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RESEARCH REPORT
Methods and issues of teaching and learning

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CHEMISTRY TEACHING IN LOWER SECONDARY SCHOOL WITH METHODS BASED ON: A) PSYCHOLOGICAL THEORIES; B) THE MACRO, REPRESENTATIONAL, AND SUBMICRO LEVELS OF CHEMISTRY

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ABSTRACT: Two teaching methods for the improvement of learning of the highly abstract and complex content of chemistry in lower secondary school were studied in this work: a) a method based on developmental psychology, and in particular on some of psychologist R. Case's proposals; (b) a 'three-cycle' method based on the distinction of school chemistry into three levels of approach according to A.H. Johnstone, namely the macroscopic, the representational, and the submicroscopic. The macro cycle did not include chemical notation, as well as the concepts of molecules and atoms. The representational cycle covered the same course material by adding chemical formulae and equations. The submicro cycle introduced atomic and molecular structure, and stoichiometry. Four teaching approaches, for three experimental groups and for one control group were tested. In the experimental groups, (a) some of Case's suggestions; (b) the three-cycle method; and (c) the combination of these two methods were applied respectively. All groups were subjected to the same evaluation tests at the end of the school year and at the beginning of the next year. The experimental groups scored higher at both tests, mainly on the theoretical questions. The group that followed the combination of Case's and Johnstone's suggestions was the best achieving one. Finally, the largest single positive effect was made by the three-cycle method. [*Chem. Educ. Res. Pract. Eur.*: 2000, *1*, 217-226]

KEY WORDS: *teaching methods; lower secondary school chemistry; developmental psychology; Case, R.; 'three-cycle' method; Johnstone, A.H; macroscopic level, representational level; submicroscopic level*

INTRODUCTION

In Greece, chemistry is taught for the first time as a separate subject in grades eight and nine of lower secondary school (*gymnasion*). Prior to that there is an integrated science course in grades five and six (primary school), where chemistry has a limited participation. According to the programme of studies and the corresponding standard chemistry school book (Frassaris & Drouka-Liapati, 1981) that were used until the school year 1996-97, many abstract chemical concepts at the submicro (molecular, atomic and subatomic) level were introduced quite early in the course: atomic and molecular structure, relative molecular mass, the mole, molar volume, Avogadro's constant, the building-up of the periodic table on the basis of the atomic (electronic) structure, chemical bonds (ionic and covalent), chemical reactions, stoichiometric calculations. (Since 1997-98, the situation has changed and improved considerably with a new programme of studies and new books.) It is well known that these concepts require formal operational reasoning in the Piagetian sense, and at the same time pose a heavy burden on students' working memory (Herron, 1978; Johnstone, 1991; Tsaparlis, 1997). This fact, combined with the very low teaching time allocated to chemistry (just one forty-five minutes period per week per year), as well as the lack of experiment/practical work from teaching, must be the causes of the very low knowledge of basic chemistry that Greek students used to demonstrate at the beginning (grade ten) of upper secondary school (*lykeion*).

An investigation of the above knowledge was carried out by Tsaparlis (1991, 1994b) in ten upper secondary schools in Ioannina, Athens and Piraeus, with respect to the following areas: chemical notation, atomic and molecular structure, chemical equations, and simple stoichiometric calculations. The average achievement was 20.5% (with standard deviation, SD, equal to 15.0%) in chemical theory, while in the problems it was 21.0% (SD = 26.4%). As we commented, 'it is as if students come to upper secondary school, and their only knowledge from foreign-language teaching is only the alphabet; no vocabulary, no grammar, no structure of the language'.

Chemistry education research has as one of its major targets to suggest new ways and methods of teaching chemistry. These ways and methods must not only be based on the proper educational theory (educational psychology, developmental psychology, science education), they must also be given support by experimental empirical work. In this paper a research effort is described that aims to improve student achievement in lower chemistry. [A preliminary account of this work was presented at the 2nd ECRICE (Tsaparlis & Georgiadou, 1993a; 1993b]. Motives in this effort were, on the one hand, the suggestions for improvement of teaching methodology by psychologist Robbie Case (Case 1977; 1978); on the other hand, the distinction of chemistry teaching into three levels, the macroscopic, the representational and the submicroscopic, a distinction that was proposed by Alex H. Johnstone (Johnstone, 1982; 1991). A great influence on this work has also been exerted by Piaget's theory of cognitive development and its implications for science education.

