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Original Article

Evaluation of Cognitive Complexity of Tasks for the Topic Hydrogen Exponent in the Solutions of Acids and Bases

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Abstract

The aim of this study was evaluation of cognitive complexity of tasks for the topic hydrogen exponent in the solutions of acids and bases and its validation. The created procedure included an assessment of the difficulty of concepts and an assessment of their interactivity. There were 48 freshmen students enrolled in the study program Basic academic studies in chemistry. As a research instrument for assessing performance, 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 invested mental effort. The evaluation of cognitive complexity was confirmed by a series of linear regression analysis where high values of correlation coefficients are obtained among the examined variables: student's performance and invested mental effort (dependent variables) and cognitive complexity (independent variable).

Keywords*: mental effort; performance; pH*

Introduction

Chemistry as a teaching subject is difficult to understand and master at all levels of students´ education. In the Republic of Serbia, students met chemistry for the first time in the seventh grade of elementary school, when they are already expected to adopt and understand a large number of unknown chemical concepts. Students need to understand the ways in which chemical processes occurre, which are not available to direct sensory observation, as well as many chemical laws. A difficult understanding of chemistry could be observed in its abstraction and in the specific chemical language, which often contains terms from everyday life (Markić & Childs, 2016). Besides, chemistry is closely related to many natural sciences and mathematics. In addition to these difficulties, students also encounter numerical problem tasks of high complexity. Numerical tasks in chemistry often include some advanced mathematical functions, such as logarithm, exponents, rooting etc. These functions are included in the problems with the hydrogen ion exponent, the reaction between acids and bases and acid-base equations, which are part of the Acid base chemistry. This topic is closely related to other areas of chemistry and it contains a large number of concepts such as: electrolytic dissociation, chemical equilibrium, chemical reactions, stoichiometry, limiting reactant and solutions. While most simple problems are easy to solve, problems that include concepts from multiple domains often involve long-lasting and strenuous numerical calculations (Chetan et al., 2005). The teaching topic of acids and bases is important in the teaching of chemistry and it is studied from elementary school to university level.

According to teachers, students rather use algorithmic approach in solving acid base numerical calculations which is not based on conceptual understanding (Curtright et al., 2004). Namely, students often only include numerical data in formulas instead of trying to conceptually understand the problem (Bransford et al., 1999 cited in Watters & Watters, 2006).

Some of the difficulties encountered in this area are the following: students think that acidity and pH are the same terms, as well as strength and concentration, then they believe that the pH scale is unique and does not depend on the temperature and nature of the solvent (Alvarado et al., 2015). It is interesting to mention that in Tümay's study, the most of students (66%), when considering the concept of the strength of acids and bases, claim that a strong acid or base is 100% dissociated in water (Tümay, 2016). Inappropriate conceptual understanding is also noticed in the definition of acids and bases (83%). Namely, students believe that all acids and bases dissolve in water producing hydrogen ions and hydroxide ions, without taking into consideration modern acid base theories. Numerous misconceptions occur in this area and they refer to the understanding of acids and bases, the strength of acids and bases, the recognition of the acid or base character of the substance, as well as the reactions between them (Cooper et al., 2016).

The concept of hydrogen exponent is very important concept especially in analytical chemistry, in the teaching theme volumetry. Understanding this concept requires the understanding of acid-base reactions at a particle level. The concept of pH is difficult for students, as they often believe that strong acids have high pH values, while weak acids are characterized by low pH values (Ouertatani et al., 2006).

