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DIFFICULTIES IN ACQUIRING THEORETICAL CONCEPTS: A CASE OF HIGH-SCHOOL CHEMISTRY

Hillar Saul[1], Eve Kikas[2]

[1]*Tallinn Pedagogical University,* [2]*University of Tartu*

Abstract. Studies from the last decades have demonstrated that pupils have difficulties acquiring the concepts of chemistry. They suggest that pupils fail to integrate the scientific explanations of school chemistry into their initial conceptions. The aim of the present study was to investigate the high-school pupils' understanding of selected theoretical concepts in chemistry and to compare this with non-conceptual algorithmic knowledge of the subject. Second, the relationship between some mental abilities and the acquisition of different types of chemical concepts was studied. A written multiple-choice chemistry test was administered to 247 schoolchildren from grades 9–12. Pupils' verbal, mathematical, spatial, and logical reasoning abilities were also assessed. Algorithmic and factual knowledge of chemistry proved to be substantially better than conceptual knowledge. In most cases only 12th grade pupils performed significantly better than pupils in lower grades, no significant differences were evident between other grades. It is possible that the possession of algorithmic knowledge is sufficient to get pupils through high-school chemistry curriculum. This study also showed that, of the four mental abilities measured, logical reasoning and verbal abilities had the highest correlations to the knowledge of theoretical concepts. Possible reasons for the difficulty of acquiring chemistry concepts were discussed.

Introduction

Great difficulties in understanding theoretical scientific concepts have been determined in different areas, including chemistry (Driver, Squirer, Rushworth, & Wood-Robinson 1995, Garnett, Garnett, & Hackling 1995, Griffiths 1994, Pozo, Gómez, & Sanz 1999, Stavy 1995). As empirical studies have shown, pupils develop synthetic conceptions that often describe microscopic processes in terms of perceptual macroscopic entities. Pupils believe that copper molecules melt when copper melts, that atoms have the colour of their substance and that they behave like tiny visible things (e.g. either float or sink to the bottom in a solution) (Albanese & Vincentini 1997, Boo 1998, Driver et al. 1995, Griffiths & Preston

1992, Stavy 1995, Valanides 2000). Similarly, instead of thinking that matter consists of particles, pupils think that particles are in the substances like germs or small pieces of material (Renström, Andersson, & Marton 1990).

It is possible that the reason children are not actually using concepts learned from school explanatively can be clarified with the help of the Vygotskian distinction between everyday and scientific concepts. According to Vygotsky (1934/1997, 1934/1994), everyday concepts develop from concrete perceptible instances when children single out some common salient features of concrete objects while abstracting from others (e.g. water or ice are different everyday concepts). Such concepts are unsystematic and strictly empirical. Scientific concepts, on the contrary, are defined in relation to each other and are connected with referents only indirectly through their integrated syntactic networks – perceptual and other features are here recombined into new, supposedly more informative, structures. For example, from the point of view of chemistry, water and ice are the same substance even if they are not perceptually similar. Scientific concepts are usually formally learned at school (by verbal definitions, models or symbols) and they refer to entities children have not immediately experienced in their lives, and therefore are difficult to make sense of.

The structure of chemical science embodies these psychological differences between everyday and scientific thinking extensively. Different configurations of atoms and molecules do not have directly perceptible referents, yet they produce different kinds of perceptible substances and their changes. What chemistry education is trying to achieve, is to set up a cognitive non-perceptual sign-mediated structure in a child's cognitive system which afterwards enables them to predict and explain the whole range of visible changes of substances. Children's initial frameworks, however, are based on everyday concepts. For example, after having observed a needle, a pin, and a coin sinking in water, a child concludes that all small objects sink and begins to use this concept for predicting the behaviour of different objects in water (Karpov & Haywood 1998). The predictive powers of these concepts are, without doubt, narrower and often misleading.

In that view, children have difficulties understanding scientific chemistry concepts because they cannot make sense of indirect and abstract chains of new concepts and simply put theoretical microscopic entities, taught in chemistry classes, alongside other perceptible things in the macroscopic world. Microscopic theoretical concepts are taken as new kinds of things one can see or touch, and these are understood in analogy to the everyday macroscopic world. As a result, as far as the explanatory framework is concerned, pupils remain within their initial conceptions, i.e. they think about chemistry in terms of everyday concepts. Hence, scientific concepts are understood as structurally equivalent to everyday concepts; pupils think that microscopic entities also melt, freeze, and evaporate and have colour like real substances (Albanese & Vincentini 1997). Vygotsky (1997) refers to such concepts as pseudo-concepts and considers them to be the transitional link between everyday thinking and scientific concepts. Pseudo-concepts may be words heard from adults and frequently used similarly to adults. Adults usually think that children have the same meaning for a word as they do. Therefore, it is very difficult for teachers to differentiate if a child has pseudo- or scientific concepts. Lots of teacher-pupils communication can take place in this situation of illusory understanding. Indeed, many studies have shown that teachers are not aware of pupils' everyday conceptions and of the difficulties they experience when dealing with new scientific concepts (Stepans 1991).

In addition to the formation of pseudo-concepts pupils have another way of dealing with scientific concepts which prove to be too complex for them – this is rote memorisation. It happens frequently in classrooms where traditional teacher-centred teaching methods are used. When students rote memorise new information, they acquire mere verbalisms, which are soon forgotten (Kikas 2000, Vygotsky 1997). It has been shown (e.g. Zoller, Lubezky, Nakleh, & Tessier 1995) that traditional chemistry education fosters recall of simple isolated facts and trains simple set of algorithmic procedures (like mechanically solving stoichiometric tasks or balancing equations).

The aims and hypotheses of the present study

This investigation aimed to study whether and to what extent pupils are able to form the theoretical conceptual systems throughout their chemistry high-school studies. The following three topics of general chemistry (which are considered essential for the explanative framework of chemistry) were chosen: 1) the notion of the chemical element, its characteristics and relation to macroscopic expression; 2) atoms and molecules, their characteristics and functions in visible chemical processes; 3) significance and function of the symbolic language, its macroscopic and microscopic meaning.

