PROCEDURE FOR ASSESSMENT OF THE COGNITIVE COMPLEXITY OF THE PROBLEMS WITH A LIMITING REACTANT

Saša A. Horvat, Dušica D. Rodić, Tamara N. Rončević, Snežana Babić-Kekez
University of Novi Sad, Republic of Serbia
E-mail: sasa.horvat@dh.uns.ac.rs, dusica.milenkovic@dh.uns.ac.rs; tamara.hrin@dh.uns.ac.rs; snezana.babic-kekez@dh.uns.ac.rs

Bojana Trifunović Horvat
HS "Borislav Mihajlović Mihiz", Republic of Serbia
E-mail: bojanaboba.trifunovic@gmail.com

Abstract

Mathematical calculations are an important part of chemistry. Those problems are difficult for students, especially if the task is set with a limiting reactant. The aim of this study was development of a Procedure for evaluation of cognitive complexity of the Stoichiometric Tasks with a Limiting Reactant. The procedure created included an assessment of the difficulty of concepts and an assessment of their interactivity. As a research instrument for assessing performance, the test of knowledge was specifically constructed for this research. Each task in the test was followed by a seven-point Likert scale for the evaluation of the invested mental effort. The research included 58 upper-secondary students. The validity of the procedure was confirmed by a series of regression analyses where statistically significant correlation coefficients are obtained among the examined variables: students' achievement and invested mental effort from cognitive complexity (independent variable).
Keywords: *chemistry education, stoichiometry, problem tasks, achievement, mental effort*

Introduction

Stoichiometry is one of the key areas of chemistry. The numerical parameters of a chemical reaction, the concentration of reactants, the amount of substance, as well as the basic parameters of chemical kinetics and equilibrium are calculated based on stoichiometric relations (Hanson, 2016). In a chemical reaction, two or more reactants react in constant molar relation - they react stoichiometrically. For example, hydrogen molecules react with oxygen molecules in a reaction where water molecules are formed as the product in a stoichiometric molar ratio of 2: 1. One of the fundamental concepts in stoichiometry is the calculation of the quantity, volume, number of particles or the mass of the products of a chemical reaction between two reactants where one of the reactants is a limiting reactant (Sostarecz & Sostarecz, 2012).

https://doi.org/10.33225/BalticSTE/2021.59

In chemical reactions - a limiting reactant, i.e., a limiting reagent, is a reactant that first reacts all in a chemical reaction, i.e., it is "consumed" first (Olmsted, 1999). A limiting reactant stops a chemical reaction when it fully reacts and therefore determines the amount of a formed reaction product (González-Sánchez et al., 2014). The tasks with limiting reactants are one of the most difficult tasks in stoichiometry (Gulacar, et al., 2013). Students often use algorithms when they solve problems with limiting reactants. They often calculate the amount of products for both reactants, and then they choose the one that produces fewer reaction products as the limiting reactant (Toth, 1999). Students do not understand the definition of a limiting reactant, what it represents, and how they decide on it. Students define a limiting reactant as the reactant with the smallest number of atoms (Marais & Combrinck, 2009). By a term limiting reactant, they mean the reactant that needs to be quantitatively higher to react completely with another reactant (Kashmar, 1997), i.e., the limiting reactant is the one that has fewer moles in the initial system (González-Sánchez et al., 2014). In a study by Dahsah and Kol (2007), students consider the reactant expressed in the smallest unit of mass the limiting reactant, without taking into account the amount of substance and the molar ratio. In the same research, some students claim that if both reactants are not present in a stoichiometric amount, there is already a limiting reactant, the chemical reaction will not happen, and no products will be formed.

The relation between the reactants which is not 1: 1 is confusing for students, even when the reactants are expressed in moles (Kalantar, 1985; Hanson, 2016). Similar results were found (Dahsah & Coll, 2007), where students always took a mole ratio 1:1 between the reactants regardless of the coefficients in a chemical reaction equation. In a study by Olmsted (1999), this result was previously confirmed in a problem with a limiting reactant where the ratio of coefficients was 3:2. Only 30% of students solved the task successfully although the reactants were given as the amounts of substances. The errors found in his research were that students did not take into account stoichiometric coefficients, and they used the wrong algorithm for calculating the limiting reactant. Haidar (1997) and Hanson (2016) have even concluded that students take molar ratios into account when they calculate substances if substances are given in terms of mass units. Hanson (2016) also noticed that there were a misunderstanding and a misuse of terms for mass, quantity, and molar mass in calculations in the problem-solving tasks with limiting reactants. Coefficients and indexes in chemical formulas are confusing for students in a chemical equation, and therefore a common cause of errors in calculations is that students misuse coefficients and indexes in chemical formulas (Chandrasegaran et al., 2009; Mulford & Robinson, 2002). Thus, Huddle and Pillay (1996) observed that a limiting reactant from the students' perspective was the reactant with the smallest stoichiometric coefficient. In research by BouJaoude and Barakat (2000), students chose a limiting reactant arbitrarily without a logical explanation, although they usually opted for the reactant expressed in units for the amount of substance. In their next research, students quoted the fact that it was easier to calculate using moles as the main reason why they chose the reactant expressed in moles (BouJaoude & Barakat, 2003). In problems, students choose a limiting reactant by observing which of the reactants contains more atoms of the elements of the desired reaction product (Wood & Breyfogle, 2006).