It seems that students encounter with problems on two levels of conceptual understanding. The first problem relates to the conceptualization of acids and bases on a meaningful and integrated level of understanding, and the second problem relates to the use of mathematics in order to successfully apply their knowledge (Watters & Watters, 2006). It has been observed that most students could define the pH value and calculate it by using the calculator, but they do not understand it conceptually. Solving numerical calculations, related to pH, are based on understanding the exponential numbers and the use of algorithms that are fundamental concepts of calculations. The pH concept, that it introduced by Sørensen (1909), is described as: $-\log[H^+]$ (Sørensen, 1909 cited in Watters & Watters, 2006). In order to understand this relationship, students have to know the meaning of “minus” and the notion of concentration, as well as to know how to calculate the concentration of hydrogen ions expressed in the exponential value from the given pH value, and vice versa. Understanding the concept of acidity and pH is also incomprehensible to students because the numerical values of hydrogen ion concentration and pH is in the indirect proportion, that is to say, the higher numerical pH value corresponds to a lower numerical value of the concentration of hydrogen ions. It has been found that students do not know what the logarithmic function means, but they know where the “log” button is on their calculator (Watters & Watters, 2006).

Many factors may be the cause of low performance in quantitative chemical problems. The complexity of tasks is often used as a variable that affects students' performance (Wood,1986). Complex tasks impose high load on the students' working memory, due to which students have to invest a great mental effort in order to solve them. Numerous studies have shown that the capacity of the working memory is a factor that must be taken into account in solving quantitative chemical problems (Johnstone & El-Banna, 1983; Niaz, 1996). The basic assumption is that short-term memory requires individual resources that are necessary for achieving the goals of specific cognitive activities in certain situations, which makes the basis for defining the theory of cognitive load (Sweller, 1988). Cognitive load is a multidimensional concept which is comprised of three components: mental effort, mental load and student performance (Pass, 1992, Pass & van Marrienboer 1994). The mental load refers to the students' cognitive capacity needed to solve the problem tasks. Mental effort is related to working memory resources that must be used to achieve the requirements of problem solving, and students' performance include students' achievement on tasks. In order to overcome overload of the working memory, which is detrimental to learning due to high cognitive load, the mental effort should be invested in processes that are essential for learning (Kalyuga, 2009).

With the aim of improving teaching, many researchers have worked to effectively measure the cognitive load. Recent research is based on a combined measurement of the student's mental effort that is invested and student's performance that is achieved by solving the numerical calculation (Pass & Merrienboer, 1993).

One of indicators of cognitive load, which has been recently used as an objective measure is the cognitive complexity (Raker et al., 2013; Harris et al., 2013). The concept of cognitive complexity was the first mentioned by George Kelly in his Personal Constructive Theory (Kelly, 1955). According to this theory, individuals are able to understand, predict, and control events in the same way as scientists work, building their own systems of (personal) constructs, using them as "cognitive patterns" to understand the world. Based on Kelly's personal constructive theory, Bieri (Bieri, 1955) proposed the concept of cognitive complexity that represents the degree of differentiation in the constructive system of an individual, or the relative number of different dimensions based on the decisions that can be made. The more complex the cognitive ability of an individual is, more the construct that this person uses to understand the world, will be differentiated (Bieri, 1955; Xin & Chi, 2007). Therefore, cognitive complexity may relate to an individual, but it can also refer to the task.

Cognitively complex tasks should be designed in a way that they encourage students to think about the problem, develop strategies, methods, and procedures for solving tasks. Students should not only reproduce the answer, but should also know and explain it in an adequate way. Tasks should also be constructed to enable a large number of solution methods to (Magone et al., 1994).

What is crucial in assessing cognitive complexity is to consider the difficulty of the elements - the concepts represented in the task and their interactivity. In order to assess the cognitive complexity, an estimation of the difficulty of the concepts represented in the assignment should be made. It is very important to establish which are the key factors that determine how complexity is elaborated, and the most important factor in the assessment is to include the degree of interactivity of the elements (Sweller, 1988, Knaus et al., 2011). Halford et al. (Halford et al., 1998) considered that the limiting factor in assessing the complexity of tasks is not the number of items or the amount of information, but the relationship between the entities. The problem becomes more complex with an increase in the number of interacting factors. Complexity can be measured by dimensioning relationships or the number of associated variables. If the task contains two items that are interacting in a binary relation, it is simpler in comparison to the task containing the ternary relation, wherein three things are in interaction, and it is again simpler than the one that includes four interconnected items, that is, one that has quaternary relation and so on. The idea of relational complexity is analogous to the number of factors in the experimental design that is considered to be the set of dependent and independent variables. According to concepts of load and resource, this relational complexity is usually used to calculate performance in cognitive psychology.