Emphasis was placed on the explanatory usefulness of these concepts; that is, the ways in which concepts, when integrated into a system, are related to the macroscopic world of substances. In addition, factual questions (including the knowledge of algorithms) were asked (cf. generative vs. factual questions by Vosniadou 1994). These answers were assumed to reflect the level of chemistry knowledge that is useful for getting good grades in school (Zoller et al. 1995). However, without conceptual understanding (which assumes connecting groups of theoretical concepts into meaningful systems) it gives only a fragmentary knowledge of the subject (Vygotsky 1997).

The first section of the test dealt with chemical elements. On microscopic level a chemical element is described as a collection of certain atoms with the same mass and arrangement of electrons. The atomic structure determines its chemical behaviour; to understand this concept, links between several non-perceptible entities must be drawn. It can be assumed that pupils tend to identify a chemical element with its macroscopic expression (e.g. with simple substances) and think that with the visible changes of a substance the same kind of changes happen to the chemical elements (e.g. change of colour).

The questions about atoms and molecules addressed the relation of macroscopic chemical changes with these particles (e.g. what kinds of changes are caused by what kinds of microscopic processes).

The questions about symbols were inspired by Johnstone's suggestion that in addition to macroscopic and microscopic levels of thinking in chemistry, there is also a third mode of representation – the symbolic level (Johnstone 1991). He proposes that the macroscopic level depicts perceptual changes of substances, the microscopic level translates these changes into terms of processes with particles, and the symbolic level presents the microscopic level in an unambiguous and strict language, transcribing the quantitative arrangement of particles (see also more recent studies on this topic, Brosnan & Reynolds 2001, Keig & Rubba 1993, Wu, Krajcik, & Soloway 2001). The questions in this study were designed to reveal pupils' ability or inability to recognise from symbolical representations the microscopic composition of the substances.

The first part of the study dealt with differences both in conceptual and factual knowledge during the high-school period. All the students questioned learned at schools where traditional teacher-centred teaching methods were used. All of them had studied the topics, but older pupils had done it several times. We wanted to know the extent to which pupils managed to learn the principles they had extensively studied at junior high school and which they had to apply to each topic about concrete groups of substances.

We assumed that factual knowledge would be substantially better than conceptual knowledge, especially in younger pupils. As understanding scientific concepts (conceptual knowledge) takes time and requires possibilities to apply the information to appropriate tasks, we hypothesised that conceptual knowledge would be significantly better in older graders as compared to younger ones.

Second, we were interested in the possible psychological abilities that can facilitate the learning of these intricate scientific concepts. Pupils differ both in their general cognitive abilities and in their success in chemistry studies. It is important to know which abilities help to form scientific concepts in school. Our chemistry test consisted of representations from three different aspects of chemistry: theoretical concepts (the sections on atoms/molecules and chemical elements), symbolic representations of chemical processes (Johnstone 1991) and nonconceptual factual/algorithmic knowledge. It is expected that these different aspects are learnt with the help of different cognitive abilities.

We chose four types of mental abilities that were thought necessary in understanding the theoretical principles of chemistry: spatial, mathematical, verbal, and logical-deductive. It is assumed that logical-deductive and verbal abilities have a general facilitating effect, as the formation of concepts (which are not based on perceptual grounds, but on supra-empirical, syntactic grounds) may take place by means of verbal and deductive thinking. It is also expected that spatial and mathematical skills would have the largest effect on the knowledge of symbolic representations as they may require visualisations and skills of thinking with quantitative relations. The relationships between abilities and factual/algorithmic knowledge were expected to be the smallest due to these tasks being the least demanding.

Previous studies have demonstrated the importance of spatial ability as a factor that facilitates visualisations of microscopic processes (chemistry being perhaps most visual of all sciences) (Chandran, Treagust, & Tobin 1987). Other studies have failed to confirm this result, but have found high correlations with general reasoning ability (Carter, LaRussa, & Bodner 1987, Keig & Rubba 1993). Rolfhus and Ackerman (1999) found that a college level chemical knowledge is best correlated with verbal abilities and to a lesser extent with numerical abilities. It is important to clarify this issue because the influences of different abilities indirectly show where the cognitive difficulties lie in the learning of chemistry.

Method

Participants

The 247 schoolchildren participating in the study included: 74 pupils from grade 9 (mean age 14.8, SD = 0.57, 32 boys and 42 girls), 71 pupils from grade 10 (mean age 15.8, SD = 0.6, 35 boys and 36 girls), 69 pupils from grade 11 (mean age 16.5, SD = 0.53, 27 boys and 42 girls), and 33 pupils from grade 12 (mean age 17.3 SD = 0.57, 10 boys and 23 girls). The participants were selected class-wise from three different Estonian state schools (as most of the Estonian schools are) with 1000 pupils in each of the schools. All three schools were from a city with a population of 100, 000, and pupils generally shared a middle-class background.

Instruments and coding

A written multiple-choice test (see Appendix A) was developed for assessing children’s knowledge of chemistry. Questions were pilot-tested on experts – chemistry researchers working in the university. In addition, the structure of mental abilities was measured by a test constructed by the authors in analogy to the traditional intelligence tests (e.g. Wonderlick 1983). The test measured verbal, mathematical, spatial and logical reasoning abilities (see below).

Knowledge of chemistry. As previously stated, the questions addressed three topics: 1) chemical elements, 2) atoms and molecules, 3) symbols. In all Estonian state schools, chemistry is taught as a separate subject from grade 8 upwards. These three topics are thoroughly studied in grades 8–11 and therefore should provide theoretical grounding for more specific topics that pupils learn in high school chemistry. All the questions used in the test were based at the eighth-grade curriculum level, with some concepts having first been introduced as early as grades 5–7.

