Summary of PhD thesis

STUDENTS' PROBLEM-SOLVING STRATEGY AND KNOWLEDGE STRUCTURES IN STOICHIOMETRIC PROBLEMS

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I. INTRODUCTION

In recent decades, chemistry has become one of the least favored school subjects among students. Learning and mainly understanding compulsory teaching materials are not easy for the majority of students. One of the greatest problems for students is problem-solving exercises. Therefore, it is important to know the features of the problem-solving process, and that is why it is necessary to study problem solving from several points of view. Today examination of problem-solving thinking plays a central role in pedagogical, psychological and methodological research. Several studies deal with identifying the types of problems, solving strategies used for the problems, modelling problem solving and the opportunities of developing problem solving.

In chemistry teaching, problem solving mostly occurs in the form of chemical calculations, which may help understand concepts or relationships significantly. Chemical calculations represent a difficult task for the students and they are often unsuccessful in solving them. Therefore, it is important to discover the reasons and find the opportunities of correction. The most difficult part of problem solving is to find the solving pathway that helps us reach the correct result. During the examination of chemical calculation tasks, it is the most important to identify the solving methods. To examine efficiency first we need to apply descriptive and mathematical statistical procedures. We can find examples of these both in domestic and international literature.

The methods of analysis mentioned above are also very important but we cannot point out the critical points leading to failure in problem solving with them surely enough. We also need a structural analysis of calculation tasks more detailed than ever and not applied in this field so far. Knowledge space theory gives us a very good opportunity to get some more precise information on the students' knowledge and to determine the knowledge structure characteristic of the years and the student groups. We can find the element of knowledge in the solution of which the students experience hardships and thus they are not able to solve the problems. Thus relying on already existing scientific results, the new data may help us more deeply understand the characteristics and difficulties of solving methods as well as teach chemical calculation tasks more effectively.

The aim of this work is to identify problem-solving strategies by students as well as to map and compare of the students' knowledge structures. And especially to find the relationship between solving methods applied in chemical calculations and knowledge structure among primary and secondary school students. It is very important because there was no such examination before.

II. THE STUDY

1. The aims and main hypotheses of this study

In my work, I examined three areas of stoichiometric chemical calculations from several points of view. These were the following: chemical calculations based on chemical equations, calculating the composition of chemical compounds, and shifting between amounts at the macro and the sub-microscopic levels.

I specified my aims of research as follows:

1. Study of the development and change in the strategies of elementary and secondary school students in three areas of chemical calculations.

- In every type of problem, exploration and analysis of the students' solving strategies.
- In every type of problem, a detailed study of the process of strategy change as chemistry teaching proceeds.

2. In the chemical calculations, a detailed description of the knowledge structures of groups selected from elementary and secondary school students by several criteria.

- Definition and comparison of the knowledge structures of student groups with different age, solving strategies, calculation techniques and performance levels, as well as definition and comparison of the knowledge structures, typical learning pathways and problem hierarchy of boys and girls.
- Analysis of the connection between problem-solving strategy and knowledge structure. Verification of the hypothesis that the characteristic knowledge structures of students using different solving strategies are different as well.
- Answering the question whether the model we use for examining knowledge structure, knowledge space theory, is suitable for the demonstration or study of differences in knowledge structure or the fine structure of knowledge organization.

3. Exploration of typical mistakes or misconceptions.

2. The sample

Students from 42 elementary and secondary schools of 21 different Hungarian townships participated in this comprehensive study. There were students attending elementary schools, four-, six- or eight-grade grammar schools, secondary technical schools or vocational schools among them. The sample is also heterogeneous according to the students' fields of interest. Of course, there were students interested in chemistry, but there were also students specialized in biology, music, foreign languages, history or sports. The tests were solved by 7th to 10th graders. The sample population consisted of 3290 students (1127 elementary school students and 2163 secondary school students) altogether.

3. Methods of this study

3.1. Instruments

We conducted an empirical survey with written tests containing self-made, open-ended items. For the purpose of examination, we selected chemical calculation tasks solvable with several strategies. The worksheets were composed in way that the students' solving strategies or any possible development or change in strategy could be induced. The Cronbach-alpha values of the measuring instruments are above 0.7: 0.726 to 0.857, thus the worksheets measure properly. According to structure, the common feature of these worksheets is that each one contains one or two complex problems and six or seven simple problems related to them. Simple problems are related to the partial steps and knowledge elements occurring in the solving strategies of complex problems. Complex problems serve as indicators; I also grouped the students according to solving. In every case, the students' grades, school type, gender and the chemistry and mathematics grades of the latest term were recorded as background variables.

Task sheets were prepared in three topics:

- Worksheet **E-1**: Calculation on the basis of chemical equation
- Worksheet **V-1**: Calculation tasks with the chemical composition of compounds
- Worksheet **R-1**: Calculation tasks with amounts at the macro and the sub-microscopic levels

The number of students is broken down according to grades in *Table 1.*

Table 1: The number of students solving the worksheets according to grades

	grade 7	**grade 8**	**grade 9**	**grade 10**	**Total**
E-1	160	210	364	338	***1072***
V-1	166	201	349	342	***1058***
R-1	192	198	408	362	***1160***
Total	***518***	***609***	***1121***	***1042***	**3290**

3.2. Conducting the research

Before the large-sample studies (2006), I carried out research in the above-mentioned three topics based on solutions by first year university students. Mostly because these students have just finished their secondary school studies, thus I could utilize these results. After considering the results, the worksheets were finished and data were collected. Worksheets were filled out in the second term of the academic year from 2005 to 2006, with the supervision of subject teachers, during normal lessons, usually during chemistry lessons.

3.3. Methods of evaluation

I analyzed the students' answers in three dimensions. In the area of chemical calculations, I supplemented my results obtained in qualitative and quantitative evaluations with the method examining knowledge structure.

3.3.1. Content analysis of the students' answers

During content analysis, I identified the already known solving strategies, examined their frequency, categorized those not yet described in literature, and collected typical mistakes and misconceptions.

