learning of decoding and encoding in that curriculum.

6.2 Research question 2: Can decoding and encoding skills of bridging students be improved within the framework of a bridging course and curriculum-related activities?

Decoding skills of bridging students in the Post Matric Program did, on average, improve in all three decoding tests. Average Hake’s Fractions of Possible Gain of 0.76, 0.61 and 0.54 were obtained for Decoding Tests 1, 2 and 3 respectively. The level of improvement achieved in Decoding Test 3 ($h = 0.54$) is probably indicative of development in decoding skills other than recall, as items used in the test were unfamiliar and not discussed in the chemistry course. Effects of recall could have contributed to improvement in Decoding Tests 1 and 2. In considering the overall improvement in decoding for individual bridging students, it is worth noting that three students did not improve in decoding when their total scores for pre-test decoding were compared to their total scores for post-test decoding.

Encoding skills of bridging students in the Post Matric Program did, on average, improve also in all three encoding tests. Average Hake’s Fractions of Possible Gain of 0.54, 0.68 and 0.44 were obtained for Encoding Tests 1, 2 and 3 respectively. The improvement in Encoding Test 3 (h = 0.44) could again be indicative of development in bridging students' cognitive skills other than recall. The test items used in Encoding Test 3 were unfamiliar and not referred to during the course. Intervention strategies aimed at reducing bridging students' assumption of 1:1 combination ratios in molecules were only partially successful. Encoding skills improved for all bridging students in the Post Matric Program.

It is therefore possible to conclude that chemistry decoding skills for the majority and chemistry encoding skills for all bridging students in the Post Matric Program could be improved within the framework of a Post Matric course and curriculum related activities. Further more this improvement is not merely due to improved recall, as might happen in a course based on drill and practice. Some positive movement from concrete to formal operational reasoning may be claimed.

6.3 Research question 3: Will decoding and encoding skills of bridging students improve equally during the course?

None of the bridging students showed similar improvement in decoding and encoding skills. The extent of improvement in decoding or encoding varied widely for individual students. No trend for improvement was apparent from the data. Data were compared for trends with respect to gender and academic performance. It was also not possible to relate improvement in decoding or encoding to other factors such as improvement in chemistry performance as measured by performance in two chemistry examinations written as part of the course in June and September.

6.4 Research question 4: Can the study identify certain problematic areas in decoding and encoding?

Two problematic areas emerged from the study. In decoding, the distinction between ions such as sulfate, sulfite and sulfide (and distinction between nitrate, nitrite and nitride) remained difficult. The contributing factors could be linguistic as well as a lack of deeper understanding.

In encoding, some bridging students persistently resorted to a 1:1 combination for different atoms/groups in molecules by default. This indicates that bridging students are able to encode on the level of finding the correct chemical symbols but they experience greater difficulty in encoding on another level where the valencies of various atoms and groups have to be taken into account. This is true even if valencies are given (as in Test 3). Lack of chunking skills was also revealed in Test 3, in spite of “chunked” information being given.

6.5 Recommendations for future research

It could be interesting to study Grade 10 learners' competence in writing of chemical formulae using the research methodology trialled in this study. One distinct advantage would be that Grade 10 learners possibly would not yet have acquired strategies to cope with the writing of chemical formulae – it has been pointed out elsewhere that Grade 9 South African chemistry learners have to date, been encouraged to rote-learn chemical symbols and corresponding names of chemical formulae. The situation might change when the new South African National Curriculum Statement for Physical Sciences is implemented early in 2006, with teachers guiding learners in the use of appropriate strategies rather than encouraging them to rely on recall.

6.5.1 Teaching of decoding in inorganic chemistry using systematic naming

It is proposed that learners are taught to write the names of chemical compounds, from a symbolic representation in a four-step strategy:

Step 1:	Identify or name atoms or common groups of atoms represented in the formula.
Step 2:	Classify the atoms or common groups of atoms as electropositive or electronegative.
Step 3:	Note the ratios of atoms or common groups of atoms
Step 4:	Formulate the name

Example: A learner is given the formula $MgCl_2$ and has to write the name of the compound represented by the formula.

It is strongly recommended that learners are given the approved IUPAC Periodic Table on which both symbols and names of elements are given.

$MgCl_2$

Step 1:	magnesium	chlorine	Names of elements obtained from an IUPAC Periodic Table
Step 2:	electropositive	electronegative	This step will require information on electronegativity or knowledge of trends in the Periodic Table
Step 3:	magnesium	dichlorine	One magnesium atom, two chlorine atoms
Step 4:	magnesium dichloride		Name of electropositive atom does not change, name of electronegative atom ends differently. Learners will need to be given a list of name endings, for example, names for halogens in a compound end with – ide.

This four-step sequence illustrates the reasoning involved in decoding and could also be extremely useful as a diagnostic tool where learners are not making progress in decoding. Correct systematic names should be used until learners have achieved competency in decoding. Once decoding strategies are in place, learners can be introduced to the use of common names.

6.5.2 Teaching of encoding in inorganic chemistry using systematic naming

The following four-step process is proposed for encoding names of compounds to symbolic representations:

Step 1: Identify/assign a symbol or formula to atoms or groups of atoms represented in the name
Step 2: Deduce electropositivity/electronegativity from the location in the name
Step 3: Note evidence of atom or group ratio in the name and/or recognise valency of the groups
Step 4: Create a chemical formula

Example: A learner is required to write a chemical formula for sodium sulfate

	Sodium sulfate		
Step 1:	Na	SO_4	The symbol for sodium can be obtained from the IUPAC Periodic Table. A suitable information sheet with names of common groups of atoms can be compiled.
Step 2:	Electropositive	electronegative	The atom which is named first would be electropositive. The atom or groups of atoms which is named last would be electronegative
Step 3:	Valency: 1	Valency: 2	If the common name is given, there will be no indication of ratios for sodium or sulfate. Learners will have to be shown how to encode to a neutral molecule
	$1\underline{(2)}$	$2\underline{(1)}$	The subscript needed in the formula can be underlined to aid the learners In the writing of the formula.
Step 4:	Na_2SO_4		

It is recommended that systematic names are initially given in encoding problems. The proposed strategy emphasises the connectivity of atoms or groups of atoms and encoding to neutral molecules in Step 3. The step-wise approach allows for easy identification of difficulties learners could experience in encoding.

Experienced science teachers decode and encode intuitively, with little or no reflection on the mental processes they use to do so. These teachers might find the proposed four-step strategy useful for teaching. Individualised, intuitive methods of decoding or encoding can often not be conveyed to novices.

Less experienced teachers often lack suitable strategies to decode and encode successfully. The proposed four-step strategy is eminently suitable for such teachers to assess their own progress and identify their own weaknesses prior to teaching the topic.

Although the proposed four-step strategy is possibly more algorithmic in nature than decoding and encoding strategies being taught at present in inorganic chemistry, it is, however, not more so than strategies used very effectively to name organic compounds.

The efficacy of the proposed teaching strategy could be investigated in a test-group, control-group research design.

6.5.3 Researching the proposed new teaching strategies

In light of the foregoing proposals for new teaching strategies, it is recommended that the new strategies be implemented and their impact measured in

1) future bridging programmes in Physical Science
2) FET (Further Education and Training) Physical Sciences classes in selected schools
3) training courses (pre-service and in-service) for teachers of FET Physical Sciences.

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