Incorrect answers for multiple-choice questions were constructed taking into account the pupils' typical conceptions described in the literature (particularly the confusion between macro and micro levels) and logically probable wrong answers in the particular context of the question (considering the logical structure of the topic and probable mistakes caused by rote memorisation). In this respect the test was constructed similarly to Sadler's (1998) test for astronomy, which also aimed to measure conceptual knowledge with multiple-choice questions, which consisted in selecting distractors (for that particular item) using knowledge about the pupils' non-scientific conceptions. We selected two types of incorrect answers: a) pseudoscientific (incomplete) (referring mostly to microscopic entities, but these notions are used inappropriately) and b) empirical, where notions of the visible (macroscopic) world are projected onto a strictly microscopic context. These correspond to the two ways of the formation of non-scientific concepts: verbalisms (pupils connect scientific conceptions with each other in an incorrect manner) and synthetic concepts (pupils project notions and phenomena of an everyday empirical level onto theoretical notions) (see Chinn & Brewer 1993, Kikas 2000, Vosniadou 1994, Vygotsky 1997).

At first, answers were coded into three types: pseudoscientific, empirical, and correct answers. This coding enabled us to study the pupils' tendency to prefer either pseudoscientific or empirical choices of items. In addition, we studied the general level of correct answers. In these statistical analyses we used a dichotomous scale, coding answers as correct or incorrect.

Factual questions measured the ability to balance equations and the knowledge of the names of elements and compounds. The answers to the factual questions were coded as correct or incorrect.

The test's reliability coefficient Cronbach's alpha was .79.

Mental abilities. Verbal, mathematical, spatial and abstract reasoning abilities were measured. These tasks were coded as correct or incorrect. Examples of the items are presented in Appendix B. The verbal subtest measured the ease with which pupils were able to detect semantic differences and similarities in the words and sentences. The participants were presented with 13 word items and 7 sentence items where they had to select the word or sentence that was the closest in meaning or opposite in meaning to the given sentences or words. For example, in some tasks they had to detect whether two words were similar, opposite or unrelated. The math subtest had two types of questions: traditional mathematical word problem (12) and number series tasks (5). To solve the word problems, a correct calculation strategy had to be found and carried out. With number series tasks, the inner logic behind the series had to be detected. Measurement of spatial abilities consisted of three 2-dimensional tasks and one 3-dimensional geometric task where particular figures had to be divided into pieces in order to construct new geometrical figures from them. Finally, 13 syllogistic reasoning problems assessed pupils' abstract reasoning. The syllogistic reasoning tasks were constructed similarly to Luria (1976). These consisted of sentences that were consistent with common knowledge, contrary to common knowledge or consisted of nonwords (see Appendix B). Syllogisms contrary to knowledge were thought to be the hardest because pupils had to detach themselves from their knowledge and to concentrate only on the given closed syllogistic structure.

The test's reliability coefficient Cronbach's alpha was .90.

Procedure

Tests were administered in schools in typical class settings. The chemistry test took 25–30 minutes to complete. Two versions with a different order of questions were composed to exclude the possible influence of the sequence of questions, and also to minimise the opportunity for copying classmates' answers. A 20-minute time limit was set for the mental abilities' test.

Results

Knowledge of chemistry

Figure 1 provides the distribution of the answers to the conceptual chemistry questions (in percentage) separately for each topic and grade. It can be seen that some pupils did not answer the questions (category "missing") and that some chose the empirical answers. However, pseudoscientific and correct answers prevailed for all topics. The easiest topic was that of atoms and molecules, where the twelfth-graders did particularly well (76% of correct answers). The most difficult questions were about symbols (41% of correct answers in grade 12 and less in younger grades).

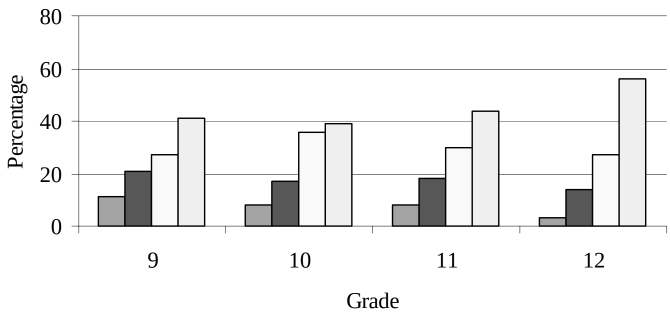
In the following quantitative analyses, dichotomous categories – correct and incorrect answers were used. The significance of grade differences was analysed using one-way ANOVA, post-hoc comparisons were made with the LSD test.

Chemical elements. There were significant grade differences in correct answers for chemical elements ($F(3,243) = 4.03$; $p = .008$), post-hoc comparisons showed the significant difference between grade 12 and all other grades (grade 9 vs. 12 $p = .002$, grade 10 vs. 12 $p = .001$, grade 11 vs. 12 $p = .02$).

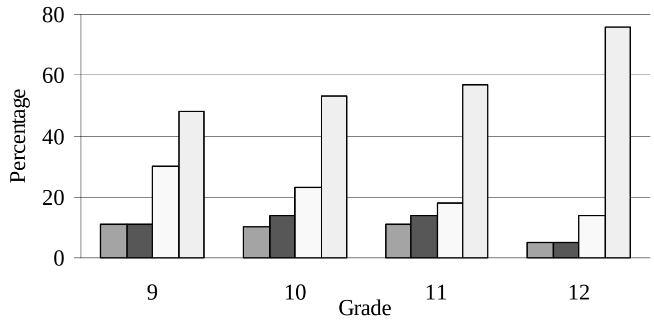
The analysis of concrete questions revealed that children knew quite well that chemical elements differ by the mass of their atoms (see Appendix A, question 4): over 60% of the answers (for all grades taken together) were correct. In contrast, the majority of pupils answered that chemical elements decompose in chemical reactions (question 1). In addition, 30% of all pupils believed that elements melt, dissolve, or change their shape.

