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Identifying Misconceptions Related to Chemical Bonding Concepts in the Slovak School System Using the Bonding Representations Inventory as a Diagnostic Tool

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ABSTRACT: In this article we present the results of a study in which we tested the use of the experimental inventory BRI (Bonding Representations Inventory), developed by Cynthia J. Luxford and Stacey Lowery Bretz. The aim of our study was to test the usability of the experimental instrument in the Slovak educational system and to identify concrete misconceptions in the theme of chemical bonding. In the conclusion, we compare the results obtained with the use of BRI in the USA educational system and the Slovak educational system. We point to the possibility of using BRI in a different educational system. The results of the prestudy and the main study showed that the BRI diagnostic instrument for identifying students' misconceptions is applicable outside the USA didactic system, for which it was developed.

KEYWORDS: *High School/Introductory Chemistry, Misconceptions/Discrepant Events, Inorganic Chemistry, Covalent Bonding, Ionic Bonding, Chemical Education Research*

FEATURE: Chemical Education Research

INTRODUCTION

Learning is a process in which students incorporate new knowledge into the existing mental structure. The students bring to school some preconceptions about scientific concepts that might interfere with a right understanding of scientific terms.[1] Therefore, there is a risk that students will understand some of the taught concepts in a way that is conflicted with established scientific theories. This misunderstanding leads to formation of "misconceptions" which are subjectively described as incorrect understanding, alternative conceptions, non-scientific conceptions, and bad science.[2−6] The notion of an alternative conception is understood as the idea being at odds with valid scientific theory after its inclusion in the mental structure. When the alternative concept is constantly used in several contexts or events, then it is called "alternative framework".[7]The occurrence of alternative conceptions in the learning process is a natural phenomenon. Thus, the provided information can be interpreted and "seen" by each pupil differently. If several students read the same scientific text, they do not necessarily remember the same arguments or facts. Furthermore, while reading the text or discussing something we can change an opinion or view of things. Not all new ideas must be correct. Many concepts that pupils encounter are very abstract or difficult to understand.[8] The term alternative conception refers to people's ideas which are inconsistent with scientifically acceptable ones. The term "misconception" is also sometimes used. (Misconceptions and alternative concepts are not clearly defined. They are often referred to as synonyms. Some authors use them as separate terms.) Concepts such as alternative concepts and frameworks are derived from constructivist theories of teaching and learning.[9]

A typical example of an alternative conception in chemical bonding teaching is the full shell explanatory principle which students use to explain formation of the chemical bonds. According to the students, shared electrons which form a covalent bond fill the valence shells of the two atoms and it is the cause of the bond formation. This idea, while being inconsistent with scientific thinking, is commonly adopted by students and forms an octet rule alternative framework that associates common student thinking about chemical stability, chemical bonding, and chemical reactions, as well as patterns in ionization energies. A prerequisite of conceptual learning, when the first idea is replaced by the idea of closer scientific concept, is inducing situations which learners are unable to interpret in a coherent manner; their idea has an alternative interpretation or is not at all able to meaningfully interpret the situation. This leads to the need for the learner to construct new or reconstruct existing concepts. Reconstructing existing concepts can be accomplished by developing an existing concept or conceptual changes.[10] Misconception research in chemistry has become the subject of many studies because misconceptions affect how students understand new scientific concepts and because they play a key role in whether the students will understand the curriculum correctly or not.[11]

OVERVIEW OF SOLUTIONS TO THE ISSUE OF CHEMICAL BONDING MISCONCEPTIONS IN THE WORLD

Students' preconceptions related to chemistry and physics subjects remain in their minds for a long time. Significant development of the basic ideas of these subjects occurs at the age of 6−12. Later this trend slows down in spite of the students still learning these subjects.[11] It is probable that alternative concepts occurring at the age of 12 years may be