3.3.2. Statistical analysis of the students' answers

I conducted evaluation on dichotomy scale (0, 1). If students did not write anything on the worksheet or the solution was wrong, they got 0 point. In each task, I gave 1 point for each good answer independent of the difficulty of the problems. During quantitative analysis, I used the Microsoft Office Excel and SPSS (Statistical Package for Social Sciences) softwares. I verified the statistical analysis of the results and significance of the differences between the groups with variance analysis, one-sample t-test, two-sample t-test, and χ^2-test. I examined the strength of the relationship between the items of the worksheets and the background variables with correlation analysis. I prepared the figures and diagrams of this paper with the help of the Microsoft Office Excel software.

3.3.3. Structural analysis of the students' answers

To define the characteristic knowledge structures of student groups, I applied the knowledge space theory.

Knowledge space describing the students' knowledge is the aggregation of elements of knowledge, which is necessary for understanding a particular topic. In the case of chemical calculation tasks, a complex problem and simple problems necessary for its solution form a hierarchical system. Problems requiring the least knowledge are at the bottom of the hierarchy; and more complex problems are at the top of the hierarchy. And the building of these problems and knowledge elements upon each other is described and interpreted by the Hasse diagrams by the answer structure of the student group. According to the basic hypothesis of the knowledge space theory, if students can solve a problem higher in the hierarchy, they are expected to solve any problems lower in the hierarchy. Every student may by characterized by a knowledge state, which is a complex of problems the student can solve. The aggregation of knowledge states characteristic of a group is the knowledge structure only containing knowledge states that are part of a hierarchical net and connected with a knowledge state below or above this.

The analytical method used for mapping the students' knowledge structure is suitable for both individual and collective analyses. The methods allows comparison between the knowledge structure characteristic of a student group and the so-called expert's knowledge structure. With the help of the learning pathway defined by knowledge structure, we can determine the correct order of teaching and study the effect of different factors (age, gender, teaching method) on the organization of knowledge. It is an efficient tool in the study of the change and development of knowledge structure as well. The novelty of this is that, as opposed to other methods used earlier for the analysis of knowledge structure, it describes the organization of knowledge with non-linear models and it also builds elements (a lucky-guess and a careless error) neglected so far in the analysis.

I used the software by Potter and an analytical software called hDA for structural analysis based on the knowledge space theory.

In the characteristic knowledge structures obtained during the structural analysis I marked the complex task blue with the bold arrows.

III. NEW SCIENTIFIC RESULTS

1. The success rate typical of all of the worksheets shows a weak-modest result in the examined population. The weakest performance occurred in the worksheet measuring the connection between quantities at the macro level and the sub-microscopic level *(Table 2)***.**

Table 2: Statistical data characteristic of the success rate of worksheets

worksheet	number	success rate and deviation (%)
E-1	1072	**41.0** ± 31.1
V-1	1058	**42.4** ± 31.3
R-1	1160	**24.4** ± 23.5

1.1. The results of the given tasks indicate that **students performed more weakly** (4-51%) **in solving calculation tasks requiring chemical knowledge than in calculation tasks that can be solved without any chemical knowledge** (49-68%). The only exception is the task based on the relationship between molar mass, mass, and amount, which is the most frequently practiced and mechanically learned calculation task (37-70%).

1.2. The students solved the two complex problems in the ***worksheet with calculation of the composition of chemical compounds*** more easily, which in performance (47% and 39%) also outnumbers the efficiency of several simpler problems. In the case of the same types of problems, students performed significantly better in solving tasks more easy to calculate ($p \leq 0.05$).

1.3. Among the problems ***in the worksheet based on the relationship between quantities at the macro and the sub-microscopic levels,*** the students coped more easily with problems (29-66%) only containing calculations related to chemical particles (atoms). Problems containing elementary particles (electrons) as well were much more difficult for them, which also showed a significant decrease ($p \leq 0.05$) in performance (4-18%). The students' performance was significantly better in the case of problems belonging to the first group ($p \leq 0.002$). The students performed better even in problems where – although their performance decreased significantly ($p \leq 0.05$) –, there was a shift between amounts at the macro (amount, mass) and sub-microscopic levels (particle number). Success in solving did not change significantly in the two groups of problems comparing the grades.

1.4. Based on the analysis of partial steps and examining ***the relationship between amounts of substance at the macro and the sub-microscopic levels,*** **I pointed out that the greatest problem is caused by the shifting from one material system to the other material system (electron → atom), especially if it happens at the sub-microscopic level (particle number).**

2. Within the worksheets, the best results were mostly achieved by 8th graders (and 9th graders in the *worksheet testing the shift from the macro level to the sub-microscopic level*) *(Figure 1)***.**

The 8th graders only show significantly better performance in ***worksheets with the calculation of the composition of chemical compounds*** compared to 7th graders (p=0.005). In the other cases, the differences between the grades did not prove to be significant. Advancement in school (chemistry) studies does not develop abilities and skills necessary for solving chemical calculations successfully.

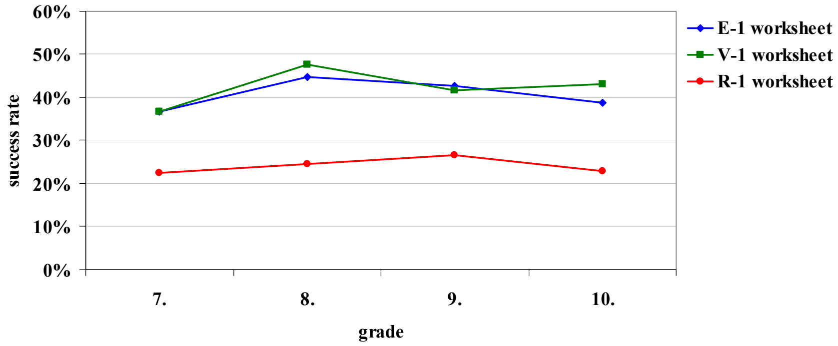


Figure 1: Success rate in the worksheets according to grades

2.1. **Great variation coefficients** (64.5-110%) **indicate that the examined student groups are very heterogeneous in solving problems.** Variation coefficient is the smallest in grade 8, which indicates that efficiency in solving among 8th graders is relatively more homogeneous than among students of the other grades.

2.2. ***In calculations with a chemical equation,*** **I could only demonstrate significant differences between the genders in the 10th grade, both in performance and strategy selection.** Boys were usually more successful than girls, but their performance demonstrably fell back in grade 10. In this grade, girls already performed significantly better (p=0.037). Both girls and boys had a very weak result in solving the complex problem (3.95-23.6%).