Atoms and molecules. We found significant grade differences in correct answers for atoms and molecules ($F(3,243) = 8.09$, $p < .001$). Post-hoc comparisons showed significant differences between grade 12 and all other grades (grade 9 and 10 vs. 12 $p < .001$, grade 11 vs. 12 $p = .002$).

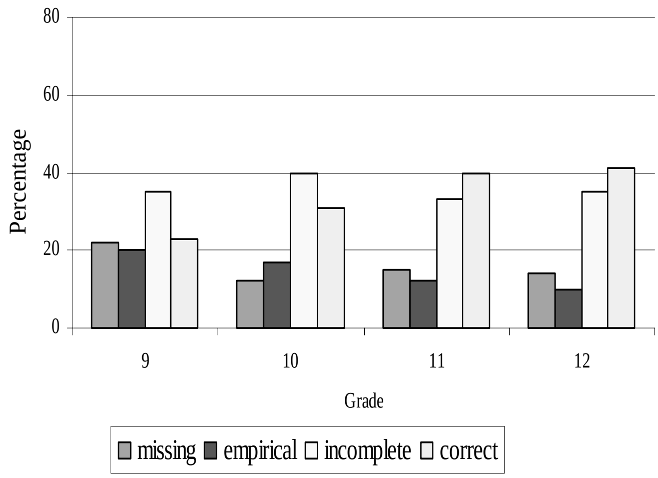
Figure 1. Distribution of pupils' answers (in percentage) to the questions about chemical elements, atoms/molecules and symbols in different grades.



A. Chemical elements



B. Atoms and molecules



C. Symbols

Similarly with chemical elements, students answered that atoms differ from each other by their mass (question 6, over 70% of correct answers). But about 50% answered that atoms or molecules change when water freezes, and that atoms change during chemical reactions (sulphur trioxide reacting with water) (questions 7 and 8).

Symbols. ANOVA results for the questions about symbols gave main effect $F(3,243) = 2.92$; $p = .035$. Post-hoc comparisons indicated significant differences between grades 9 and 11 ($p = .01$) and grades 9 and 12 ($p = .05$). Only 23% of the children knew that the formula HCl signifies a molecule (question 12). Pupils had considerably good balancing skills (over 50% solved all these problems correctly, and over 75% had two correct answers out of three) (see below, factual questions). However, far less (39%) pupils knew why it was necessary to balance (question 11).

Factual questions. There were 70% correct answers in grade 9, 81% in grade 10, 88% in grade 11, and 81% in grade 12. Grade differences for factual questions were also significant ($F(3, 243) = 7.19$; $p < .001$). Post-hoc comparisons indicated significant differences between grade 9 and others (grade 9 vs. 10 $p = .002$, grade 9 vs. 11 $p < .001$, grade 9 vs. 12 $p = .02$). Children answered much better to these questions than to the conceptual questions. They knew the correct names of elements and compounds and balanced different equations correctly. T-tests for dependent samples showed that pupils chose significantly more ($p < .001$) correct answers for factual questions than to any conceptual topic (chemical elements, atoms and molecules and symbols) in all the grades. Exceptionally, the difference between the means of the correct answers to factual and atoms/molecules' topics was non-significant in grade 12 ($t(32) = 1.17$; $p = .25$).

Relations between mental abilities and knowledge of chemistry

Table 1 shows the means and standard deviations of verbal-, mathematical-, spatial- and reasoning abilities in different grades. It can be seen that all the tasks were performed significantly better by older graders.

Table 1. Means and standard deviations of mental abilities and their grade differences

	grade 9		grade 10		grade 11		grade 12		F	p
Ability	M	SD	M	SD	M	SD	M	SD		
Verbal	10.34^{12}	2.48	10.68^{12}	2.03	10.41^{12}	2.26	$12.76^{9–11}$	2.25	9.97	0.000
Math	$3.45^{10,12}$	2.72	4.59^{9}	2.43	4.23	2.55	5.00^{10}	2.35	3.83	0.011
Spatial	$1.78^{11,12}$	0.90	1.96	0.85	1.67^{12}	0.95	$2.18^{9, 11}$	0.92	2.91	0.035
Logic	$4.07^{10–12}$	2.63	$4.42^{9–12}$	2.20	$5.54^{9–12}$	2.56	$7.06^{9–11}$	2.47	13.52	0.000

Note. Superscripts show significant differences among groups according to the LSD test at $p < .05$; the samples marked are as follows: 10 = grade 10, 12 = grade 12.

Table 2 indicates the correlations between the scores of chemistry and ability-tests. The majority of the correlations were significant, the few nonsignificant correlations were, as expected, correlations with factual questions. Correlations between the total score of the ability test and all other sections of the chemistry test show that the relationships were the strongest between logical reasoning and chemistry learning, but generally all abilities play a part.

Table 2. Correlations (Pearson's r) between chemistry knowledge and mental abilities

Tasks	Atoms and molecules	Symbols	Chemical elements	Factual questions	Total of CT	Total of MAT	Verbal tasks	Math tasks	Spatial tasks
Atoms and molecules	–								
Symbols	.35***								
Chemical elements	.37***	.27***	–						
Factual questions	.20**	.17*	.04	–					
Total of CT	.62***[a]	.52***[a]	.46***[a]	.43***[a]					
Total of MAT	.36***	.32***	.31***	.20**	.45***				
Verbal tasks	.23**	.19**	.32***	.10	.31***	.47***[a]			
Math tasks	.23***	.23***	.18**	.25***	.33***	.56***[a]	.29***		
Spatial tasks	.16*	.26***	.16*	.02	.22***	.42***[a]	.28***	.31***	
Syllogistic tasks	.37***	.19**	.23***	.24***	.40***	.50***[a]	.36***	.43***	.16*

Note. * p < .05; **p < .01; *** p < .001; Total of MAT – Total score of the mental ability test; Total of CT – Total score of the chemistry test; [a] – when total scores are correlated with sections of the same test, the section was subtracted from the total score

We conducted several multiple-regression analyses to predict the value of different abilities together with the grade and gender variable for the knowledge of theoretical concepts, symbolic representations and facts/algorithms. The results are given in Table 3.