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maintained up to the age of 18 or even throughout the entire life. Research shows that nearly 10% of primary school students have the wrong idea about substances and atoms. 10% of high school and university students also make the same mistakes.[12] One of the key core terms in chemistry is chemical bonding. Correct understanding of this concept depends on other terms, which the students encounter in chemistry classes whether it is in high school or in college.[13] The theme of chemical bonding is usually divided into four subthemes: ionic bonding, covalent bonding, metal bonding, and intermolecular forces. The causes, nature, and possibilities in preventing and eliminating misconceptions in this have been discussed elsewhere.[14] Understanding the concept of chemical bonding is a fundamental presumption for the subsequent learning of other themes in chemistry such as chemical balance, thermodynamics, molecular structure, and chemical reactions.[15] Studies focused on misconceptions of chemical bonding can be analyzed in many ways. Halim et al.[16] studied students' misconceptions in chemical bonding based on tasks in which students had to describe compounds on three levels: microscopic, macroscopic, and symbolic. Luxford and Bretz[17] developed an experimental instrument, which we will discuss in more detail later in this article, in order to detect misconceptions in ion and covalent bonding. Peterson et al.[18] studied covalent bonding and its structure in high school students, where they used a two-tier multiple choice test as an experimental instrument. This study resulted in describing some of the students' misconceptions concerning the chemical bonding. These misconceptions are divided into more categories: bonding polarity, appearance of molecules, octet rule, and ion grid. The other part of the studies was focused on the possible ways to eliminate or minimalize students' misconceptions present in the chemical bonding theme. Unal, Costy, and Ayas[19] have done a study focused on detecting the misconceptions of covalent bonding in Turkish high school. As an experimental instrument they used a test with four open questions and half-structured interviews. Based on the recommendations coming from the study, the teachers should use simulations, analogical models, theoretical models, and concrete models to be able to describe abstract terms or realities. Apart from that, teachers should emphasize shifts between macroscopic characteristics of compounds and submicroscopic ones.

Nahum, Mamlok, and Hofstein[20] compared the traditional approach of chemical bonding teaching with a new alternative („new bottom") approach. The traditional curriculum is insufficient and lacks accuracy in accordance with scientific theories. The authors of this study propose the introduction of the conceptual model in line with current scientific theory that would help students create correct understanding of chemical bonding for further study.

Birk and Kurtz[21] designed and performed a study capable not only of detecting misconceptions of chemical bonding but also of finding out if and when these misconceptions would disappear. They used a test designed by Treagust, Petterson, and Garnett.[22] They found out that college students do not understand molecular and chemical structure, because they do not have sufficiently developed abstract thinking or they have poor high school knowledge. A two-tier test was used in many studies as an experimental instrument. Coming from the given situation, we aimed to identify students' misconceptions in the chemical bonding theme using the experimental instrument BRI (Bonding Representation Inventory) developed by Luxford and Bretz[17] and to test its ability to detect misconceptions in a different didactic system.

CONCEPT CHEMICAL BONDING IN THE SLOVAK CURRICULUM

In Slovakia, the schools follow the National Chemistry Education Standards (NChES), which is a binding school document. NChES includes educational standards which set the requirements the students have to fulfill. These requirements are stated as competences which include knowledge, skills, attitudes, and values in the context of defined content of education. Educational standards represent the minimal requirements which each school can broaden and fill in using the schooling educational system. The textbooks are written in the spirit of the schooling educational program (in Slovak—ŠVP).[23]

To emphasize our decision to use BRI in Slovakia, we would like to explain the concept of chemical bonding in NChES. In valid high school chemistry textbooks which come from NChES, we are presented with the basic division of chemical bonding into four main categories: covalent bonding, ion bonding, metallic bonding, and intermolecular forces.

Covalent bonding is interpreted as a mutual sharing of bond electron pairs. It occurs by overlapping of chemical orbitals, and it has directional character. Due to the existence of covalent bonding, connected atoms form a molecule. The students have to understand the polarity of covalent bonding during atomic bonding with different electronegativity. They have to know and be able to work with the concept coordinate bonding. Also, they should be familiar with simple and multiple covalent bonding, bonding force, and the length of the bonding.