RATIONALE

The *information processing* model of learning (Sanford 1985; Johnstone, 1991) maintains that *perception*, driven by *long-term memory*, makes us distinguish the familiar from the unfamiliar. The new information is passed to *working memory*, where it is processed in an effort to be learnt, that is, stored in long-term memory. Working memory has a limited capacity (with some variation among people), so it can process only a few pieces of information at a time (Baddeley, 1986, 1990). This has considerable implications for learning. In addition, working-memory theory "can account for performance on tasks that involve both processing and storage, and both of these cognitive functions are likely to be required for most forms of scientific problem-solving" (Niaz & Logie, 1993, p. 519).

According to Case (1978a; 1978b), successful instruction must somehow accomplish the following two objectives: (a) to demonstrate to students that their current strategy must and can be improved upon, and (b) to minimise the load on students' working memory.

For the first objective to be accomplished, instruction must:

a. provide the student with some meaningful procedure for determining whether his or her approach has been successful;
b. present the student with problems for which his or her current strategy will not work;
c. provide an explanation for why the current strategy will not work, if this is not apparent to the student;
d. provide a demonstration of (or invite the student to discover) the correct strategy;

e. explain why the correct strategy works better, if this is not apparent to the student;
f. provide a period for practice with coaching, together with the opportunity to transfer the new strategy to new situations.

To minimise the burden on working memory, instruction must:

(i) reduce to a minimum the number of items of information that require student's attention;
(ii)insure that all cues to which the student must attend and all responses he or she must exhibit are familiar ones;
(iii) insure that all stimuli to which the student must attend are salient, either because of their physical characteristics make them stand out from their context, or because they are pointed out verbally by the instructor.

Chemistry is a difficult discipline to teach. According to Johnstone (2000), "the difficulties may lie in human learning as well as in the intrinsic nature of the subject". The concepts of chemistry are of a very different kind to most others met by learners. "The psychology for the formation of most of the concepts in chemistry is quite different from that of the 'normal' world." Johnstone (1991, 2000) maintains that in chemistry "we have the added complication of operating on and interrelating three levels of thought: the macro and tangible, the sub micro atomic and molecular, and the representational use of symbols and mathematics". In the case of the macro level, it is possible to have direct concept formation, as in the case, for instance of recognising metals and non-metals, acids and bases, flammable substances, etc. In the case, however, of concepts like elements or compounds, molecules, atoms, or electrons, bonding types, we are at the submicro level and it is very difficult for concepts to form. "It is psychological folly to introduce learners to ideas at all three levels simultaneously. The trained chemist can keep these three in balance, but not the learner".

With respect to Piaget's theory of cognitive development, we are aware, of course, of the problems and the criticisms this theory has faced - in particular his general postulated sets of cognitive structures (e.g. Lawson, 1991; Shayer, 1993). However, we count ourselves among those who believe that "*evidence indicates that there are sets of cognitive structures that significant numbers of people do in fact have in common*'' (Shayer, 1993). In our opinion, serious consideration should also be given to Niaz's argument (1993) that Piaget has used the scientific research methodology of idealisation to develop his genetic epistemology in a similar way to that used in various physics theories (e.g. Galileo's, Newton's, and the ideal gas law). Finally, we must take into account that Piaget is well-recognised as a constructivist.

METHOD

Four teaching methods were designed for the comparative study, and these were applied for three consecutive school years (1990-91, 1991-92, and 1992-93) by the same teacher, the one of the authors (A. G.), to a total of 380 grade-eight students of the same school. The school is a relatively prestigious experimental *gymnasion* in Piraeus, for which, however, the students are selected (as for all experimental schools in Greece) by drawing lots among all applicants.

The same research methodology was used in all three school years of the study. Table 1 has the topics that were taught. Each year, the students were divided into four groups, one control group and three experimental groups.

TABLE 1. *The chemical topics taught each school year (grade eight).*

- Chemistry as an experimental applied science.
- Soil - Mixtures.
- Atmospheric air.
- Water - Pure substances.
- Decomposition and synthesis of water - Compounds and elements.
- Molecules and atoms.
- Atomic and molecular mass - Avogadro constant - The mole - Molar volume of gases.
- The building up of atoms (electronic shell structure) - Periodic table.
- Formation of compounds - Types of bonding in molecules (ionic - covalent) - Valence.
- Chemical formulae - Writing and naming of inorganic compounds.
- Chemical reactions - Chemical equations - Stoichiometric calculations.
- Categories of inorganic chemical reactions.
- Acids - Hydrochloric and sulphuric acid.
- Bases - Sodium hydroxide.

All methods had the same general educational web: a constructivist teaching method, based on Piaget's theory of cognitive development; the instructor was constantly using experiments, models and dialogue in an effort to guide the students into the construction of new knowledge and its incorporation and connection with students' prior knowledge and mental structures. In all four groups, we had in common the following teaching features: planning, inductive approach to concepts, student-centred, attractive presentation.