Table 3. Beta levels of multiple regressions (N = 247, d.f. 5,241) with grade, gender and mental abilities' variables for different sections of chemistry test

	Theoretical concepts	Symbols	Factual questions	All conceptual questions	All questions
Grade	.17**		.19**	.18**	.22***
Gender	–.17**				
Verbal tasks	.18**			.16**	.14*
Math tasks			.16*		
Spatial tasks		.20**		.14*	
Syllogisms	.22**			.19**	.21**
R^2	.24	.12	.11	.24	.27
F	12.36***	5.00**	4.33***	11.48***	13.33***

Grade and gender variables had significant betas only with the section on theoretical concepts, with the girls being superior in this section. Better acquisition of theoretical concepts was predicted by superior verbal and syllogistic reasoning abilities while spatial abilities predicted better the understanding of symbolic language. The latter result could imply that when pupils try to understand what is microscopically behind the symbolic notation, visualisations might have a facilitating effect. The high relationship between mathematical abilities and factual knowledge is explained by the fact that the balancing tasks that were included in the factual section were, in essence, mathematical tasks. In general, the differently structured sections of the chemistry test indeed received differential impact from cognitive abilities.

Discussion

The development of conceptual and factual knowledge of chemistry at high school

The first part of the study focused on the understanding of the theoretical basics of chemistry, studied extensively at junior high and high school, and also on comparing pupils' conceptual and factual knowledge.

The conceptual understanding (as assessed with multiple-choice questions) was quite low. Although the test's questions addressed the most central issues of chemistry, very few perfect or near perfect answers were obtained even in grade 12 (see Figure 1). The largest progress was evident with questions about atoms and molecules. However, some of these issues were studied as early as in grade 5 (e.g. molecules don't change during freezing/melting). But even here the progress was slow and the concepts were not acquired fully before grade 12. The growth of knowledge was not as impressive for the topic of chemical elements, and stayed slightly above 50% even after the chemistry studies of high school were completed (in grade 12). Particularly and rather alarmingly weak was the comprehension of the actual meaning of the symbolic language. Despite the fact that pupils are frequently required to represent chemical processes with equations containing symbols, they do not know how to link these symbolic representations with atoms and molecules. As expected, the pupils' factual knowledge was largely better than their conceptual knowledge.

Why is the difference between factual and conceptual knowledge so large? Conceptual understanding of chemistry entails comprehension of the whole network of concepts with the ability to apply them in new and unfamiliar situations (cf. generative knowledge Vosniadou 1994). It should also contain certain metacognitive aspects (the ability to think about concepts) and the ability to use this metacognitive awareness to employ concepts creatively. The possibility to use knowledge enables pupils to make abstract concepts concrete and, accordingly, encourages the development of scientific concepts instead of pseudo-concepts (see Vygotsky 1997). Such learning with understanding takes time (see Smith, Maclin, Grossligth, & Davis 1997). Factual or algorithmic knowledge, on the other hand, implies simple memorisation of the facts or the use of predetermined fixed steps of a known procedure (in familiar situations) and is easier to obtain (see also Zoller et al. 1995).

Actually, pupils have studied the topics several times. The theoretical framework of chemistry is first introduced in grade 8 (as mentioned, some topics even earlier); in later grades it is applied to different kinds of substances. So, even if the concepts are not theoretically studied in higher grades, pupils have to use them to solve various problems and apply the abstract concepts learnt earlier in concrete situations. However, as the study showed, chemistry classes have enhanced the knowledge of facts but not conceptual understanding. The reason why conceptual understanding is not gained lies possibly in the type of problems used at school (cf. Zoller et al. 1995), but this question needs further empirical investigation.

The pattern of pupils' incorrect answers showed the preference of pseudoscientific answers over more perceptually oriented ones. These results are in agreement with the earlier studies at schools with traditional teaching methods (e.g. Kikas 2000). However, it should be stressed that there could be more empirical and less pseudoscientific (and also scientific) answers for open-ended questions. Pupils may choose the answers that resemble school answers in case of multiple-choice test but may ground more on empirical knowledge when having to produce the answers on their own. With no certain conceptual understanding, in unfamiliar situations pupils do not know how to use their knowledge and they may regress to their initial explanatory frameworks, which are based on perceptually guided concepts. To illustrate the distinction, on the level of factual knowledge H_2SO_4 signifies sulphur oxide, a certain substance (this formula, when understood on factual level, i.e. macroscopically, is not different from, say, the word "butter"). Conceptual understanding, on the contrary, allows to deduce from the formula its molecular-atomic structure and predict its possible reactions with other substances.

It should be mentioned that even if our aim was to select the most central issues of theoretical chemistry, the acquisition of which should indicate conceptual understanding of the subject, the multiple-choice test as such cannot give a completely adequate picture of the pupils' conceptions. In several ways it is necessary to be cautious, mainly the level of correct answers would be lower with open-ended questions, also the high quantity of pseudoscientific answers (verbalisms) found are likely to be replaced with more empirical answers (synthetic concepts) in that case. Nevertheless, following Sadler (1998) we tried to carefully select the multiple-choice tests' distractors so that the possible conceptions of the pupils would be reproduced in the test with the end of making the measurement error as low as possible. Thus, the general level of correct answers is hopefully quite adequate.

Different psychological abilities and learning chemistry

The second aim of the investigation was to study the relations between mental abilities and the level of the knowledge of chemistry. The study demonstrated that all the assessed abilities may be utilised in mastering chemistry concepts. Verbal, mathematical and spatial thinking employ distinct and differently structured sign systems and may even be cognitively independent modules, yet they all play their role in learning chemistry. The correlations between the total score of the chemistry test and the syllogistic logical reasoning tasks were the highest (as compared with other abilities tasks). This result is in agreement with the earlier studies showing that the reasoning ability has the largest impact on chemistry learning (Carter et al, 1987, Keig & Rubba 1993). Carter et al. (1987) and Keig and Rubba (1993) failed to find significant correlations with spatial reasoning while Chandran et al. (1987) revealed correlations as high as .30. Our test confirmed the results of the latter study. It is possible that differently organised measurement instruments show different results – chemical concepts are complex and different parts of chemistry may vary substantially from the cognitive points of view.