3. Only 29 to 46% of the students applied any of the solving methods in solving complex problems. They mostly used solving strategies learnt at school.

3.1. ***In calculation with a chemical equation,*** there was no difference between grade 7 and grade 8 with respect to the use of both methods (mole method, proportionality method) *(Figure 2).*

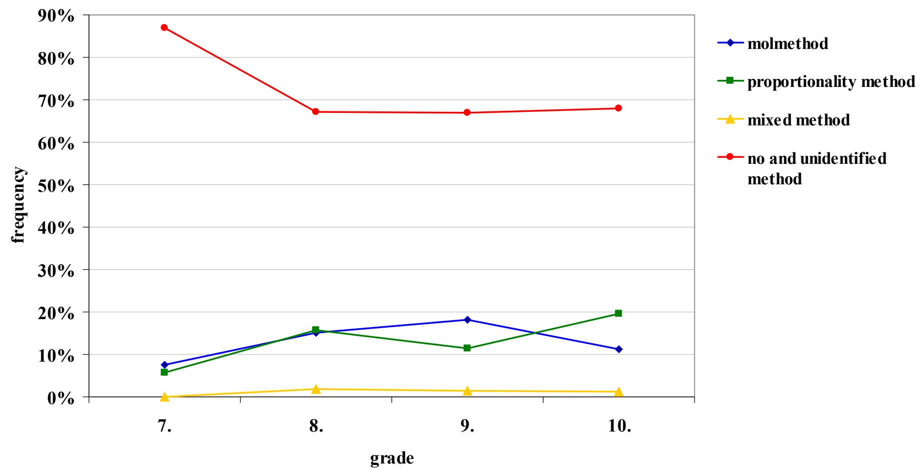
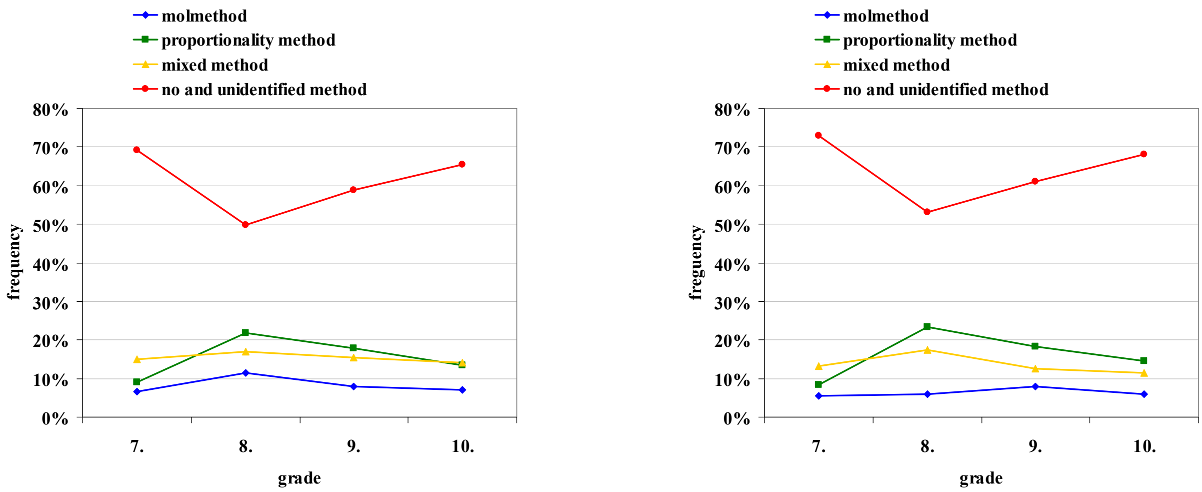


Figure 2: Frequency of solving methods in the complex problem ***in worksheet E-1***

In the 9th grade the mole method requiring algorithmic knowledge, in the 10th grade the proportionality method built on simple proportionality was typical ($p=0.001$). The mixed method occurred only by chance. The frequency of the no and unidentified solving method is greater ($p=0.000$) in the 7th grade compared to the other grades *(Figure 2)*.

3.2. ***To calculate the composition of chemical compounds,*** the majority of students selected the rule of three and the mixed method from among solving strategies. 8th and 9th grade students preferred to apply the rule of three compared to their 7th grade fellows ($p \leq 0.053$). The mole method was only used by a minority of students. The logical procedure did not occur at all. The frequency of the no and unidentified solving method is greater ($p=0.001$) in the 7th grade compared to the 8th grade *(Figure 3)*.



a) b)

Figure 3: Frequency of solving methods in problem 1 (a) and problem 2 (b) ***in worksheet V-1***

3.3. In the complex problem in ***the worksheet testing the connection between amounts at the macro and the sub-microscopic levels,*** the majority of students preferred the stepwise I solving method in every grade to other identifiable solving pathways ($p \leq 0.05$), which begins with shifting levels within the same system (particle number of the electron → amount of the electron) *(Figure 4)*.

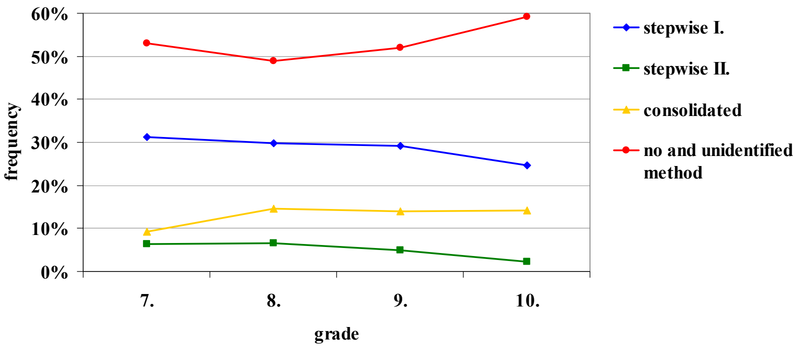


Figure 4: Frequency of solving methods in the complex problem ***in worksheet R-1***

Only few students chose the contracted solving method and especially the stepwise II solving strategy, which starts with shifting from one system (particle number of the electron) to another system (particle number of the atom). There was no traceable strategy change with the advancement of chemistry teaching *(Figure 4)*.