In addition to all the misconceptions, students' difficulties arising during the resolution of limiting reactant stoichiometry problems are caused by the complexity of

https://doi.org/10.33225/BalticSTE/2021.59

the tasks themselves. Namely, problem-solving tasks contain a large number of chemical concepts that are interconnected by different relationships, which imposes a cognitive load on students (Kalyuga, 2009).

While being processed in the working memory, new information is recombined and brought into connection with already acquired knowledge and then stored as schemas in the long-term memory. The working memory becomes overloaded if it simultaneously processes more information. That is a cognitive load (Kalyuga, 2009). The cognitive load is a multidimensional construct consisting of three measurable components: a mental workload, mental effort, and performance. The mental load is imposed by the teaching parameters, the mental effort is determined by the available capacity of the working memory assigned to solve a task, and the performance is the student achievement. According to Sweller et al., (2011), the self-assessment of mental effort is the most sensitive component in assessment of the differences in the cognitive load imposed by different teacher's instructions. One of the cognitive load indicators which have been used as an objective measure recently is cognitive complexity (Harris et al., 2013; Raker et al., 2013).

Bieri (1955) introduced the term cognitive complexity that reflects a high degree of differentiation of the system of the constructs that individuals use. Concerning the cognitive complexity of a task, the key component is its characteristics. These characteristics can be dimensioned by the experts' estimation. They can evaluate the requirements of the task from the aspect of the cognitive load theory. Recent studies have shown that cognitive complexity can be used to predict student achievement in assignments and invested mental effort (Knaus et al., 2011; Raker et al., 2013).

Different tools have been developed - Rubrics for estimating the cognitive complexity of problems in chemistry (Knaus et al., 2011; Raker et al., 2013). The developed Rubrics were created based on the theory of complexity (Goldreich, 2008), which defines a system of more related concepts, and the theory of cognitive load (Sweller et al., 2011), which defines interactivity among the concepts in a task. The use of the Rubric provides an easy way to quantify the cognitive demands of a problem (Knaus et al., 2011; Raker et al., 2013). To assess the cognitive complexity of tasks, experts assess the number of elements, i.e., the concepts needed to solve a test task. They also assess the difficulty of each concept from students' perspective as easy, medium, and difficult. When all the concepts needed for solving the task are recorded, the complexity of the task is determined with the use of the Rubric. After determining the difficulty rating of the concept, interactivity is calculated. Interactivity increases the cognitive complexity of the task when students need to use the interdependence of the components to solve the task. Interactivity is assessed as insignificant, basic, and complex. Further development of the Rubrics for the cognitive complexity rating is presented in the works of Horvat et al. (2016, 2017, 2020).

Research Problem

So far, the Rubrics for the cognitive complexity rating in several domains of chemistry have been developed. All of them show satisfactory coefficients of the correlation between cognitive complexity and student performance, and between cognitive complexity and mental effort. However, there was a need for the correction

https://doi.org/10.33225/BalticSTE/2021.59

due to the specificity of domains in all the Rubrics. One of the many concepts present in stoichiometry problems that further complicate them is the concept of a limiting reactant. Problem-solving tasks with a limiting reactant are characterized by high complexity, and therefore they are often confusing for students. In this paper, a Procedure for assessment of the cognitive complexity of stoichiometric tasks with a limiting reactant has been developed.

Research Focus

This research aim was to develop and validate the procedure for determining the cognitive complexity rating of the stoichiometric tasks with a limiting reactant. The specific research objectives for determining a numerical rating of cognitive complexity were:

- Construction of a Table for assessing the difficulty of concepts and their interactivity needed for the assessment of cognitive complexity of chemical technology problem-solving tasks;
- Determination of cognitive complexity of test tasks using a combination of a constructed Table for assessing the difficulty of concepts with a cognitive complexity rating rubric proposed by Knaus et al. (2011);

From specific research objectives research questions for validation of the procedure were created as follows:

- Is there a statistically significant correlation relationship between the students' performances and the numerical rating of the cognitive complexity of problems, and
- Is there a statistically significant correlation relationship between the invested mental effort and the cognitive complexity.