We structured questions with the aim of grouping together different aspects of chemistry. The sections concerning atoms/molecules and chemical elements were intended to measure the knowledge of theoretical concepts of microscopic entities and their explanatory relation to the macroscopic world of substances. The section concerning symbols was intended to address the understanding of how the structural positions of atoms and molecules are translated into quantitative relations (i.e., how many molecules and atoms take part in a particular process, but also their configurations). This symbolic aspect is different from learning the theoretical verbally defined concepts (it is more similar to the understanding of the meaning of the equations in physics). We assumed that the abilities used for factual and algorithmic tasks are distinct from the above more conceptual issues. We indeed found (see Table 3) that the predictive value of different abilities varies when these three aspects are considered separately.

The best predictors of the conceptual knowledge were (besides grade) verbal and logical abilities. Verbal abilities measured the ease and rapidity of assessing the semantic structure of words and sentences (detecting differences and similarities). Logical abilities, on the other hand, required the skills of deductive reasoning while remaining detached from previous knowledge. Both of these skills could be the psychological means ensuring the formation of concepts distanced from the perceptual world. First, deductive thinking teaches children to focus on the syntactic connections between concepts, instead of using only ambiguous associations provided by the immediate perceptual world. Second, in the framework of the Vygotskian approach it is the system of language with its internal structure and logic, which constitutes the grounding for the learning of scientific concepts. When a child’s language use becomes metacognitively aware of the system of language, it will be used as an internal tool allowing the child to go beyond perceptual experience and help utilise theoretical concepts in the prediction of new aspects in the surrounding world.

Spatial reasoning had a significant effect on the symbolic aspect of chemistry. It may be that when pupils have to link symbolically represented chemical processes to the configurations of atoms and molecules they are using visualisations. Very few of the pupils were able to do this and perhaps teachers overlook the difficulty of this task. The importance of this task lies in the fact that the translation of different representations is necessary – microscopic theoretical entities have to be represented with the quantitative language of equations (see also Keig & Rubba 1993). Our finding suggests that teachers should try to elicit visualisations of particles to enhance the ability to connect these two kinds of representations.

Zoller et al. (1995) used the concept of lower-order and higher-order cognitive skills and suggested that the former are sufficient for the learning of algorithmic knowledge while the latter have to be utilised to master chemistry at the conceptual level. Our study also shows that different cognitive abilities are used in the acquisition of algorithmic as opposed to conceptual knowledge.

However, it should be emphasised that the models described less than 30% of variation in knowledge scores. There might be two reasons explaining this fact. Firstly, acquisition of chemistry does not depend exclusively on these four types of abilities. Children's learning motivation and the time they devote to learning are possibly much broader factors (Pintrich, Marx, & Boyle 1993). Secondly, we measured chemical knowledge with a multiple-choice test with four choices. It is obvious that the possibility to guess correctly added some unnecessary noise to our data.

Conclusions and implications for education

Our study indicates that the most basic theoretical concepts of chemistry are not understood to a sufficient degree at high school. Also, it suggests that factual and algorithmic knowledge may constitute separate levels of pupils' chemical knowledge, creating the illusion that pupils have understood the particular topics. However, in reality the knowledge may consist only of quite meaningless verbalisms and fixed sets of procedures. Chemical education has two separate parts. First, the conceptual framework of chemistry, its general theory and, second, the applications of this theory to different substances. It is the latter where factual knowledge is essential. Without the comprehension of the theory, mere factual knowledge is nevertheless of questionable value.

What can be done to enhance the pupils' understanding of the theoretical concepts of chemistry? We suggest that it would be useful to be aware of the distinction between everyday and scientific concepts and the fact that they require different psychological resources. As opposed to empirical everyday concepts, scientific concepts can be successfully utilised to explain and predict the surrounding world only when they are comprehended within the system of related scientific concepts. In addition, the real understanding of scientific concepts is time-consuming, demands the preliminary development of certain psychological abilities, everyday concepts and memorising factual knowledge. To understand scientific concepts, they must be "filled" with experience, which can be done using various types of tasks and problems (Vygotsky 1997).

Although pupils have studied the topics several times, the connections between systems of scientific concepts and the everyday world have not been drawn out sufficiently and have remained ambiguous. As shown before, traditional teaching (which was used at these schools) stresses the memorisation of facts and procedures of solving problems; there is little time for discussions (Kikas 2000, Smith et al. 1997, Zoller et al. 1995). Recently, a lot of attention has been paid to this problem. Several systems of constructive learning have been developed where students have to relate to their previous experience or discover the solutions to the problems at hand in discussions with peers (e.g. Glynn & Duit 1995, Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou 2001). Also, the approaches stressing the importance of anomalous data in conceptual change contribute to the problem of linking new theoretical knowledge to children's previous conceptions (e.g., Posner, Strike, Hewson, & Gertzog 1982; more recently Chinn & Brewer 1993). These approaches claim that, in analogy to scientific revolutions, which are elicited by new data not fitting into the existing theories, the pupils' conceptual change can also be induced and facilitated by showing them the new information they are not able to explain. Without doubt, it is an important factor. In addition to creating cognitive conflicts to which the solutions are then immediately given, the emphasis on the predictive value of the new theories also helps to fill supra-empirical concepts with real empirical data.

Another problem of traditional education is that different meaningful relations between concepts remain implicit. Albanese and Vincentini (1997) noted that even from the perspective of an intelligent adult many "rules of the game" of chemistry are not explicated in chemistry textbooks. For example, in the case of the atomic model it is not mentioned that all the properties of the bulk matter are reduced to and explained by the mass and motions of the atoms, and that atoms themselves, therefore, cannot have colour. High-school pupils need more explications because new concepts are most probably first understood as psychologically equivalent to everyday concepts.