3.4. **In the analysis of *the worksheet with calculation of the composition of chemical compounds,*** as opposed to those found in international literature, I found that **selection of a solving method does not depend on the database of the two complex problems,** i.e. whether the two-component chemical compound contains atoms in the mass proportion of 1:1 or 3:2. The fundamental reason for this is that the logical pathway, whose usefulness, according to literature, is affected by the data given in the problems, did not occur among the solving strategies used.

4. In all of the three worksheets and in each grade, students using a well identifiable solving strategy for complex problems worked more successfully ($p \leq 0.05$) compared to students using a no and unidentified solving strategy, regarding both the worksheets as a whole and the complex problems.

4.1. Examining both the complex problem ***related to calculation with a chemical equation*** and the entire worksheet there was no significant difference between the performance of students using the mole method and students calculating with the rule of three in any of the grades. Examining the particular solving method, there were no significant differences in the performances of the grades either *(Figure 5)*.

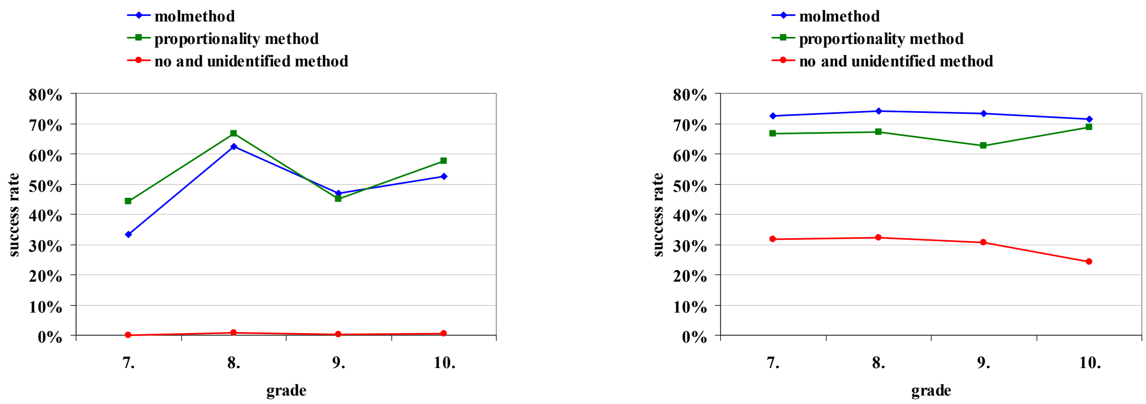


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Figure 5: Success rate in the complex problem (a) and (b) in the whole worksheet ***in worksheet E-1***

4.2. Examining the complex problems separately ***in the worksheet with calculation of the composition of chemical compounds,*** 7th grade students calculating with the mixed method ($p=0.031$) are more successful in task 2 than using the mole method. There are no significant differences between the particular grades in the case of a given solving strategy. Performances are very similar comparing the two complex problems *(Figure 6)*. Considering the entire worksheet, the performances of students achieved in solving methods only differ in the 9th grade. In this grade, students working with the mole method and the mixed method performed significantly better ($p=0.041$; $p=0.001$) compared to students using the rule of three. Taking the effectiveness of the particular solving procedures into consideration, I could not demonstrate any significant differences among the grades *(Figure 7)*.

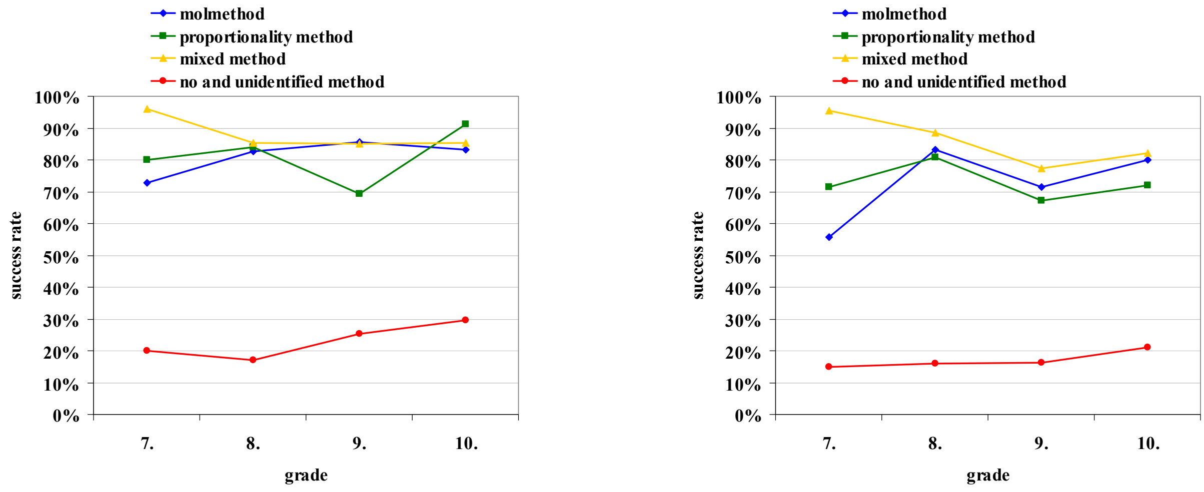

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Figure 6: Success rate on the basis of solving methods occurring in problem 1 (a) and in problem 2 (b) ***in worksheet V-1***