Ionic bonding should be understood as electrostatic force interaction between cations and anions, which occurs from bonded atoms by transferring valence electrons to the atom of the more electronegative element. Ion crystals occur due to the existence of ionic bonding. Respecting a certain portion of covalent bonding in typical ionic compounds should be a part of understanding ionic bonding.

In textbooks, metallic bonding is interpreted as bonding shared between freely moving electrons between closely aligned cations which originate from tearing off valence electrons from atoms of a metallic element. Due to the existence of metallic bonding, metallic crystals occur.

When it comes to intermolecular forces, the students are introduced to hydrogen bonding and van der Waals forces.

As shown by the indicated concept of chemical bonding in NChES, the content and character of BRI should be applicable to the Slovak schools as well.

Regarding study questions of the main research, using BRI in a research survey in Slovakia provides interesting opportunities to better understand some characteristics of origin and character of misconception in different didactic systems. The main reason why BRI has been used comes from the fact that the content and depth of interpretation of the chemical bonding concept are similar in the USA and SR. However, it is evident that there are a lot of differences between educational systems in these countries, such as the cultural background, dominant methods and means of teaching, material, and technical background of schools. Therefore, it would be interesting to discover if BRI would find the same misconceptions and if there would be differences in frequency of their occurrence in the given countries. The results could contribute to enlightenment of the nature of misconceptions,

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importance of some factors involved in their formation, character, and frequency of occurrence.

The main study questions are

1. Which typical Slovak student misconceptions regarding the chemical bonding concept are BRI able to identify?
2. Do the frequency and character differ between misconceptions identified by BRI in USA and SR?

METHODS, MEANS, AND REALIZATION OF THE RESEARCH

In our study we used the following research methods and means: item discrimination, item difficulty, Ferguson's δ, Cronbach alpha, and frequency analysis. As an experimental instrument for identifying misconceptions we used BRI, which was designed by Luxford and Bretz.[17] The test was especially oriented toward the covalent and ionic bonding misconceptions. The test can be divided into five groups related to the chemical bonding theme: periodic table trends, electrostatic interactions, octet rule, structure representation, and term confusion. The test comprised 23 multiple-choice questions (7 one-tier and 8 two-tier questions) with one correct choice. Each test item was carefully and systematically designed by Luxford and Bretz.[17] These authors have also dealt with the inclusion and formulation of the keys and distractor for each test item so that they would correspond to the understanding level and expression of the students of the given age category. After that they conducted a broad confirmation of the validity of this test. In our study, we used the full version of the test. We have agreed to the rules of using BRI set by the authors: do not allow any students to keep a copy of the concept inventory and do not post any of the questions or answers on the Internet. The only changes we made to the test were related to its translation, and we strived to avoid any substantial changes that the change of languages could bring to the test.

PRESTUDY

In order to use BRI in Slovak conditions, we had to answer two core questions:

1. Does the content validity of BRI correspond to the teaching of the chemical bonding concept in Slovak schools?
2. Are the key and distractor formulations in each BRI item acceptable regarding the knowledge level and the form of expression of the Slovak students of the given age category?

To answer the first question, we collaborated with competent educators and lectors. After translating BRI to the Slovak language, we asked the experts from high school and college to estimate whether the scope and the depth of the BRI content corresponds to the Country educational program of Slovakia in the given field by using the chemistry textbooks and teaching experience in Slovakia. We collaborated with two college teachers from the Department of inorganic chemistry at Comenius University in Bratislava, who analyzed the technicality and the accuracy of the translation. We also asked two college teachers from the department of chemistry didactics to determine if the test corresponds to the teaching standards in the chemical bonding theme in Slovak high school and to the knowledge level of students.

After the reviews of our experts, we administrated the BRI in one class of 28 students aged 15−16. After we graded the test, we conducted interviews with students regarding their remarks about the test. It was confirmed that not all the questions were easy for students to comprehend and the students were not able to understand all the tasks correctly.