In this respect it is paramount to be aware that the cognitive mechanisms underlying the pupils' initial everyday theories and scientific theories may require different psychological structures. As we, following Vygotsky's ideas, mentioned earlier, thinking with the concepts so detached from perceptible phenomena is structured differently, namely it is mediated by sign-systems. When scientific concepts are not understood systematically, their explicative power remains deficient. A disciple of Vygotsky, the Russian psychologist Galperin (1985) developed and empirically tested a special kind of instruction – system-theoretic teaching – where the very differences of scientific concepts and methods of analysing them were explicit from the beginning. In different domains, several general top-down analytic procedures can be discovered to teach pupils to be more aware and systematic in their study of science (for recent discussions of Galperin's instructional system and its relations to the contemporary Western psychology see Arievitch & Stetsenko 2000, Karpov & Haywood 1998, van der Veer 2000). We suggest that the special analysis of what is empirical and what is scientific in chemistry (which would reveal also the implicit differences between these two facets) has to be attempted.

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Address:
Hillar Saul
Department of Psychology
Tallinn Pedagogical University
Narva mnt 25
10120 Tallinn, Estonia
Tel: + 372 6409 470
Fax: + 372 6409 475
E-mail: hillar@psych.ut.ee

References

Albanese, A. & Vincentini, M. (1997) "Why do we believe that an atom is colourless? Reflections about teaching of the particle model." *Science & Education* 6, 251–261.

Arievitch, I. M. & Stetsenko, A. (2000) "The quality of cultural tools and cognitive development: Galperin's perspective and its implications." *Human Development* 43, 69–92.

Boo, H. K. (1998) "Students' understanding of chemical bonds and the energetics of chemical reactions." *Journal of Research in Science Teaching* 35, 569–581.

Brosnan, T. & Reynolds, Y. (2001) "Student's explanations of chemical phenomena: Macro and micro differences." *Research in Science & Technological Education* 19, 69–78.

Carter, C. S., LaRussa, M. A., & Bodner, G. M. (1987) "A study of two measures of spatial ability as predictors of success in different levels of general chemistry." *Journal of Research in Science Teaching* 24, 645–657.

Chandran, S., Treagust, D. F., & Tobin, K. (1987) "The role of cognitive factors in chemistry achievement." *Journal of Research in Science Teaching* 24, 145–160.

Chinn, A. & Brewer, W.F. (1993) "The role of anomalous data in knowledge acquisition: a theoretical framework and implications for science instruction." *Review of Educational Research* 63, 1–49.

Driver, R., Squirer, A., Rushworth, V., & Wood-Robinson, M. (1995) *Making Sense of Secondary Science: Research into Science Ideas*. London & New York: Routledge.

Galperin, P. Y. (1985) *Metody obutscheniya i umstvennoe razvitie rebenka.* [Methods of instruction and the child's mental development.] Moscow: Izdatelstvo MGU.

Garnett, P. J., Garnett, P. J., & Hackling, M. W. (1995) "Students' alternative conceptions in chemistry: a review of research and implications for teaching and learning." *Studies in Science Education* 25, 65–95.

Glynn, S. M. & Duit, R. (1995) Learning science meaningfully: Constructing conceptual models. In *Learning Science in the Schools.* S. M. Glynn & R. Duit, eds. 3–33, Mahwah, NJ: Lawrence Erlbaum Associates.

Griffiths, A. K. (1994) A critical analysis and synthesis of research on students' chemistry misconceptions. In *Problem Solving and Misconceptions in Chemistry and Physics. Proceedings at the 1994 International Symposium.* H.-J. Schmidt, ed. 70–99, Hong Kong: ICASE.

Griffiths, A. K. & Preston, K. R. (1992) "Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules." *Journal of Research in Science Teaching* 29, 611–628.

Johnstone, A. H. (1991) "Why is science difficult to learn? Things are seldom what they seem." *Journal of Computer Assisted Learning* 7, 75–83.

Karpov, Y. V. & Haywood, H. C. (1998) "Two ways to elaborate Vygotsky's concept of mediation: Implications for instruction." *American Psychologist* 53, 27–36.

Keig, P. F. & Rubba, P. A. (1993) "Translations of representations of the structure of matter and its relationship to reasoning, gender, spatial reasoning, and sepcific prior knowledge." *Journal of Research in Science Teaching* 30, 883–903.

Kikas, E. (2000) "The influence of teaching on students'explanations and illustrations of the day/night cycle and seasonal changes." *European Journal of Psychology of Education* 15, 281–295.

Luria A. R. (1976) *Cognitive development: Its cultural and social foundations*. Cambridge, MA: Harvard University Press.

Pintrich P. R., Marx, R. W., & Boyle, R. A. (1993) "Beyond cold conceptual change: the role of motivational beliefs and classroom contextual factors in the process of conceptual change." *Review of Educational Research* 63, 167–199.

Posner, G. J., Strike, K. A, Hewson, P. W., & Gertzog, W. A. (1982) "Accommodation of a scientific conception: toward a theory of conceptual change." *Science Education* 66, 211–227.

Pozo, J., Gómez, M., & Sanz, A. (1999) When change does not mean replacement: Different representations for different contexts. In *New perspectives on conceptual change.* W. Schnotz, S. Vosniadou, & M. Carretero, eds. 161–174, Amsterdam et al.: Pergamon.

Renström, L., Andersson, B, & Marton, F. (1990) "Students' conception of matter." *Journal of Educational Psychology* 82, 555–569.

Rolfhus, E. L. & Ackerman, P. L. (1999) "Assessing individual differences in knowledge: knowledge, intelligence, and related traits." *Journal of Educational Psychology* 91, 511–526.

Sadler, P. M. (1998) "Psychometric models of student conceptions in science: Reconciling qualitative studies and distractor-driven assessment instruments." *Journal of Research in Science Teaching* 35, 265–296.