The experimental groups followed the following methods:

1. Experimental group one, the *Case group*. Some of the Case's psychological suggestions were applied (see below).
2. Experimental group two, the *Johnstone group.* Johnstone's three-cycle model was used.
3. Experimental group three, the *Johnstone-Case group.* The above two methods were combined.

For the Case and the Johnstone-Case groups, teaching material and tasks were prepared that aimed at showing students the way they can and should improve the strategies they followed, but also at easing as much as possible the load on their working. The educational material included concept maps (Novak & Gowin 1984), simulation games and concrete models. To avoid misconceptions that are caused by the complete identification of concepts with models, we used a variety of models (Schrader, 1985; Stavridou, 1991). In addition, we used materials familiar to students from daily life, for example, colour paper-disks of various shapes for modelling metals and non-metals; students had to make these interlock with each other, as in a jigsaw game (Sapwell, 1990). The Moire pattern analogy of Bard (1981) was used to show that electrons move and form an electron cloud. Elements were represented with small spheres from plastelene bearing wire hooks, equal in number to the valence of the element: when atoms combine to form compounds, all hooks must be hooked (Schrader, 1985).

In addition, the following notations were used:

- symbols for physical states after chemical formulae (s, l, g, aq);
- electrical charges in the formulae of ionic compounds (e.g. Na^+Cl^-);
- parentheses for all ionic molecular groups, even in the case where they occurred only once in the formula of the compound, e.g. $(NH_4)^+(NO_3)^-$, $Ca^{2+}(SO_4)^{2-}$.

The traditional, algorithmic 'rule of three' which is being used as a rule in Greece for solving numerical stoichiometric problems was abandoned in favour of a 'logical method' that is based on logical thought and the use of simple arithmetic, and is well known to the students from their early elementary-school years (Zarotiadou, Georgiadou, & Tsaparlis

1995). Similar calculations of everyday life such as shopping transactions and measuring at home were used as analogues to stoichiometric calculations.

In applying the Johnstone model, we adopted the three cycle educational approach to chemistry. The first cycle (at the macro level) did not include either atomic and molecular structure or the use of chemical notation, and occupied half of the teaching time (the largest part of the lessons: 13/26). During this cycle, the students became familiar with the chemical substances and their properties. In the second cycle (the representational), the same course material was covered by adding now chemical formulae and equations, after an initial brief reference to atoms and molecules. Finally, in the third cycle, the same material was treated again, this time by introducing and using the abstract concepts of atoms and molecules, chemical bonds, the periodic table, relative atomic and molecular mass, molar volume, Avogadro's constant, and stoichiometry. Table 2 provides in detail the features of the three experimental teaching methods, together with those of the method used with the control group.

All students were subjected to Lawson's paper-and-pencil test of formal reasoning (Lawson, 1978) with the aim, firstly to classify them in the cognitive developmental stages, and secondly to check the equivalence of the groups. It was found that 22.1% of our sample (N= 380) were formal thinkers, 44.5% were in the transitional stage, and 33.4% were concrete thinkers. These findings are consisted with those reported by Shayer (1991) ($\chi^2 = 5.17$ and $p = 0.076$).

The students were distributed evenly in the four groups as was indicated by the crosstabulation statistical procedure. In addition, the four groups were found equivalent with regard to the cognitive ability: $\chi^2 = 0.125$ ($p = 0.99$). The same conclusion for the homogeneity of the samples was also found by means of one way analysis of variance (ANOVA): $F = 0.93$ ($p = 0.43$).

The chemistry tests

All groups (total $N = 380$) were subjected to the same evaluation tests twice: (a) immediately after completion of the teaching year (initial test); (b) at the beginning of next school year, that is, after about four months (retention test). Each test was given without notice. The tests lasted one teaching period (45 minutes), and aimed at checking retention, understanding and coding of basic chemical concepts and procedures. Two and the same tests were used in both the initial and the retention testing:

1. A test of theoretical knowledge of general and inorganic chemistry, on the following topics: (a) chemical notation (40% of the marks), (b) atomic structure (15%), (c) molecular structure (15%), and (d) chemical reactions-equations (30%). Table 3 provides an outline of this test.
2. A test on stoichiometric calculations, consisting of two problems: one consisting of five simple interdependent problems-steps (50% of the marks); and one composite problem, equivalent in content to the previous one (50%). Table 4 provides an outline of this test.