- The students complained the most about the question No. 16: most of the students have never met with a similar representation of bonds as in our tasks. In our school system, the students are not introduced to this kind of bond representation until organic chemistry.
- Students also reacted to the term octet rule, which is commonly used but it is not included in the new NChES. In the current chemistry textbook for the first high school grade, this term is included in expanded learning material.

The analysis of student and expert reviews showed that regarding scope and content of BRI there are no essential obstacles in using BRI in Slovakia. Evaluation of the experts and their comments were taken into account when revising the translation of some formulations in BRI. We followed the principle that the nature and the character of the given item should not be different from those of the original.

After conducting the prestudy and its evaluation, we did not find any essential obstacles in using BRI in Slovakia, not even regarding the students' perception of BRI formulations. Taking into account the findings that came from the prestudy, we partially edited some formulations in the Slovak translation. In this case, we followed the principle that the nature and the character of the given item should not be different from those of the original. The changes we made were mostly related to the Slovak mutation, and based on the above stated facts we concluded that it is possible to use BRI in a wider drafted study.

MAIN STUDY

We collaborated with 7 high schools from 6 different cities in Slovakia. All schools that participated in the research were public. Teachers read the information about the BRI to students before the test. Students had 45 min to complete the test, and they all gave us their personal information (name, class, and their chemistry marks).

The test results were compared to the study,[17] where 433 USA high school students were tested. In the Slovak study, 343 students aged 15−16 were tested (this age corresponds to the age of USA high school students). The students who did not complete the whole test were not included in the study. In the end, 330 students took part in the whole study.

DATA ANALYSIS

We used MS Excel to analyze the collected data: we calculated the average and frequencies of each answer for the whole test and for the two-tier questions separately. The data was converted to the binary system. Instead of naming the answers A, B, C, D, the right answer was coded as "1" and the wrong one as "0". The total score was calculated from the binary data. In Table 1 we can see the results achieved in the USA from Luxford and Bretz's study[17] and the results achieved in Slovak high schools. The achieved number of point distribution for one-tier and two-tier questions can be seen in Figure 1.

Ferguson's δ was calculated using MS Excel. Ferguson's δ determines the extent to which a diagnostic tool is able to distinguish the individuals. It determines the ratio between the maximum theoretical differences and the realistic differences that were measured by the diagnostic tool. In our study the

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Table 1. Statistical Comparison of the Slovak and U.S. High School Results for the BRI

Statistic: 1-Tier (2-Tier)	Slovak High Schools		U.S. High Schools[a]	
Number of students	330	330	433	433
Number of test questions (2-tier)	23	(15)	23	(15)
Score[b]	10.57	(7.88)	8.71	(5.48)
Standard deviation	3.334	(2.71)	3.2	(3.15)
Ferguson's δ	0.9555	(0.9185)	0.94	(0.91)

[a]Statistical information reported from U.S. high schools comes from the Luxford and Bretz study, ref 17. [b]Maximum possible score is 23 for 1-tier questions and 15 for one 2-tier questions.

achieved Ferguson's δ value was 0.95 for one-tier and 0.92 for two-tier questions. In the case of no differences Ferguson's δ is equal to 0. In the case of the maximum possible number of differences achieved Ferguson's δ is equal to 1. Ferguson's δ is usually used for questionnaires with dichotomous tasks.[24]

The difficulty of each item is shown by the difficulty index (Index Facility), which represents the percentage of students who correctly answered the question and solved the task. The ideal value of the difficulty of the items in the test is between 40% and 60%, although in many assays values between 30% and 70% are also accepted. The closer the index is to 100%, the easier is the test. If a certain item is answered correctly by 50% of respondents, then the difficulty index is 0.5. The average item difficulty for the Slovak high school students was 0.46, and the value range was between 0.13 and 0.79.

Item discrimination is an indicator that shows the degree of item ability to distinguish between successful and less successful respondents. The index divides more competent (more successful) respondents from the less capable ones (successful). If students who have achieved a high overall score correctly responded to the particular question and less successful students did not, then we can say that the issue (item) is good, because it distinguishes "good" and "weak" students in the same way the overall test results do.[25] The effective discrimination should achieve a discrimination index value of at least 0.3, but higher values are better. If the value is very low, it means that there is no difference in the responses between successful students and unsuccessful ones.[26] The average item discrimination for the Slovak high school students was 0.36, and the range of values was between 0.13 and 0.79. Figure 2 shows the four items for the Slovak high school students that achieved low discrimination index.