Smith, C., Maclin, D., Grossligth, L., & Davis, H. (1997) "Teaching for understanding: A Study of students preinstruction. Theories of matter and a comparison of the effectiveness of two approaches to teaching about matter and density." *Cognition and Instruction* 15, 317–393.

Stavy, R. (1995) Conceptual development of basic ideas in chemistry. In *Learning Science in the Schools.* S. M. Glynn & R. Duit, eds. 131–154, Mahwah, NJ: Lawrence Erlbaum Associates.

Stepans, J. (1991) Developmental patterns in students' understanding of physical concepts. In *The psychology of learning science*. S. Glynn, R. Yeany, & B. Britton, eds. 89–116, New Jersey & London: Lawrence Erlbaum.

Valanides, N. (2000) “Primary student teacher’s understanding of the particulate nature of matter and its transformations during dissolving.” *Chemistry Education: Research and Practice in Europe* 1, 249–262.

van der Veer, R. (2000) “Some reflections concerning Galperin's theory.” *Human Development* 43, 99–102.

Vosniadou, S. (1994) “Capturing and modeling the process of conceptual change.” *Learning and Instruction* 4, 45–69.

Vosniadou, S., Ioannides, C., Dimitrakopoulou, A., & Papademetriou, E. (2001) “Designing learning environments to promote conceptual change in science.” *Learning and Instruction* 11, 381–419.

Vygotsky, L. S. (1934/1997) *Thought and language.* (Revised edition of 1986). Cambridge, MA: MIT Press.

Vygotsky, L. S. (1934/1994) The development of academic concepts in school aged children. In *The Vygotsky reader*. R. van der Veer & J. Valsiner, eds. 355–370, Oxford & Cambridge: Blackwell.

Wonderlick, E.F. (1983) *Wonderlick Personnel Test Manual*. Northfield, IL: E. F. Wonderlick & Associates.

Wu, H.-K., Krajcik, J. S., & Soloway, E. (2001) “Promoting understanding of chemical representations: Students’ use of a visualization tool in the classroom.” *Journal of Research in Science Teaching* 38, 821–842.

Zoller, U., Lubezky, A., Nakleh, M.B., & Tessier, B. (1995) “Success on algorithmic and LOCS vs. conceptual chemistry exam questions.” *Journal of Chemical Education* 71, 987–989.

Appendix A

Questions of the chemistry test

Chemical elements

1. In chemical reactions, chemical elements
   a) melt or dissolve – empirical
   b) they do not change – correct
   c) decompose – pseudoscientific
   d) change their colour and shape – empirical
2. How can you determine the characteristics of a chemical element (e.g. iron)
   a) indirectly, observing the reactions – correct
   b) separating a pure piece of iron – empirical
   c) determining its molecular composition – pseudoscientific
   d) determining its density and melting point – pseudoscientific
3. The chemical activity of a particular element is determined:
   a) by its temperature - empirical
   b) by its state (whether it is solid, liquid, or gaseous) – empirical
   c) by the composition of its atom – correct
   d) by molecules – pseudoscientific
4. Chemical elements differ
   a) by their shape and form – empirical
   b) they are of different thickness (solidity) – empirical
   c) in different elements there are different molecules – pseudoscientific
   d) by the mass of its atoms – correct

Atoms and molecules

5. Sugar dissolves in water and we have an ideal solution. Does sugar decompose into
   a) atoms – pseudoscientific
   b) molecules – correct
   c) pieces of sugar – empirical
   d) electrons – pseudoscientific
6. Atoms differ from each other
   a) by their form – empirical
   b) by their colour and smell – empirical
   c) by their molecules – pseudoscientific
   d) by their mass – correct
7. When water freezes, changes happen to
   a) atoms – pseudoscientific
   b) molecules – pseudoscientific
   c) with none of them – correct
   d) both with atoms and molecules – pseudoscientific

8. We put sulphur trioxide into water and we have sulphuric acid, which of the following does not change
   a) atoms – correct
   b) molecules – pseudoscientific
   c) pieces of sulphur – empirical
   d) water – empirical
9. Larger amount of atoms in molecules makes the substance
   a) stronger and thicker – empirical
   b) chemically less active – pseudoscientific
   c) chemically more active – pseudoscientific
   d) none of the given answers are right – correct

Symbols

10. Number 2 in formula H_2 refers to
   a) number of molecules – pseudoscientific
   b) number of atoms – correct
   c) number of moles – pseudoscientific
   d) mass – empirical
11. Balance the equation …H_2 + … $O_2 \rightarrow$ …H_2O
   Why do we have to do that? (why is this necessary)What does it chemically mean?
   a) hydrogen weighs less, therefore we have to have more hydrogen – empirical
   b) it means nothing, it is just right to do so – pseudoscientific
   c) the number of oxygen and hydrogen molecules has to remain the same – pseudoscientific
   d) the number of oxygen and hydrogen atoms has to remain the same – correct
12. Formula HCl signifies
   a) one atom – pseudoscientific
   b) one molecule – correct
   c) one electron – pseudoscientific
   d) chemical element – empirical

Factual questions

13. Which of the following is not a chemical element
   a) Pb
   b) Hg
   c) G – correct
   d) B
14. H_2SO_4 signifies ....….
15. HNO_3 signifies ...….
16. Balance the equations
   a) …H_2 + … $O_2 \rightarrow$ …H_2O
   b) …Li + …$O_2 \rightarrow$ …Li_2O
   c) …Na + …Na_2O2 $\rightarrow$ …Na_2O

Appendix B

Examples of the syllogisms

1. Consistent with knowledge

French people are not Italian
Some of the actors are French
Conclusion: … (correct is "some of the actors are not Italian)

2. Inconsistent with knowledge

No metal corrodes
Some things made of iron corrode
Conclusion… (correct is "some iron things are not made of metal")

3. Nonwords

No tset koobes
Some tiirps koobe
Conclusion… (correct is "some tiirps are not tsets")