The tests were given in four equivalent forms, so as to avoid students' interaction in neighbouring seats. No significant difference was found among the four variations, as shown by ANOVA. Cronbach's *alpha* reliability coefficient was found equal to 0.79 (a satisfactory value), for the test of theoretical knowledge, and 0.58 for the test on stoichiometric calculations (a relatively satisfactory value, if we take into account that we had calculations here).

TABLE 2. *The features of the four teaching methods.*

GROUP →	**CONTROL**	**CASE**	**JOHNSTONE**	**JOHNSTONE-CASE**
Administration of educational material	According to Greek National Curriculum	According to Greek National Curriculum	In three cycles: Macro, representational sub-micro	In three cycles: Macro, representational submicro
Textbook	Standard textbook	Standard textbook	Modified textbook in three cycles	Modified textbook in three cycles
Experiments	Experiments demonstrated by the teacher	Students performed guided discovery experiments in groups of four	Experiments demonstrated by the teacher	Students perform guided discovery experiments in groups of four
Chemical notation	Classic (e.g. $NaCl$, NH_4NO_3, $MgSO_4$)	-Electrical charges in the formulae of ionic compounds (Na^+Cl^-); -Parentheses for molecular groups [e.g.$(NH_4)^{+(}NO_3)^-$ $Mg^{2+}(SO_4)^{2-}$] -Symbols for physical states (s, l, g, aq)	Classic (e.g. $NaCl$, NH_4NO_3, $MgSO_4$)	-Electrical charges in the formulae of ionic compounds (Na^+Cl^-); -Parentheses for molecular groups [e.g.$(NH_4)^+(NO_3)^-$ $Mg^{2+}(SO_4)^{2-}$] -Symbols for physical states (s, l, g, aq)
Models **&** **Analogies**	Classic models of textbooks Drawing of models on paper	Proper original solid models and mechanical analogues for abstract concepts Construction of solid models by students	Classic models of textbooks Drawing of models on paper	Proper original solid models and mechanical analogs for abstract concepts Construction of solid models by students
Heuristic tools	-	Concept maps	-	Concept maps
Stoichiometric calculations: (a) Teaching method	Mechanical method: *algorithmic rule of three*	Logical method: *unit-base*	Mechanical method: *algorithmic rule of three*	Logical method: *unit-base*
(b) Teaching period	Whole school year	Whole school year	At the submicro level only	At the submicro level only

TABLE 3. *An outline of the theoretical test. Within parentheses, the percentage marks/weights, corresponding to each test item, are given.*

A. CHEMICAL NOTATION (40%)
1. Symbols of elements. (5)
2. Symbols of ions. (5)
3. Symbols of charged molecular ions. (5)
4. Compounds. (25)

B. ATOMIC STRUCTURE (15%)
5. Number of electrons in a neutral atom, given the number of protons and neutrons. (5)
6. Arrangement of electrons to electron shells. (5)
7. Number of electrons in ions (in comparison to neutral atoms). (5)

C. MOLECULAR STRUCTURE (15%)
8. Diatomic molecules. (7.5)
9. Ionic and covalent compounds. (7.5)

D. CHEMICAL REACTIONS (30%)
10. Coefficients of chemical equations. (10)
11. Chemical reactions (product prediction). (20)

TABLE 4. *An outline of the test on stoichiometric calculations. Each problem had an equal weight (50%). Equal weights (10% each) had the five steps of the fist problem.*

A. PROBLEM IN FIVE STEPS
1. Number of molecules of products, given the number of molecules (or atoms) that reacted.
2. Number of moles of products, given the number of molecules (or atoms) that reacted.
3. Number of gr-atoms or gr-molecules, given the number of molecules (or atoms) that reacted.
4. Number of moles that are produced from the reaction of the gr-molecules or gr-atoms of question (3) above.
5. Volume under STP of moles of gas that was produced according to question (4) above.

B. COMPOSITE PROBLEM
A complete chemical equation is given, and the student is asked to calculate the volume of the gas produced under STP from given mass of one of the reactants.

RESULTS

Achievement in theory

Table 5 contains the relative data. For the initial test (end of school year), the statistic F assumed the value 5.19 ($p = 0.002$). All experimental groups outperformed the control group with a large significant difference. On the contrary, there was no significant difference among the experimental strategies. On the other hand, no statistical difference was detected among the experimental groups. For the retention test, F was found equal to 8.36 ($p = 0.00$). In this case, the Johnstone and the Johnstone-Case groups outperformed the Case and the control groups with a very large significant difference.