The researchers designed special instruments for the assessment of cognitive complexity, which are based on the creation of the Rubrics which helped in determining numerical value of cognitive complexity (Knaus et. al., 2011; Raker et al., 2013; Horvat et al., 2016). This type of instrument is based on assigning numerical values of the cognitive complexity of a given task. The estimation of the number of elements, the expert's estimation of the difficulty of the concepts represented in the task, and the assessment of their interactivity are the three steps during obtaining a numerical rating of cognitive complexity.

It is important to note that every rating system of complexity contains a certain dose of subjective components, since it relies on expert assessments. For this reason, the creation of Rubrics must be carried out in such a way that the results are valid and reliable, so that the expert method for the complexity rating can serve as a substitute for the objective complexity (Knaus et al., 2011).

The instrument for assessing the cognitive complexity of chemical tasks that proved to be valid and reliable was first constructed by Knaus et al. (Knaus et al., 2011) who called it the "Rubric for the Cognitive Complexity of Chemical Problems". The validity of the instrument has been confirmed in two ways: (1) a statistically significant correlation between the cognitive complexity by experts and student performance, and (2) a statistically significant correlation between the expert assessment of cognitive complexity and students' assessment of mental effort. Calculation of the numerical value of the cognitive complexity rating is based on the principle of additivity of the difficulty rating of the skills and concepts represented in the task and the factor of interactivity between these concepts (Knaus et al., 2011; Raker et al., 2013; Horvat et al., 2016). The great advantage of the Rubrics for cognitive complexity rating is that they rely on the assessment of interactivity among the concepts that are present in the task - the aspects of cognitive load theory, more precisely on intrinsic cognitive load (Sweller et al., 1998).

The creation of a Rubric has repeatedly proven to be a good method for calculating the cognitive complexity rating. The reason lies in the fact that the subjectivity of an expert is reduced to a minimum.

Methods

Aim of the research

The aim of this paper is to design and validate the Table for assessing difficulty of concepts and their interactivity for topic hydrogen exponent in the solutions of acids and bases.

Research sample

The sample of this research consisted of 48 freshmen students enrolled in the study program Basic academic studies in chemistry at the Faculty of Sciences in Novi Sad. All respondents previously completed different profiles of secondary education and were aged 19 to 20 of mixed socioeconomic status. All of them agreed to voluntary participate in this research. The research was conducted in October 2017/18 academic year.

Research instruments

As a research instrument, we used a Test, which was specifically constructed for this research. The time available for test solving is 45 minutes. Respondents previously studied all the concepts presented in the tasks during regular chemistry classes within secondary school. A test contained six tasks. Each correct answer is scored by one point, so that the maximum total score on the test was six points. Incomplete tasks were not taken into consideration and scoring.

In addition to performance, students' mental effort was also evaluated. Assessment of invested mental effort was measured by a subjective technique with the use of seven-point Likert scale. After each task accomplished, students were asked to express an assessment of the mental effort they had invested in solving the task by choosing the appropriate descriptive grade on the scale. During statistical data processing, numerical values of estimates have been assigned to descriptive estimates. 'Extremely easy' - assigned a numerical value of 1 while 'extremely difficult' - the numerical value 7.

The quality of the test, was evaluated by pre-test and post-test assurance parameters. The obtained results were processed by statistical software programs Stat Graphics Centurion XVI and IBM SPSS Statistics 22.

Instrument psychometric

Pre-test assurance parameters were determined by experts in the field Didactics of Chemistry. Due to the compliance of tasks with a valid curriculum and proposed textbooks, the authors concluded that the test is valid for this testing. The tasks on the test are defined by experts as diverse, with clearly defined requirements.