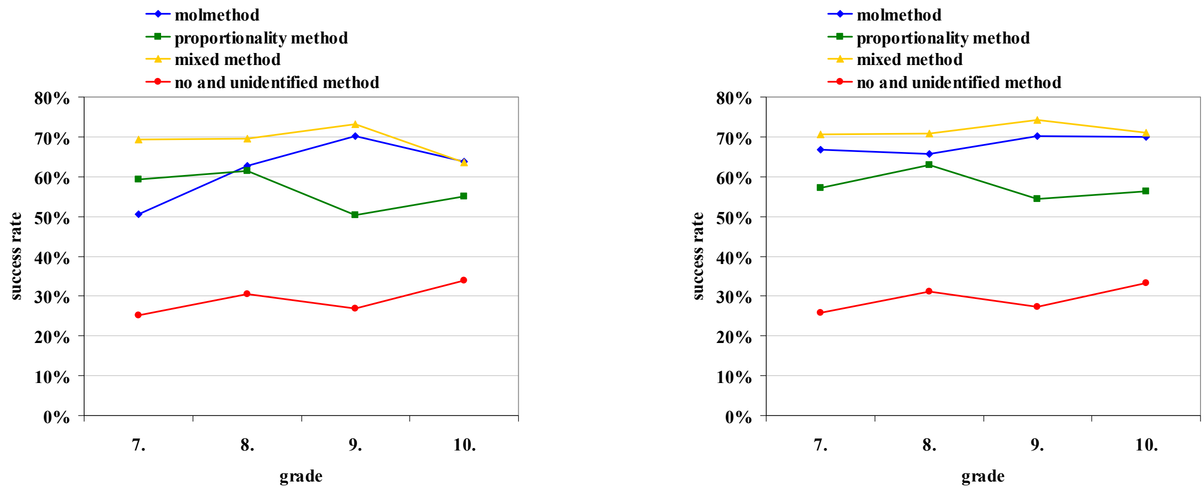

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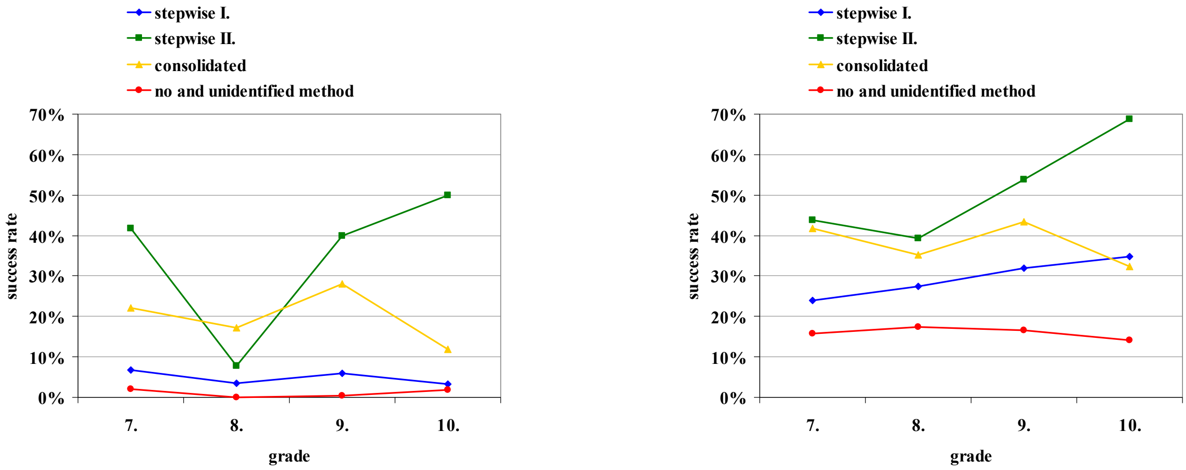
Figure 7: Success rate by solving methods occurring in problem 1 (a) and in problem 2 (b) in the whole ***worksheet V-1***

4.3. ***The worksheet testing the relationship between amounts at the macro and the sub-microscopic levels.*** Regarding performance in the complex problem and the entire worksheet *(Figure 8)*, students – with the exception of the 8th grade – are demonstrably more effective in working with the less typical stepwise II solving strategy ($p \leq 0.004$), than calculating with the stepwise I solving procedure. The reason is that the first step in the stepwise II solving strategy (particle number of the electron → amount of the electron) is the most difficult part of solution, thus if the students managed to solve this, they would surely get the correct result in practice. The performance of those working with the contracted method also proved to be good, but only few students selected this solving method. There are no significant differences among the grades with respect to solving methods.



a) b)

Figure 8: Success rate in the complex problem (a) and in the whole worksheet (b) ***in worksheet R-1***

4.4. ***In the case of the worksheet testing calculation with a chemical equation***, 80% of the students used one of the two (or both of the) calculation techniques (formula, induction) in calculation related to molar mass and molar volume. In every case, their effectiveness exceeded (41-59%) that of students working with a no and unidentified calculation technique (10-16%).

The majority of students – except 8th graders – preferred calculation with a formula to solving with induction from among the calculation techniques ($p \leq 0.007$) but regarding success, those calculating with induction achieved a better result in the examined group of problems. However, there was a significant difference only in the 8th grade regarding performance in the two calculation techniques ($p=0.014$). This calculation technique was probably selected by students understanding the meaning of concepts. In this manner, they could apply this safely enough and they were more successful in solving the problems.

There is an increase in performance among those using a formula as age proceeds but there are no significant differences. Comparing the grades, in the case of those calculating with induction, 8th graders scored excellently: they performed significantly better ($p=0.037$) than 7th graders. In grade 9 and grade 10, the students' performance decreased.

4.5. Students successfully solving the complex problem scored significantly better ($p \leq 0.05$) in the entire worksheet than students calculating incorrectly. **Success in solving partial problems does not guarantee a success in solving multiple-step problems.**

5. With the help of knowledge structure analyses, I proved that there are differences in the typical knowledge structures of student groups selected by several criteria.

5.1. *<u>The worksheet with calculations based on chemical equations:</u>*

- **The Hasse diagram describing the knowledge structure of 7th graders is different from the knowledge structures of the other grades**.

In grade 7, every problem is a prerequisite of solving a complex problem. In the other grades, a knowledge element related to molar volume is not a prerequisite of solving a complex problem successfully. Besides, in grade 8, the same is true for interpreting a chemical equation. In all the four grades, the basis of knowledge structure is molar mass and direct proportionality. Differences in knowledge structures derive from the fact that the students' prior knowledge necessary for solving a complex problem was not identical.

- **I managed to demonstrate differences in the characteristic knowledge structures of groups using two different solving methods.**

Students have schemes formed earlier. In the Hasse diagrams best describing the knowledge structure of students using the mole method, the complex problem rests on molar mass and direct proportionality. In the knowledge structure of students using proportionality method, solution of a complex problem is mainly defined by the knowledge of direct proportionality, it is not necessary to mobilize all partial knowledge. It indicates that the students applied the solving methods learnt at school without understanding conceptual knowledge. For the group of students working with a no and unidentified solving method, I got knowledge structures similar to an expert's knowledge structure; the students used all conceptual knowledge for solving a complex problem *(Figure 9)*.