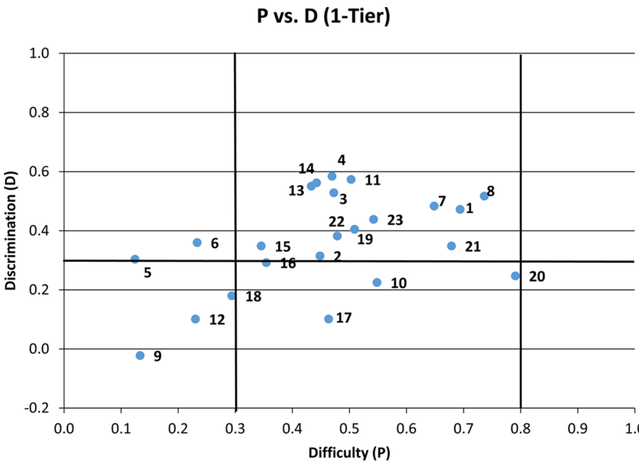

Figure 2. Difficulty versus discrimination for Slovak high school students.

RELIABILITY

Cronbach's alpha measures the relationship between the individual items and is therefore a measure of internal consistency test. Cronbach's alpha indicates the reliability of the diagnostic instrument. The premise is that all items measure a single property and the strength of their dependence is high, and therefore the only differences are due to measurement errors.[27] If the obtained value is higher than 0.7, the correlation between items is acceptable. Lower values indicate a weak correlation between items. Cronbach's alpha values for the Slovak high school students were $\alpha = 0.58$ for one-tier and $\alpha = 0.57$ for two-tier. These results indicated that some questions should be removed from the test. According to the BRI authors,[17] the test was focused mainly on the covalent and ionic bonding related misconceptions, and in the case in which the students have these misconceptions fixed, the test does not have to reach more than 0.7 Cronbach's alpha.

In our study, apart from frequency analysis of two-tier tasks, we summarized the percentage of misconceptions which the BRI distractors are able to detect. Table 2 contains the percentage of misconceptions identified by BRI. To identify misconceptions based on distractors, we used the table of misconception from Luxford and Bretz's study.[17]

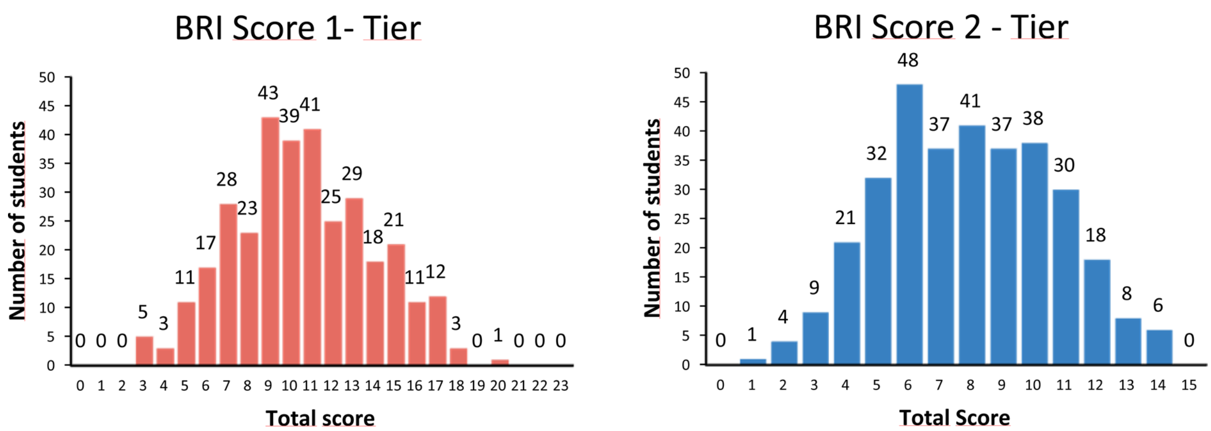

Figure 1. Distribution of BRI scores separately for 1-tier and 2-tier questions for Slovak high school students.