Post-test assurance parameters of quality are defined as basic statistical parameters: indices of item difficulty, index of test difficulty, the coefficient of reliability, discrimination indices, as well as discrimination index of the test. Created test showed good metric characteristics. Reliability is calculated as a measure of internal consistency and expressed as a Cronbach α coefficient of 0.61 for performances, and 0.84 for self-assessed mental effort thus indicating good reliability. Cronbach α values above 0.6 are acceptable when a small number of tasks are represented on the test (Moss et all., 1998; Loewenthal, 2004). Indices of taks' difficulty are in the range of 5.26% to 78.95% (average value of test difficulty is 39.04%, which makes it a test of moderate difficulty). One task has a difficulty index less than 25% which makes it difficult, while one task has a difficulty index greater than 75% which makes it easy task (Towns, 2014). Discrimination indices are in the range of from 0.10 to 0.80 (average of 0.55 which is an excellent discrimination index). Five tasks have an excellent discrimination index, greater than 0.4, while only one task has a poor index of discrimination (0.10), so it should be revised for future usage.

The basic statistical test parameters are shown in Table 1.

Validation of instrument for assessment the mental effort was also confirmed by linear regression related to observing the dependence of student performance and self-invested mental effort. Graphic dependence and statistical parameters of regression analysis are shown in Figure 1 and Table 2.

Table 1. Descriptive statistics for the students' performance and mental effort.

Parameter	Students' performance [1] (N=48)	Students' mental effort [2] (N=48)
Average	2.34	4.02
Standard deviation	1.36	0.84
Minimum	0.00	2.00
Maximum	6.00	5.50
Range	6.00	3.50
Standard Skewness	1.98	- 1.72
Standard kurtosis	0.70	0.70

[1] Students' performance could range from 0 to 6.
[2] Possible ratings for invested mental effort could range from 1 to 7: extremely easy (1) to extremely difficult (7)

This dependence describes a very strong correlation (R=-0.80; P=0.03). *P - value* is less than 0.05, indicating a statistically significant correlation between mental effort as dependent variables and performances as independent variables at the confidence level of 95%.

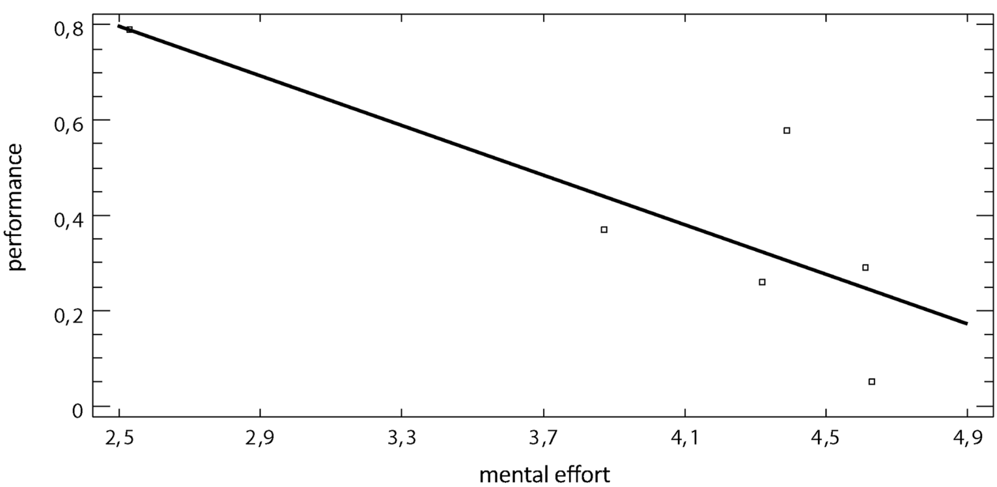

Figure 1. Correlation of students' performances and students' evaluation of invested mental effort.

Table 2. Statistical parameters of the regression analysis of students' performance and students' evaluation of invested mental effort.