Research Methodology

General Background

The research was conducted in May 2017, during the second semester of the school year 2016/2017. Students solved the test of knowledge with 7 tasks. With the test of knowledge, a collection of students' achievements and a collection of students' invested mental effort were collected. Students' achievements and invested mental effort were dependent variables, and previously determined cognitive complexity was an independent variable. Validation of procedure and research instrument was confirmed with basic statistics parameters, descriptive statistics, and correlation coefficients.

Sample

The total sample of this research consisted of two classes made up of 58 students from the Gymnasium in Prijepolje. According to the Curriculum (The Institute for the Advancement of Education, 2013), the students of this school attend chemistry classes during their four-year schooling. According to the Curriculum, general chemistry is studied in the first grade, inorganic chemistry with laboratory exercises in analytical chemistry is studied in the second grade, organic chemistry is studied in the third grade, while the basics of biochemistry are studied in the fourth grade.

The students who participated in this study attended the first grade and were aged 15-16. According to the grades in chemistry at the end of the first semester, the structure of the students who were included in the sample for this research was the following:

- 18.96% of the respondents had a grade 2 in chemistry at the end of the first grade,
- 32.76% of the respondents had a grade 3 in chemistry at the end of the first grade,
- 37.93% of the respondents had a grade 4 in chemistry at the end of the first grade and
- 10.35% of the respondents had a grade 5 in chemistry at the end of the first grade.

The respondents belonged to the urban population of different socioeconomic statuses, and they voluntarily joined the research. All students voluntarily participated in the research. Informed consent was obtained from students and school administration.

Instrument and Procedures

The Knowledge Test was specially designed for this research. The students had 45 minutes (one school class) to solve the test. The respondents studied all the concepts present in the test tasks in chemistry classes. The test created for this research contained 7 tasks. The students got one point for each correct task, so the maximum possible score on the test was 7 points. The incomplete tasks were not taken into consideration.

In addition to the achievement, the test also measured the mental effort that a student invests while solving the task. The assessment of the invested mental effort was measured by a subjective technique with the application of the 7-point Likert scale. After each completed or uncompleted task, the students were asked to assess their mental effort by selecting an appropriate descriptive grade on the scale. During the statistical analysis of the results, the descriptions were numerically coded from "extremely easy" – numerical value 1 to "extremely difficult" – numerical value 7.

To ensure objectivity in the estimation of cognitive complexity, the Table for the assessment of the difficulty of concepts and the estimation of their interactivity in problem tasks with a limiting reactant has been developed. The difficulty of the concepts is also estimated by the Rubric developed by Knaus et al. (2011). Concepts are rated according to their difficulty as easy, medium, or difficult. Table 1 describes the Table for estimating the difficulty of the concepts and their interactivity in the stoichiometric problems with a limiting reactant.

https://doi.org/10.33225/BalticSTE/2021.59

Table 1

The Table for the Assessment of the Difficulty of the Concepts and the Estimation of Their Interactivity in the Stoichiometric Tasks with a Limiting Reactant

A CHEMICAL EQUATION WITH GIVEN QUANTITATIVE RELATIONS	
The ratio of the reactants, the ratio between the given and the required substance is 1: 1	Easy
The ratio of the reactants, the ratio between the given and the required substance is 1:X (X≧2)	Medium
The ratio of the reactants, the ratio between the given and the required substance is X: Y (X≧2; Y≧2 X≠Y)	Difficult
A LIMITING REACTANT	
The reactants, the given and the required substances are given in a formula about the amount of substance	Easy
The reactants, the given and the required substances are given in the units of mass	Medium
The reactants, the given and the required substance are given in the ratio amount: mass or mass: amount	Difficult
THE INTERACTIVITY OF THE CONCEPTS	
The task contains up to 2 concepts	0
The task contains 3 concepts	1
The task contains over 3 concepts	2