In all groups there was a significant statistical difference in the achievements between the initial and the retention tests. For the control group, the difference of the means of the two tests was 7.2% (retention 79.9%), with statistic $t = 4.9$ (two-tailed $p = 0.00$). For the Case group the difference was 12.8% (retention 69.8%), with t = 7.1 ($p = 0.00$). For the Johnstone group the difference was 9.9% (retention 79.2%), with $t = 6.3$ ($p = 0.00$). Finally, for the Johnstone-Case group the difference was 5.7% (retention 87.7%), with $t = 3.20$ ($p = 0.00$).

TABLE 5. *Achievement in the basic theory of chemistry*.*

	PREVIOUS WORK** (*N* = 408)	**CONTROL** (*N* =92)	**CASE** (*N* = 89)	**JOHNSTONE** (*N* =94)	**JOHNSTONE-CASE** (*N* =105)
Initial test	-	35.8 *(21.5)*	42.3 *(19.8)*	47.5 *(24.5)*	46.0 *(22.5)*
Retention test	20.5 *(15.0)*	28.6 *(19.2)*	29.5 *(17.7)*	37.6 *(21.2)*	40.3 *(20.9)*

*Mean achievement, with maximum 100% (*standard deviations in parentheses*).
** Tsaparlis (1994).

Achievement in stoichiometric calculations

Table 6 contains the relative data. For the initial test, one-way analysis of variance gave a value for statistic $F = 0.73$ ($p = 0.54$). For the retention test, F=1.32 ($p = 0.27$). There was no significant difference between the groups in both the initial and the retention test. On the other hand, for all groups there was a large significant difference in the achievement between the initial and the retention test: for the control group, the difference in the means was 12.7% (retention 68.5%), with $t = 4.6$ (two-tailed $p = 0.00$); for the Case group the difference was 14.4% (retention 64.0%), with $t = 5.72$ ($p = 0.00$); for the Johnstone group the difference was 10.2% (retention 73.3%), with $t = 4.66$ ($p = 0.00$); finally, for the Johnstone-Case group the difference was 23.5%, with $t = 9.42$ ($p = 0.00$).

TABLE 6. *Achievement in stoichiometric calculations*.*

	PREVIOUS WORK** (*N*= 408)	**CONTROL** (*N*=92)	**CASE** (*N*= 89)	**JOHNSTONE** (*N*=94)	**JOHNSTONE-CASE** (*N*=105)
Initial test	-	40.2 *(29.3)*	40.0 *(26.2)*	38.2 *(29.3)*	44.1 *(31.1)*
Retention test	21.1 *(26.4)*	27.5 *(29.0)*	25.6 *(28.8)*	28.0 *(30.7)*	20.6 *(29.7)*

* Mean achievement, with maximum 100% (*standard deviations in parentheses*).
* * Tsaparlis (1994).

DISCUSSION AND CONCLUSIONS

On the theoretical test, the Johnstone-Case group, that combined Case's principles with Johnstone's three level model, took the lead; the Johnstone group followed, while in the third place was the Case group, that used Case's psychological proposals; the control group was last. We conclude that the teaching model that makes a distinction into the three cycles (levels) of chemistry, compared with the traditional simultaneous treatment, contributes to better learning of the theory of chemistry.

As long as teaching is recent, the positive influence of the features of the Case methodology, in particular when it is used by the textbook, is larger. Otherwise it seems that it loses its value, and in the worst case it may cause some confusion. To this then we could attribute the low retention demonstrated by the Case group.

In the test of stoichiometric calculations, achievement did not exceed 50% in the first test, and 37% in the second test. The abstract concepts of the submicro level and the use of analogical reasoning that necessarily enters these calculations, combined with the widely held view that solving numerical exercises is a difficult task, constitute restraining factors for the students of this age. The various methods of stoichiometric problem-solving did not seem to make a differentiation of any statistical significance, while a long term practice with such calculations, using either method, had a positive effect. By and large, stoichiometric calculations are difficult for many lower secondary students.

The aim of this research was to present experimental teaching strategies that might be more effective than those usually used. In comparison with the results of previous work (Tsaparlis, 1991; 1994), all groups outperformed the students of the previous study, with a statistically significant difference. This must be attributed to a higher than average level of the school of this study, coupled with certain conditions which were observed in the case of the current work, namely a systematic methodology, programming and planning of teaching, clear statement of objectives, experimental approach to phenomena, the specific educational features (child-centred constructivist approach, induction, overview, attractiveness). Without radical changes, with simple but systematically observed conditions, IT IS possible to significantly improve the prevailing picture. All in all, the suggested methods, enriched with features based on psychological theory, but especially with the distinction of the three levels of chemistry, could be more effective.

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