Parameter	Value
The correlation coefficient	-0.80
R-square	63.59%
P-value	0.03
Equation	$P = 1.44- 0.26\times ME$

Results and Discussion

In order to successfully evaluate the cognitive complexity it is necessary to validate the procedure for determining cognitive complexity of the problems with the hydrogen exponent in the solutions of acids and bases. In order to ensure objectivity in assessing cognitive complexity, a Table for assessing difficulty of concepts and their interactivity has been developed. The basic concepts that were considered were: *Dissociation degree of acids and bases, Dissociation constant of acids and bases,* and *Ostwald's dilution law*. In accordance with the Rubric developed by Knaus et al. (Knaus el al., 2011), assessment of difficulty of the concepts was made. Concepts were estimated as easy, medium and difficult:

1. The concept Dissociation degree is structured in three levels: the calculation of pH (pOH) from dissociation degree in the solution of monobasic acid and monoacidic base, which is an easy concept when calculating the pH in the acid solution, or pOH in the solution of the base. The concept is of medium difficulty if it is necessary to calculate the pOH value in the acid solution, or pH value in the solution of the base. This concept is also of medium difficulty if it is necessary to calculate the pH value in the polybasic acid solution, or pOH in the solution of the polyacidic base. If it is necessary to calculate the pOH value of the polybasic acid, or the pH value of the polyacidic base, the concept is difficult.
2. The concept of Dissociation constant of acids and bases is structured in two levels. It is medium when calculating the pH from K_a in a solution of weak monobasic acid, or pOH from K_b in a solution of a weak monoacidic base. If the pH is calculated in a base solution based on K_b, or pOH in the acid solution based on the K_a concept is difficult.
3. Ostwald's dilution law is a difficult concept because it links dissociation degree, dissociation constant and the concentration of the acid or base solution.

In addition, in the Table for assessing the difficulty of concepts, the concept of a solution is presented as an additional concept, which is numerically expressed in the rating of cognitive complexity and it contributes to the increase of interactivity.

If it is necessary to calculate the molar concentration from the mass concentration or from the mass and the volume of the solution it has additivity value 1. If it is necessary to calculate the molar concentration from the mass fraction and the density it has additivity value 2.

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 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.

In the Table 3, Table for assessing difficulty of concepts and their interactivity in the

Table 3. Table for assessing difficulty of concepts and their interactivity in the tasks with the hydrogen exponent in solutions of acids and bases.

Dissociation degree of acids and bases	
Calculation of pH (pOH) for monobasic acids (monoacid bases)	Easy
Calculation of pOH (pH) for monobasic acids (monoacid bases) Calculation of pH (pOH) for polybasic acids (polyacid bases)	Medium
Calculation of pOH (pH) for polybasic acids (polyacid bases)	Difficult
Dissociation constant of acids and bases	
Calculation of pH (pOH) of weak monobasic acids (monoacid bases)	Medium
Calculation of pOH (pH) of weak monobasic acids (monoacid bases)	Difficult
Ostwald's dilution law	
Connection of Kd and α	Difficult
Solutions (additional concept)	
Calculation of concentration from mass concentration	1
Calculation of concentration from mass and volume	
Calculation of concentration from mass fraction and density	2
Concept interactivity	
Task contains up to two concepts	0
Task contains three concepts	1
Task contains more than three concepts	2

tasks with the hydrogen exponent in solutions of acids and bases is presented.

The Table is simple and objective to use. The tasks used in the test have different levels of cognitive complexity. The method for calculation of cognitive complexity rating will be shown in the following examples:

Task 1. Calculate pOH of a solution of sodium hydroxide, concentration of which is 0.001 mol/dm^3. Consider that the dissociation of sodium hydroxide is complete.

To solve this task, the student needs to know that the concentration of hydroxide ions can be determined from the total concentration of sodium hydroxide, because there is a complete dissociation in the solution of sodium hydroxide, i.e. α = 1.

From Table 3, it can be seen that the task contains an easy concept and refers to the calculation of the hydrogen exponent from the degree of dissociation. According to the Rubric from Knaus et al. (2011), the rating of cognitive complexity that contains only one easy concept is 1. According to this procedure, to assess the difficulty of concepts, it is also necessary to determine the degree of interactivity of the elements, and since this task contains only one concept, the interactivity is 0 and thus the overall complexity 1.