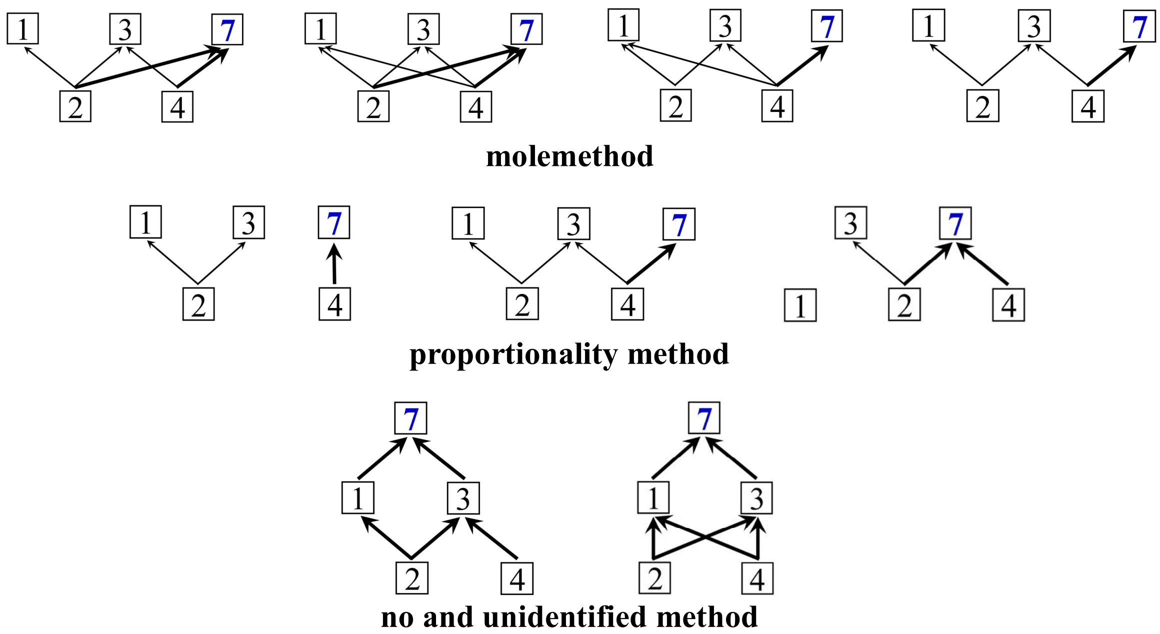


Figure 9: *The best models for the organisation of knowledge in students' mind in different solving methods*

1: calculation task related to molar volume
2: calculation task related to molar mass
3: calculation task related to interpreting a chemical equation
4: calculation task related to direct proportionality
7: complex problem*: calculating the mass of a reactant from the volume of another reactant with a chemical equation*

- **Typical differences could be discovered even in the knowledge structures of groups selected by calculation techniques.**

In the case of students calculating with a chemical formula, correct solution of a complex problem assumes the knowledge of molar mass, direct proportionality and chemical equations.

In the case of students calculating with induction, such models occur where mostly direct proportionality is the determining element of knowledge. As opposed to these, molar mass is the basic element of knowledge in the case of students working with a no and unidentified calculation technique.

- **There is also a difference between the knowledge structures of students correctly solving the complex problem and students unable to solve the complex problem.**

While in the knowledge structure of the students correctly solving the complex problem the chemical equation problem is only built on molar mass, in the knowledge structure of students incorrectly solving the complex problem, direct proportionality is also a prerequisite of this problem. The prerequisite of correctly interpreting a chemical equation is the knowledge of the concept of mole. It is characteristic of the knowledge structure of students unable to solve the complex problem that knowledge of the solution of every simple problem is the prerequisite of the solution of the complex problem. It is typical of the knowledge structure of those correctly solving the complex problem that it is not necessary to mobilize every element of knowledge to solve a complex problem correctly. For unsuccessful solvers, the prerequisite of correctly solving a complex problem is knowledge of the solution of every simple problem. Here knowledge elements necessary for solving simple problems do not constitute a unified system of associations yet, while in the case of students correctly solving the complex problem these knowledge elements already function at the level of skills and constitute a well-functioning and coherent structure in the knowledge of the students.

- I verified that similarly to earlier studies, **in the knowledge structures of the student groups, the concept of molar volume rests on the concept of molar mass**.

5.2. *The worksheet with calculation of the composition of chemical compounds:*

- I established from the knowledge structures characteristic of the four examined grades that **knowledge of direct proportionality is the prerequisite of solving a complex problem in almost every case**.

In each grade, in the group with a more difficult indicator problem (the mass proportion of atoms was 3:2), the complex problem was integrated into the knowledge structures while in the group with the simpler indicator problem (the mass proportion of the atoms was 1:1), the complex problem was separated from the structure containing the other knowledge elements.

- **I could observe a difference in the characteristic knowledge structures of student groups using different solving methods.**

Surprisingly, there is no relationship between the complex problem and the simple problems in the knowledge structure of students applying the mole method. It refers to the fact that students use the mole method mechanically as an algorithm. Among students working with the proportionality method, direct proportionality is the most determining knowledge element in the case of the complex problem. In the knowledge structure of students calculating with the mixed method, the complex problem usually rests on the knowledge element requiring the knowledge of direct proportionality. It is apparent in the knowledge structure of students using the no and unidentified solving method that they also use the direct proportionality alone for solving the complex problem (*Figure 10)*.