The concept of *a chemical equation with given quantitative relationships* was chosen because the understanding of quantitative relationships among the participants in a chemical reaction is a key step in solving stoichiometric problems (Robinson, 2001). This problem is particularly pronounced if the quantitative relationship between the given and the required substance in the chemical equation is not 1: 1 (Dahsah & Coll, 2007; Hanson, 2016). Students sometimes choose the ratio 1: 1 in the problems with a limiting reactant regardless of the ratio of the stoichiometric coefficients of the participants in a chemical reaction, (Olmsted, 1999). If the given and the required substance are expressed in the same physical entity, the concept is considered easy (Robinson, 2001). If the given and the required substance are given in the same physical entity in the Rubric for the rating of the concepts that are present in stoichiometric problems, the concept is considered easy, regardless of whether the substances are expressed as the amount of substance, a mass, the number of particles, etc. (Horvat et al., 2016). However, it is documented that students achieve better results if the given and the required substance are expressed in the units of the amount of substance than if they are expressed in the units of mass (Astudillo & Niaz, 1996). So, the concept of a limiting reactant is the easiest if the substances are expressed in moles. A concept is a medium difficulty if the substances with which the calculations are made are given in the units of mass, and difficult if the given or the requested substance is expressed in the unit of quantity and the other substance is expressed in the mass unit.

https://doi.org/10.33225/BalticSTE/2021.59

Interactivity is evaluated based on the number of concepts in the task. If one concept is represented in the task, interactivity is evaluated with a value of 0. If the task contains two concepts, interactivity has value 1, and if the task contains three or more concepts, interactivity is evaluated by a numerical value 2.

Data Analysis

The quality of the test was evaluated by pre-test and post-test quality assurance parameters. Pre-test quality assurance parameters are determined by experts, whose narrow field of study is the methodology of chemistry teaching, as well as chemistry teachers in secondary schools. The test was assessed as valid based on the compliance of the tasks with the valid curriculum and the recommended textbooks. The experts assessed the tasks on the Test as diverse, with clearly defined requirements and meaningful sentences in compliance with language rules. Post-test quality assurance parameters are defined as basic statistical parameters: reliability coefficients, task discrimination indexes, the index of the discriminative property of a test, task difficulty indexes and test difficulty indexes.

The obtained results were analyzed using IBM SPSS Statistics 22 software program.

Research Results

Tasks of different levels of cognitive complexity were used in this research. The complexity of the tasks depends on the concepts which are present in the task and defined in Table 1. All tasks are complex problem-solving tasks that include two sub-problems: determining the limiting reactant and calculating the required substance. The principle of using this Table is simple and objective. The procedure for calculating the rating of cognitive complexity is presented in the following example (Task number 1 in the Test): *7.3 grams of hydrogen chloride and 4 grams of ammonia were mixed in the reaction vessel. The mentioned gases react according to the following reaction*:

$$HCl_{(g)} + NH_{3(g)} \rightarrow NH_4Cl_{(s)}$$

Calculate how many grams of ammonium chloride is obtained in this reaction.

The first phase involves determining the limiting reactant and the second phase involves calculating the mass of the formed product. The task contains the four concepts presented in Table 1. In the first phase, the limiting reactant is determined based on the data from the text of the task and the chemical reaction equation. The quantitative ratio between the reactants is 1: 1, and the reactants are given in the units of mass. The limiting reactant is determined based on the chemical reaction equation and the molar masses of the reactants. Using the Table for assessing the difficulty of the concepts and their interactivity in stoichiometric tasks with limiting reactants, their difficulty is estimated. The following concepts are present in this task:

- The stoichiometric ratio of the reactants is 1:1 - The chemical equation concept with the given quantitative relationships which is "easy";
- The stoichiometric ratio of the reactant to the reaction product is 1:1 - The concept of a chemical equation with the given quantitative relationships which is "easy";

https://doi.org/10.33225/BalticSTE/2021.59

- The reactants are expressed in the units of mass - The concept of a limiting reactant that is "medium" difficulty;
- The reactant (the given substance) and the reaction product (the required substance) are expressed in the units of mass – The concept which is "medium" difficulty;
- The task contains 4 concepts – Interactivity has a value of 2.

Using the Rubric developed by Knaus et al. (Knaus et al., 2011), gives the total numerical rating of cognitive complexity of task number 1 in the test, which is 7.

Table 2

Numerical Rating of Task Number 1

The difficulty of the concept	Number of concepts	Numerical rating
Easy	2	2
Medium difficult	2	3
	Interactivity:	2
	Total rating of cognitive complexity:	7

As in this case, the numerical rating of the cognitive complexity of other test tasks is calculated. The values are shown in Table 3.