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Table 2. Distribution of the Most Common Student Misconceptions Detected by the BRI in the Slovak School System

Misconceptions by Topic[a]	Students Holding These Misconceptions, % (n = 330)
Covalent bonding	
Covalent bonds have very different electronegativity	16.9
There is a transfer of electrons in covalent bonding	12.5
The covalent bond forms between two electrons	36.4
The covalent bonding is formed based on octet rule	39.6
Ionic bonding	
Formation of shared electron pair in ionic compounds	39.1
Cl^- gives its electron to the sodium atom in NaCl	11.5
Ionic bonding is formed based on the octet rule	21.8
NaCl is a molecule	17.6
The molecules of NaCl form the NaCl structure	32.7
The atoms of Na and Cl attract each other and form NaCl	21.1
Symbolic level	
Spacing of dots between atoms indicates equal sharing	48.6
Similar spacing indicates same bond type	48.5
Dots represent all the electrons in the compound	23.9
Microscopic level	
Choosing ionic bonding on a picture representing shared electron pair	25.5
Bond type depends on atoms being labeled	13.5
Bond type cannot be determined without ± showing	15.1
Other	
Inability to classify as metals/nonmetals	32.1
Chlorine has smaller electronegativity than carbon	16.1
Slightly different electronegativities means equal sharing	48.5
Transfer of electrons is more accurate than attractions	15.0
Cations get rid of electrons to become stable	33.9

[a]See the Luxford and Bretz study, ref 17.

■ FREQUENCY ANALYSIS OF MISCONCEPTION

All the two-tier questions were analyzed in detail using frequency analysis. According to the teaching of chemical bonding and the level of question layout, we divided the misconceptions detected by BRI into more categories: misconceptions related to covalent bonding, misconceptions related to ionic bonding, misconceptions related to understanding the symbolic level, misconceptions related to understanding the microscopic level, and misconceptions related to understanding macroscopic level. Misconceptions, which could be assigned to all categories, were labeled as "other". As an example of the analysis, we list the analysis of the question No. 3, where students had to mark which picture represents the bonding between sodium (Na) and chlorine (Cl) in sodium chloride (NaCl) better.

The question No. 3 had two pictures: one represented the chemical bonding in NaCl as a shared electron pair between sodium and chlorine, while the other one represented the chemical bonding between sodium and chlorine as a transfer of electron from sodium atom to the chlorine atom.

Choosing the correct answer to question No. 3 is conditioned by understanding the essence of ionic bonding, which is based on electron mobility from the more electronegative atom element along with understanding of covalent bonding as mutual sharing of bonding electrons. It was necessary to identify the essence of the picture, from what was represented in it. From 330 students, 36% (120 students) marked the first answer (A), which shows the bonding between chloride and sodium as a shared electron pair, whereas 47% (156 students) marked the correct answer, second (B), where the picture shows sodium giving away its valence electron to chloride. From the 47% of students (156 students) who answered the question correctly, 77% (120 students) justified their answer correctly in the following question. We wanted to know if the 36% (120 students) who did not answer the question correctly (they marked the ionic bonding as a shared electron pair), would justify their answer as the essence of ionic bonding.

From these 36% (120 students), this option was marked by 70% of them (84 students). From the whole number of students (330), 36% of them chose the right answer to both questions. These students have the correct idea about sodium chloride bonding and know how to explain its formation correctly. The frequency analysis of incorrectly answered question, by choosing the first option (A), brings interesting information. This mistake was made by one-third of the students, three-quarters of whom understand the essence of covalent bonding as sharing a mutual electron pair, but do not know that the bonding in sodium chloride is ionic. We believe that they failed to notice the huge electronegativity difference between sodium and chloride.