In addition, there are tasks that contain additional concepts that increase the overall cognitive complexity of tasks. In the following example we present a task which contain an additional concept.

Task 4. Calculate pOH value of ammonia solution which was prepared by introducing 1.7 grams of gaseous ammonia in 2 dm^3 of distilled water. Consider that all the mass of ammonia is dissolved in distilled water, and the change in volume due to dissolution is negligible. The ammonia base constant is K_b = 1.8 x 10^{-5}.

In this task, two concepts, one basic and one additional concept, are represented. The basic concept is the calculation of pOH of weak monoacidic base, which is of medium difficulty, and the additional concept is related to calculation of molar concentration of ammonia from the mass and volume. According to the Rubric (Knaus et al., 2011), the cognitive complexity of this task is 3, because the task contains one basic concept of medium difficulty (2) and one additional concept and because of the presence of two concepts the interactivity is 1.

The results for all tasks from the test are summarized in Table 4.

Table 4. Cognitive complexity ratings for test tasks.

Number of task	Cognitive complexity rating
1	1
2	6
3	2
4	3
5	4
6	6

Procedures for assessing the cognitive complexity of tasks are validated by comparing with student performance measures and measures of mental effort (Knaus et al., 2011).

In his paper, the correlation of the estimated cognitive complexity of tasks with student performance and self-assessment of mental effort is described by graphic dependences and basic statistical parameters.

In the first phase, the regression analysis of the dependence of students' performance (dependent variable) from the estimated cognitive complexity (independent variable) was done. Linear regression is applied in accordance with previous studies (Knaus et al., 2011; Raker et al., 2013; Horvat et al., 2016). The results of the regression analysis, are presented graphically in Figure 2 and tabular in Table 5.

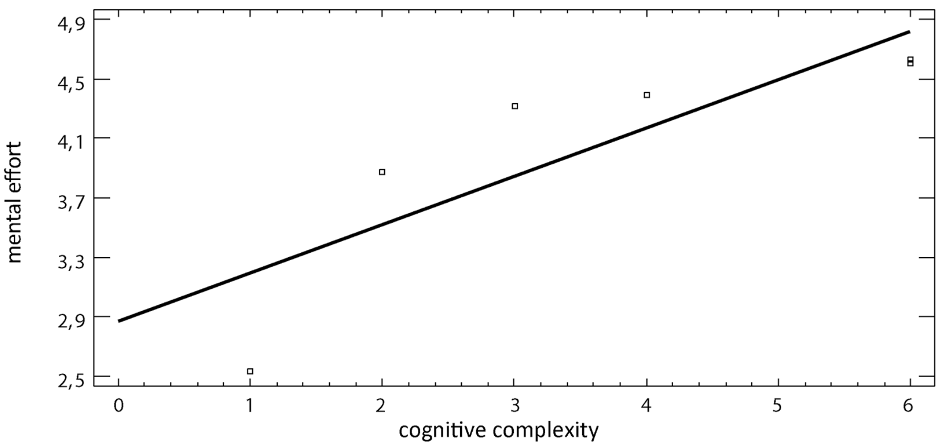

Figure 2. Correlation of students' performance with cognitive complexity.

It is worth to mention that in the correlation analysis the student’ performance was calculated as the average performance value of all students in the test tasks. Observing the *P-value* which is greater than 0.05, no statistically significant linear correlation between the dependent and the independent variable was found, even though the correlation coefficient (R = -0.71) indicated a strong, negative correlation between the variables

Table 5. Statistical parameters of the regression analysis of students' performance and cognitive complexity.