Table 3

Numerical Rating of Cognitive Complexity of Test Tasks

Task number	A numerical rating of cognitive complexity
1	7
2	7
3	8
4	6
5	10
6	10
7	9

The test used in this study showed good metric characteristics. Reliability was calculated as a measure of internal consistency and expressed as a Cronbach’s coefficient α which valued .65 for the achievements, and .73 for self-estimated mental effort, which indicates good reliability (Jonsson & Svingby, 2007). The task's difficulty index ranges from 13.79% to 96.55% (the average value is 49.51%, which makes the test moderately difficult). The value of the difficulty index of two tasks is less than 25%, which makes them difficult, whereas the difficulty index value of one task is higher than 75%, which makes it an easy task (Towns, 2014). The values of the discrimination index range from .07 to 1 (the medium value is .59 which represents an excellent discrimination index of the test). Six tasks have an excellent index of discrimination which is higher than .4 (even 3 tasks have an index of discrimination higher than .94), whereas only one task has a poor index of discrimination (.07), so it should be revised for future use.

https://doi.org/10.33225/BalticSTE/2021.59

The basic statistical parameters of the test are shown in Table 4.

Table 4

Descriptive Statistics for the Students' Performance and Mental Effort

Parameter	Students' performance[1] (*N*=58)	Students' ratings of mental effort[2] (*N*=58)
Average	3.46	3.80
Standard deviation	1.71	.90
Standard skewness	-.12	.67
Standard kurtosis	-1.03	.12
Minimum	0	1.86
Maximum	7	6.14
Range	7	4.28

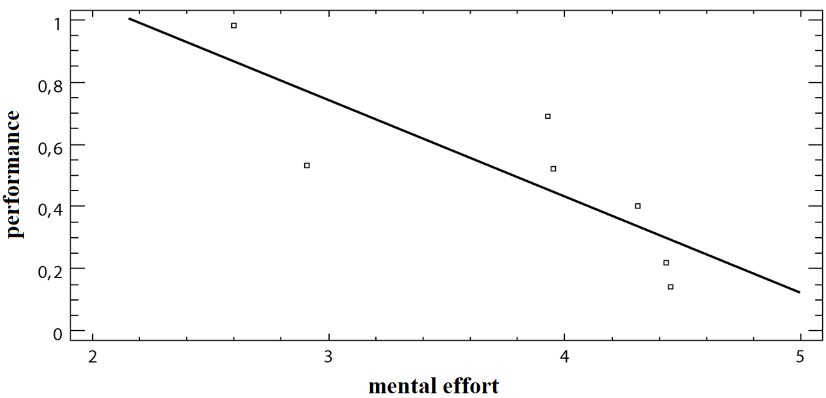
[1] Students' performances could range from 0 to 7.[2]Possible ratings for invested mental effort could range from 1 to 7: extremely easy (1) to extremely difficult (7)

The values of the standard skewness and kurtosis for the performance and the invested mental effort indicated that in both cases a normal distribution was presented. Additional Shapiro-Wilk's test did not confirm the assumption of the normal distribution of students' performances (F=.20; p<.05) and students' mental effort (F=.16; p<.05).

The validation of the test was performed by Spearman's correlation which refers to the observation of the relation between the students` performances and self-estimated mental effort. The graphic dependence and the statistical parameters of regression analysis are shown in Figure 1 and Table 5.

Figure 1

The Correlation of the Students' Performance with the Students' Ratings of the Invested Mental Effort



https://doi.org/10.33225/BalticSTE/2021.59

Table 2
The Statistical Parameters of the Regression Analysis of the Students' Performances and the Students' Ratings of the Invested Mental Effort

Parameter	Value
The correlation coefficient	-.58
p-value	.02
Equation	Performance = 1.67 - .31×ME

This dependence describes a moderate correlation (r_s=- .58; *p*=.02). P-value is less than .05, which indicates that there is a statistically significant correlation between measures of mental effort and performances at the 95% confidence level. The existence of a significant correlation between performance and mental effort has already been confirmed in the studies about the dimensioning cognitive complexity of the problems (Knaus et al., 2011; Raker et al., 2013; Horvat et al., 2016; 2017; 2020).

Procedures for assessing the cognitive complexity of problem tasks are usually validated by combining with measures of students' performances and measures of mental effort (Knaus et al., 2011; Raker et al., 2013; Horvat et al., 2016; 2017; 2020).

In the first phase, the regression analysis of the dependence of students´ performances on the estimated cognitive complexity. As the distribution of performances and mental effort did not satisfy the normal distribution criterion and since the performance values can only be zero or one, it was done with biserial correlation analysis. The results of the analysis are tabulated in Table 3. The dependence of the numerical rating of the cognitive complexity from the students' performances on test tasks (406 items) was observed.

Table 6
Statistical Parameters of the Regression Analysis of Students' Performance and the Cognitive Complexity

Parameter	Value
The correlation coefficient	- .37
p-value	$p < .001$
Equation	Achievement = 1.64 - .13×CC

The coefficients obtained by the regression analysis (r_{bs} = -.37; $p < .05$) indicate that there is a moderate but statistically significant correlation between the dependent and the independent variables (Evans, 1996). The negative value of the correlation coefficient shows that the increase in the cognitive complexity of the problem results in performance decreases.