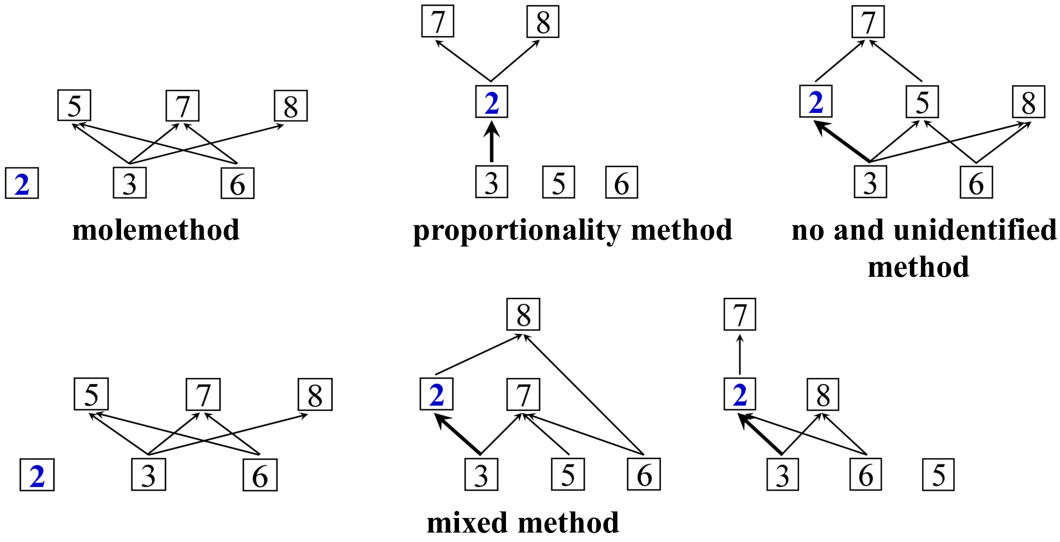


Figure 10: The best models for the organisation of knowledge in students' mind in different solving methods

__2: complex problem__: calculating the mass of a constituent atom from the mass of a chemical compound in view of molar mass
3: calculating the mass of a constituent atom from the mass of a chemical compound by direct proportionality
5: giving the amount of a chemical compound by the help of mass and molar mass
6: calculating the mass of a constituent atom from the mass of a chemical compound in view of the mass proportion of constituent atoms
7: defining the amount of a constituent from the amount of a chemical substance
8: calculating the mass proportion of the constituent atoms from the ratio of the molar mass and amount of atoms constituting the chemical compound

- **There are differences in the characteristic knowledge structures of beginners and advanced learners with respect to the relationship between the solving methods used in the complex problem.**

The connection between the solving methods showed that use of a logical procedure in no case did fully integrate into the hierarchy describing the connections between the strategies. It rested on the mole method and the proportionality method. There is no connection between the mole method and the logical procedure. There was no change in the relationships of solving procedures either with respect to the efficiency of the complex problems, the students practically treated the algorithmic solving methods learnt at school and the logical procedure making them think separately. The mole method is at the top of the hierarchy in the group of students unable to solve the complex problem. In the knowledge structure of those correctly solving the complex problem, the mole method rests on the proportionality method and the mixed method. It is apparent that in the case of beginners, solution with the mole method while as students get older, calculating with the proportionality and the mixed method is closer to the students' way of thinking.

5.3. *The worksheet between amounts at the macro and the sub-microscopic levels:*

- In view of the analysis of the students' knowledge structures, **the problematic knowledge element determining within the same material system is calculation requiring a shift between the macro and the sub-microscopic levels**. This difficulty in shifting decreases with the number of the years.

- **There were differences in the knowledge structures of student groups selected according to solving methods.**

In the knowledge structure of students calculating with the stepwise I solving method, shifting between the macro and the sub-microscopic levels as a knowledge element is the prerequisite of successfully solving the complex problem. In the knowledge structure of students calculating with the stepwise II solving method, conversion from the sub-microscopic level to the macro level as a knowledge element is not a prerequisite of successfully solving the complex problem, as in this case shift from one system to another system takes place at the sub-microscopic level. In the group of students applying the consolidated solving procedure, correct solution for the complex problem does not require conversions at the sub-microscopic level. The knowledge structure of students using the no and unidentified solving method is marked by a strict, back-to-back order: solution of a complex problem rests on every single knowledge element *(Figure 11)*. It is also apparent from each of the knowledge structures characteristic of the solving methods that the problem with level shifting is essential for solving the complex problem.

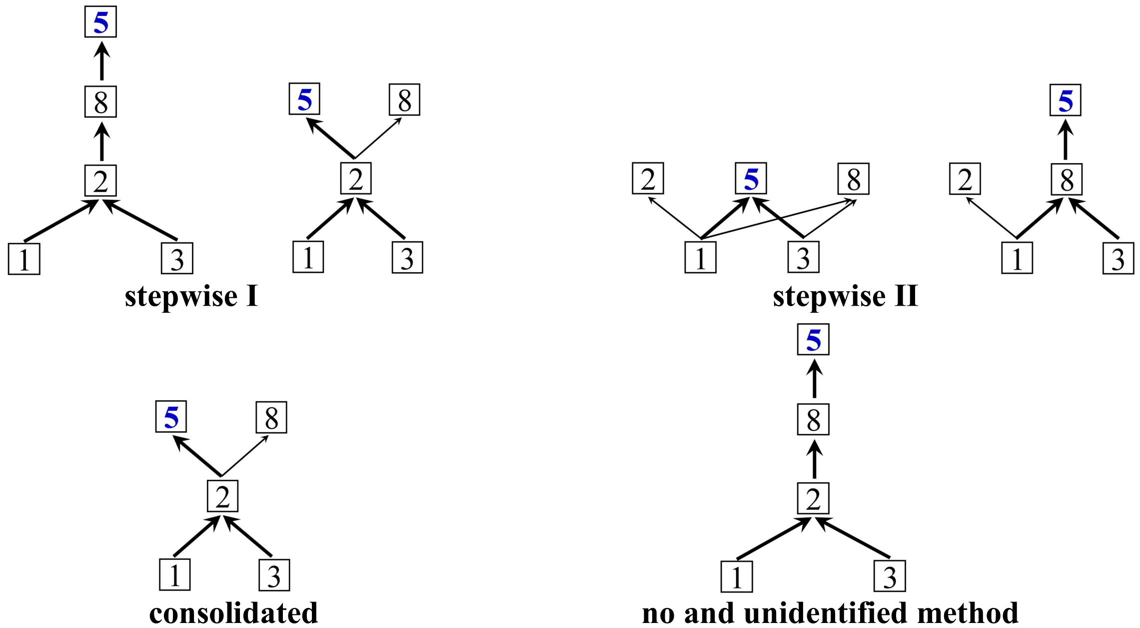


Figure 11: The best models for the organisation of knowledge in students' mind in different solving methods

1: calculating the amount of the atom from the mass of the atom
2: calculating the amount of the atom from the amount of the electron
3: calculating the particle number of the atom from the amount of the atom
***5: complex problem**: calculating the mass of the atom from the particle number of the electron*
8: calculating the particle number of the atom from the particle number of the electron

- The characteristic knowledge structures described above also prove that **shifting from one material system to another material system (electron → atom) is a greater problem for students than shifting between amounts at the macro and the sub-microscopic levels. It is especially true at the sub-microscopic level (particle number)**.