One of the misconceptions that appeared in many students is the idea of a shared electron pair between the atoms of sodium and chlorine in sodium chloride. Therefore, the students either do not pay attention to cation and anion interactions, or they believe that the bonding in sodium chloride is covalent. This could be the reason the students marked the shared electron pair as the answer to question No. 3.

After the analysis of all the questions, we assume that many students do not understand the essence of ionic bonding since they understand it as a formation of a shared electron pair which they marked on many ionic compounds. We believe that one of the causes of this misunderstanding can be students neglecting the electronegativity difference (the same when it comes to covalent bonding), or because they fail to realize the Coulomb interaction between positive and negative particles. It is also possible that the students do not understand the way the atoms bind together in ionic structures completely. They explained the formation of ionic structure in NaCl by bonding formation between NaCl molecules, which indicates another misconception: that the students think of NaCl as a molecule.

When it comes to the questions related to the covalent bonding, students have problems with the positions of elements in Periodic System of Elements (PSE), which is why they face difficulties when determining the type of the bonding based on the electronegativity. The term electronegativity played a role

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in more students' misconceptions such as confusing ionic bonding with covalent in the PCl_5 molecule. The students chose the answers which stated a big difference in electronegativity due to which an electron pair is made, or the answer which stated that the electronegativity difference was not big and that the electron from the atom of the less electronegative element is attracted by the atom of the more electronegative element.

The questions in which the students had to determine the correct type of bonding from the representation on the symbolic and microscopic level, or had to characterize compounds in the pictures in terms of bonding type, indicated insufficient knowledge of the students. To be able to answer these questions correctly, it was necessary to use the information provided in the pictures as well as other information which was not shown (i.e., electronegativity value). This missing information could be one of the reasons why the students had problems with answering these questions correctly.

■ CONCLUSION

The results obtained by the translated version of BRI were compared to the results published in the article by the authors of BRI.[17] The average BRI score of one-tier in Slovak high schools is 10.58 ± 3.34. The average BRI score of one-tier questions in USA high schools is 8.71 ± 3.20. The average BRI score of two-tier questions in Slovak high school is 7.88 ± 2.71 while the average score for the same question in the USA high schools is 5.48 ± 3.15. If we had the original data obtained by the authors of the diagnostic instrument in the USA high school, we could compare these two groups by other methods such as ANOVA, Mann−Whitney, and Kruskal−Wallis. The results of discrimination of the diagnostic instrument show that the questions No. 9, 12, 15, and 18 fell within the difficult item−low discrimination category in both Slovak and USA high schools.

This conclusion shows the similarity of the teaching results of the chemical bonding concept in different didactic systems but also similar misconceptions of the students in different didactic systems. The α values for the Slovak high school were $\alpha = 0.58$ for one-tier and $\alpha = 0.58$ for two tier, and α values for the USA high school were $\alpha = 0.54$ for one-tier and $\alpha = 0.45$ for two-tier.

This fact indicated that, despite the translation into the Slovak language, we have managed to keep the necessary reliability of the diagnostic instrument the same as in the original version. Hence, we did not change the essence of the questions. It would be interesting to find out which answers should be changed in the original test in comparison to its translated Slovak version. The results of the prestudy and the main study showed that the BRI diagnostic instrument for identifying students' misconceptions is applicable outside the USA didactic system, for which it was developed.

Using BRI in Slovakia has contributed to the closer identification of some students' misconceptions related to the chemical bonding theme, for example, NaCl is a molecule, or there is a shared electron pair between the atoms of sodium and chlorine in NaCl. The similarity of misconception occurrence identified by BRI in USA and Slovakia indicated that the student misconceptions are not dominantly affected only by objectives and characters of educational system, cultural background, dominant teaching concepts and methods, or textbooks. The dominant level of thinking in students given by their age category (in the sense of Piaget's theory) probably plays an important role. Of course, it is necessary to confirm this claim in a specially drafted study in order to be able to interpret the mentioned indications as scientifically proven.

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Notes

The authors declare no competing financial interest.

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