The second phase of validation of the procedure for the assessment of cognitive complexity of the tasks with limiting reactants is a correlation analysis of the dependence of self-invested mental effort on the rating of the cognitive complexity of the tasks. Since mental effort does not satisfy normal distribution, the Spearman's ρ correlation

https://doi.org/10.33225/BalticSTE/2021.59

coefficient was determined. Statistical parameters and graphic dependence are shown in Table 7.

Table 7
Statistical Parameters of the Regression Analysis of the Student’s Self-invested Mental Effort and the Cognitive Complexity

Parameter	Value
The correlation coefficient	.54
p-value	$p < .001$
Equation	Mental Effort = -.35+.47×CC

The correlation coefficient (r_s =.54) and the *p*-value (p<.05) indicate a moderately strong statistically significant correlation between the mental effort as a dependent variable and the numerical value of the cognitive complexity rating as an independent variable.

Discussion

The test used in this research had good statistical parameters. The average achievement of students was 3.46, which means that students could solve a minimum of three tasks. The average value of students’ mental effort on the test was 3.80. According to the 7-point Likert scale, the test was “neither easy nor difficult”.

The validity of the procedure was confirmed with a correlation between students’ performances and the average value of students’ self-invested mental effort from the numerical rate of cognitive complexity. The positive value of the coefficient of correlation indicates that students invest a higher mental effort to solve the task with increasing cognitive complexity. At the same time performance decreases. This is consistent with the results of Pollock et al., (2002). Since the information is selectively processed during the process of solving the task, it is necessary to optimize its cognitive complexity when designing the task (Halford et al., 1998). Cognitively more complex tasks impose a greater mental load on the working memory of respondents and condition lower student achievement (Campbell & Gingrich, 1986).

The rating of the cognitive complexity of the examined tasks ranges between 6 and 10. The first and second tasks have the value 7 of cognitive complexity, where the average achievement is .97 and .53. A strikingly significant difference in the achievement is the consequence of the strategy for solving stoichiometric tasks that is favorable in the used textbook literature which favors the comparison of masses (Nikolajević & Šurjanović, 2015). Namely, in the first task, the reactants are expressed in mass units, and in the second task, their amounts in moles are given. A similar situation has been noticed in two of the most difficult tasks. The rating of the cognitive complexity of the fifth and sixth tasks is the same - 10. The average students’ achievements in these tasks are .69 and .22. And in this case, student achievement is the highest in the fifth task in which the participants of the reaction are expressed in the mass units. It can be noted that students manipulate the mass more effectively than the moles in tasks with limiting reagents, which is unexpected. Olmsted (1999) noted that students solved problems with a limiting reactant with the strategy used by the teacher, or that is recommended in textbooks. Namely, the students insisted on comparing the mass of the reactants rather than on comparing the amounts of the substances.

Conclusions and Implications

The basic research task was to create a procedure for assessment of the cognitive complexity of stoichiometric tasks with a limiting reactant. To accomplish this, a Table for assessing the difficulty of the concepts and their interactivity was constructed. Thus, a valid procedure was obtained for assessing the cognitive complexity of stoichiometric problems with a limiting reactant.

The validity of the Procedure was confirmed by a series of regression analyses of the dependence of students` performances and their assessment of invested mental effort from the cognitive complexity. High values of correlation coefficients were determined: -.37 for the dependence of achievement-cognitive complexity and 0.54 for the dependence of mental effort-cognitive complexity. The results of these analyses are presented in graphical and tabular form and the form of equations of regression analysis.

The process developed in this research should help teachers in the design of the tasks with a limiting reactant of different levels of cognitive complexity. By gradually developing the complexity of problem-solving tasks with a limiting reactant, the teacher can develop problem-solving strategies, taking care of the mastered concepts. This can affect the cognitive development of each student. The design of the tasks of different levels of cognitive complexity is a way to estimate the learning outcomes better and to determine cognitive load using the measures of mental effort.

The limitation of this survey is a sample of respondents. Also, when literature is concerned, a small number of stoichiometric tasks with limiting reactants are present in it and they are exclusively expressed in the units of mass. Therefore, students' mistakes and increased amount of their mental effort come from an algorithmic approach to solving these problems, which also arise from the teacher's strategy.

The implications for further research in this area are the design of problem-solving assignments in which the reactants will be expressed, in addition to the units for mass and the quantity of substance, in another unit (the number of particles, volumes, etc.).