6. Content analysis of the answers revealed several problems in conceptual understanding: I noticed several typical mistakes and misconceptions. Partly due to the lack of chemical knowledge, partly due to reading comprehension mistakes, the students did not interpret the questions correctly many times.

6.1. **It is true *for solving each worksheet* that understanding the concepts necessary for chemical calculations was problematic for some student groups.**

Not every student knew the meaning of molar mass, molar volume and particle number exactly. Besides, they mixed up the expressions 'the amount of substance' and 'amount' due to the unexplained concept of amount. In addition to understanding the important amounts in chemistry correctly, recognition of the relationship among them was also problematic for the students. Learning basic relationships and formula (mass–molar mass–amount; volume–molar volume–amount; particle number–constant of Avogadro–the use of amount) probably took place by rote learning, thus they were mechanically recorded without any conceptual understanding hereby they could not use them safely enough, which led to the development of misconceptions. It meant 10 to 23% among the students answering the questions.

6.2. ***When calculating with a chemical equation,*** many students (18%) made a mistake in solving the problem due to a faulty understanding of the chemical equation.

6.3. ***When calculating the composition of chemical compounds,*** part of the students could not differentiate the chemical particles constituting the substances and they mixed up the concepts of atom, elementary molecule and compound molecule. The students also used the symbols O_2, Li_3, C_2 to denote the atoms constituting the chemical compounds. Similar to this, understanding the quantitative meaning of a formula was also problematic.

6.4. The results in the ***worksheet testing the relationship between amounts at the macro and the sub-microscopic levels*** further verify that grouping of chemical particles causes a lot of problem to students. Another problem is to recognize what kind of connection exists between the chemical particles and the subatomic particles constituting them as well as to recognize that they are not equivalent.

IV. THE APPLICATIONS OF THE RESULTS

In this study, I mostly aimed at gathering information in three areas of stoichiometric calculation to promote ***a more effective teaching and learning process*** with special respect to chemistry teaching in elementary and secondary schools. First of all I would like to give assistance with my work to teachers to teach more effectively and to students to learn more successfully. The data collected in the three topic areas support that before applying the solving methods, it is necessary to know solving strategies used by students and taught by teachers in the given topic. We can organize our teaching process only being aware of all these. Applying the knowledge space theory for structural analyses, it was proved that we can gather valuable data about the relevant knowledge of the student groups. For example, a correct knowledge of relationships and an understanding of the meaning of concepts. I think the most important benefit of knowledge structure analyses is that we can choose the correct order of teaching elements of knowledge by the help of learning pathways and typical problem hierarchies described above and thus we can optimize the teaching process. If these are achieved, students will be able to acquire knowledge adjusted to their abilities hereby they will have more success in solving chemical calculation problems. Detailed analysis of the connection between knowledge structure and solving strategy may promote the development of the general knowledge of students related to problem solving as well.

The results will ***allow the elaboration of new teaching aids***. After the content analysis of the worksheets, it turned out unambiguously that students prefer solving methods already learnt at school. I think we should compensate it by all means, because the exact aim of teaching parallel problem solving methods is to develop the cognitive ability of students to select a solving method always corresponding to the type of problem. The students used the solving strategies learnt at school as algorithms even if they got integrated mechanically in their minds and there was no conceptual understanding associated with them thus they could not apply them safely enough. Consequently, it is not enough just to teach the solving methods, because, as the results show, solving chemical calculations is unfortunately a more complex task. We have to search for, remove and fill in the gaps, which lead to an unsuccessful solving of the problem. We must try to understand relationships and chemical concepts necessary to solve chemical calculations more deeply and more punctually, assisted by preparing tasks to check them. I also have to mention errors in chemistry books, as they only refer to a small part of solving methods or there are no solving procedures presented in some topic areas by the authors at all.

My results are useful in teacher training as well. ***My results may be directly built in the methodological training of teacher trainees who major in chemistry***, as well as ***in the basic training of university students who major in chemistry***. The results allow a methodological renewal of teaching chemical calculations, which rests on the learners' prior knowledge and the known solving methods with more emphasis. It is important to call the teacher trainees' attention to the critical points and pitfalls occurring during problem solving which appeared as typical mistakes in the worksheets. In the future, they must be corrected by the teachers.

As a conclusion, my research work suggests further areas of study: mostly ***it may serve as an example for a detailed analysis of other subject matters in chemical calculation.*** Concerning the results, I think that similar types of research could be carried out in the future. Later, research may be worth extending to other types of tasks also causing a problem to students. I think we need much more methodological research to clarify problems in the subject of chemistry, because the results of recent years are unfortunately not very promising.

I hope that, with my work, I could at least partly help understand the failure to solve chemical calculation tasks and I can contribute to teaching more effectively.

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TUDOMÁNYOS EREDMÉNYEK

PUBLICATIONS

Az értekezés témájához kapcsolódó tudományos közlemények
Publications related to the dissertation

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1. Zoltán Tóth, Annamária Sebestyén
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10th European Conference for Chemistry Teachers, Salzburg, 2009. (Book of Congress: page 82.)

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Publication not related to the dissertation

Magyar nyelvű, lektorált folyóiratban megjelent közlemény

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A tanulók tévképzetei és fogalmi fejlődése a fizikai változás és kémiai változás témakörében
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List of publications related to the dissertation

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1. **Sebestyén, A.**: A tudásszerkezet és a problémamegoldó stratégia kapcsolata kémiai kontextusban.
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Foreign language scientific articles in Hungarian journals (1)

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Foreign language scientific articles in international journals (1)

7. Tóth, Z., **Sebestyén, A.**: Relationship between students' knowledge structure and problem-solving strategy in stoichiometric problems based on the chemical equation.
Eurasian J. Phys. Chem. Educ. 1 (1), 8-20, 2009. ISSN: 1306-3049.
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8. Kiss, E., **Sebestyén, A.**, Tóth, Z.: A tanulók tévképzetei és fogalmi fejlődése a fizikai változás és kémiai változás témakörében.
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