Acknowledgments

The authors acknowledge the financial support of the Ministry of Education, Science and Technological Development of the Republic of Serbia (Grant No. 451-03-9/2021-14/ 200125)”.

Declaration of Interest

Authors declare no competing interest.

References

Astudillo, L. R., & Niaz, M. (1996). Reasoning strategies used by students to solve stoichiometry problems and its relationship to alternative conceptions, prior knowledge, and cognitive variables. *Journal of Science Education and Technology*, *5*(2)*,* 131-140. https://doi.org/10.1007/BF01575153

Bieri, J. (1955). Cognitive complexity–simplicity and predictive behavior. *Journal of Abnormal and Social Psychology*, *51,* 263–268. https://doi.org/10.1037/h0043308

BouJaoude, S., & Barakat, H. (2000). Secondary school students' difficulties with stoichiometry. *School Science Review*, *81*(296), 91–98. https://www.academia.edu/28644313/Secondary_school_students_difficulties_with_stoichiometry

BouJaoude, S., & Barakat, H. (2003). Students' problem solving strategies in stoichiometry and their relationships to conceptual understanding and learning approaches. *Electronic Journal of Science Education*, *7*(3), http://wolfweb.unr.edu/homepage/crowther/ejse/boujaoude.pdf

Campbell, D. J., & Gingrich, K. (1986). The interactive effects of task complexity and participation on task performance: A field experiment. *Organizational Behavior and Human Decision Processes*, *38*, 162-180. https://doi.org/10.1016/0749-5978(86)90014-2

Chandrasegaran, A. L., Treagusta, D. F., Waldripb, B. G., & Chandrasegaran, A. (2009). Students' dilemmas in reaction stoichiometry problem solving: Deducing the limiting reagent in chemical reactions. *Chemistry Education Research and Practice*, *10*, 14–23. https://doi.org/10.1039/B901456J

Dahsah, C., & Coll, R. K. (2007). Thai grade 10 and 11 students conceptual understanding and ability to solve stoichiometric problems. *Research in Science and Technological Education*, *25*(2)*,* 227-241. https://doi.org/10.1080/02635140701250808

Evans, J. D. (1996). *Straightforward statistics for the behavioral sciences*. Brooks/Cole.

Goldreich, O. (2008). *Computational complexity: A conceptual perspective*. Cambridge University Press.

González-Sánchez, A. M.., Ortiz-Nieves, E. L., & Medina. Z. (2014). A hands-on activity incorporating the threefold representation on limiting reactant. *Journal of Chemical Education*, *91*(9), 1464–1467. https://doi.org/10.1021/ed4003783

Gulacar, O., Overton, T. L., Bowman, C. R., & Fynewever, H. (2013). A novel code system for revealing sources of students' difficulties with stoichiometry. *Chemistry Education Research and Practice*, *14*(4), 507-515. https://doi.org/10.1039/C3RP00029J

Haidar, A. J. (1997). Prospective chemistry teachers' conceptions of the conservation of matter and related concepts. *Journal of Research in Science Teaching*, *34*(2), 181–197. https://doi.org/10.1002/(SICI)1098-2736(199702)34:2<181::AID-TEA5>3.0.CO;2-P

Hanson, R. (2016). Ghanaian teacher trainees' conceptual understanding of stoichiometry. *Journal of Education and e-Learning Research*, *3*(1), 1-8. https://10.20448/journal.509/2016.3.1/509.1.1.8

Harris, J. Wiggins, M., Morrison, B., & Morrison, N. (2013). Differentiating cognitive complexity and cognitive load in high and low demand flight simulation tasks. In Wyeld, T. Calder, P., & Shen, H. (Eds.), *Computer-human interaction cognitive effects of spatial interaction, learning, and ability OzCHI 2013. Lecture notes in computer science*. (Vol. 8433, pp. 133–152). Springer. https://doi.org/10.1007/978-3-319-16940-8_7

Horvat, S., Segedinac, M. D., Milenković, D. D., & Hrin, T. N. (2016). Development of procedure for the assessment of cognitive complexity of stoichiometric tasks. *Macedonian Journal of Chemistry and Chemical Engineering*, *35*(2), 275–284. https://doi.org/10.20450/mjcce.2016.893

Horvat, S., Rodić, D. D., Segedinac, M. D., & Rončević, T. N. (2017). Evaluation of cognitive complexity of tasks for the topic hydrogen exponent in the solutions of acids and bases. *Journal of Subject Didactics*, *2*(1), 33-45. https://doi.org/10.5281/zenodo.1238972

Horvat, S., Rončević, T. N., Arsenović, D. Z., Rodić, D. D., & Segedinac, M. D. (2020). Validation of the procedure for the assessment of cognitive complexity of chemical technology problem tasks. *Journal of Baltic Science Education*, *19*(1), 64-75. https://doi.org/10.33225/jbse/20.19.64

Huddle, P. A., & Pillay, A. E. (1996). An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African university. *Journal of Research in Science Teaching*, *33*, 65-77. https://doi.org/10.1002/(SICI)1098-2736(199601)33:1<65::AID-TEA4>3.0.CO;2-N

Jonsson, A., & Svingby, G. (2007). The use of scoring rubrics: Reliability, validity and educational consequences. *Educational Research Review*, *2*, 130–144. https://doi.org/10.1016/j.edurev.2007.05.002

Kalantar, A. H. (1985). Limiting reagent problems made simple for student. *Journal of Chemical Education*, *62*(2), 106. https://doi.org/10.1021/ed062p106

Kalyuga, S. (2009). *Managing cognitive load in adaptive multimedia learning*. Information Science reference.

Kashmar, R. J. (1997). The use of cut-out molecular models on the overhead projector to illustrate stoichiometry and limiting reactants. *Journal of Chemical Education*, *74*(7), 791–792. https://doi.org/10.1021/ed074p791

Knaus, K., Murphy, K., Blecking, A., & Holme, T. (2011). A valid and reliable instrument for cognitive complexity rating assignment of chemistry exam items. *Journal of Chemical Education*, *88*, 554–560. https://doi.org/10.1021/ed900070y

Marais, F., & Combrinck, S. (2009). An approach to dealing with the difficulties undergraduate chemistry students experience with stoichiometry. *South African Journal of Chemistry*, *62*, 88–96.

Mulford, D. R. and Robinson and W. R. (2002). An inventory for alternate conceptions among first-semester general chemistry students. *Journal of Chemical Education*, *79*, 739–744 https://doi.org/10.1021/ed079p739

Nikolajević, R., & Šurjanović, M. (2015). *Zbirka zadataka iz hemije za I i II razred gimnazije i srednje škole* [*Task compilation in chemistry for I and II grade of high school and high school*], Zavod za udžbenike i nastavna sredstva.

Olmsted, J. III (1999). Amounts tables as a diagnostic tool for flawed stoichiometric reasoning. *Journal of Chemical Education*, *76*(1), 52–54. https://doi.org/10.1021/ed076p52

Pollock, E., Chandler, P., & Sweller, J. (2002). Assimilating complex information. *Learning and Instruction*, *12*, 61−86. https://doi.org/10.1016/S0959-4752(01)00016-0

Raker, J. R., Trate, J. M., Holme, T. A., & Murphy, K. (2013). Adaptation of an instrument for measuring the cognitive complexity of organic chemistry exam items. *Journal of Chemical Education*, *90*, 1290–1295. https://dx.doi.org/10.1021/ed400373c

Robinson, P. (2001). Task complexity, task difficulty, and task production: Exploring interactions in a componential framework. *Applied Linguistics*, *22*(1), 27–57. https://doi.org/10.1093/applin/22.1.27

Sostarecz, M. C., & Sostarecz, A. G. (2012). A conceptual approach to limiting-reagent problems. *Journal of Chemical Education*, *89*, 1148–1151. https://doi.org/10.1021/ed200420h

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive Load Theory*. Springer.

Toth, Z. (1999). Limiting reactant. An alternative analogy. *Journal of Chemical Education*, *76*(7), 934. https://doi.org/10.1021/ed076p934

Towns, M. H. (2014). Guide to developing high-quality, reliable, and valid multiple-choice assessments. *Journal of Chemical Education, 91*, 1426−1431. https://dx.doi.org/10.1021/ed400476f

Wood, C., & Breyfoglem, B. (2006). Interactive demonstrations for mole ratios and limiting reagents. *Journal of Chemical Education*, *83*(5), 741–748. https://doi.org/10.1021/ed083p741

Received: *May 26, 2021* Accepted: *August 09, 2021*

Cite as: Horvat, S. A., Rodic, D. D., Rončević, T. N., Babić-Kekez, S., & Trifunović Horvat, B. (2021). Procedure for assessment of the cognitive complexity of the problems with a limiting reactant. In. V. Lamanauskas (Ed.), *Science and technology education: Developing a global perspective. Proceedings of the 4th International Baltic Symposium on Science and Technology Education (BalticSTE2021)* (pp. 59-73). Scientia Socialis Press. https://doi.org/10.33225/BalticSTE/2021.59