Parameter	Value
The correlation coefficient	-0.71
R-square	50.49%
P-value	0.11
Equation	P= 0.71 - 0.09×CC

(Evans, 1996). The reason for such results might be in the students' low performance in the several tasks that were estimated with relatively low cognitive complexity. Further analysis of our students' written responses revealed a number of conceptual misunderstandings which might cause low performance in these tasks. For example, students possessed the misunderstandings about the basic concept of the dissociation degree of acids and bases, i.e. about the strength of acids and bases. They observed poor acids - vinegar and butyric acid, as strong acids, which reflected on their calculations. Namely, they believed that such acids are 100% dissolved on ions in the aqueous solutions, not taking into account the value of the acid constants given in the text of the tasks. They made the similar mistake in the calculations in which the aqueous ammonia solution was observed as a strong base. Also, in the tasks for determining the pH value of weak acids and bases, students forgot to apply the mathematical operation of the roots, which exists in the expression for the concentration of hydrogen ions, $[H^+]=\sqrt{K_a \times c_a}$. Therefore, they got the incorrect value for concentration, and the obtained pH value was greater than 7 in the solution of weak acid. According to this, it could be assumed that students memorized and used algorithmic approach to solve such problems. Additionally, students calculated the pOH value of a solution of a weak ammonia base using the formula $[OH^-]=\sqrt{\frac{K_w}{K_b} \times c_b}$ believing that the concentration of hydroxide ions can be obtained by rooting the product of the acidity constant and the concentration of the base. Students also possessed misunderstandings about the calculation of pOH value in the solution of strong bases. For example, they calculated pH value 3, or pOH value 11, in the sodium hydroxide solution concentration of 0.001 mol/dm^3. In addition, students observed polybasic acids as monobasic, regardless the notation in the task text about the complete

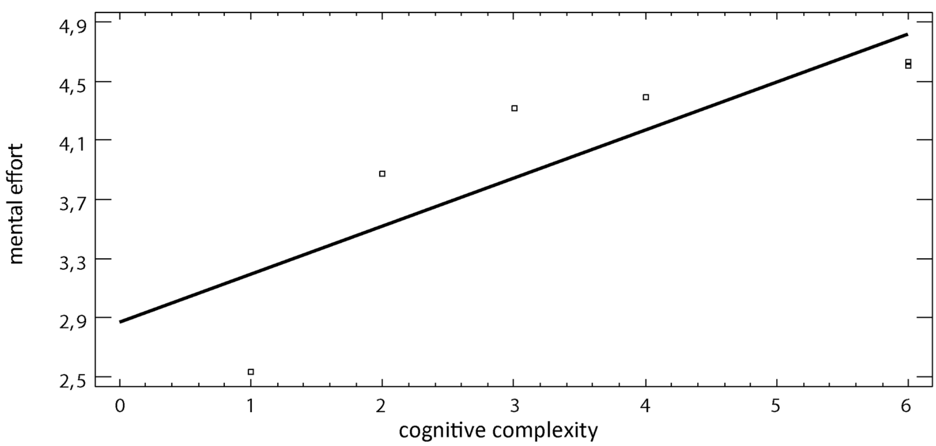

Figure 3. Correlation of students' mental effort with cognitive complexity.

dissociation of sulfuric acid in both stages. The similar results were previously obtained by Watters & Watters. (Watters & Watters, 2006).

In the second phase, the regression analysis of the dependence of invested mental effort (dependent variable) from the estimated cognitive complexity (independent variable) was done. Statistical parameters and graphical dependency are shown in Figure 3 and in Table 6.

Table 6. Statistical parameters of the regression analysis of students' mental effort and cognitive complexity.

Parameter	Value
The correlation coefficient	0.84
R-square	71.11%
P-value	0.03
Equation	$ME = 0.32 \times CC + 0.86$

The correlation coefficient (R = 0.84) and the P-value (P = 0.03) indicated a very strong correlation between the mental effort as dependent variable and the numerical value of the cognitive complexity rating as independent variable. The positive value of the correlation coefficient indicated that with increased cognitive complexity, students have to invest more mental effort to solve the task.

Conclusions

In this study, the Table for assessing difficulty of concepts and their interactivity for topic hydrogen exponent in the solutions of acids and bases was developed. The procedure for estimating the cognitive complexity of the tasks was evaluated by a series of regression analyzes of the dependence of students' performance, as well as invested mental effort, from cognitive complexity. During the evaluation, several students' conceptual misunderstandings were observed and described, in accordance with some previous studies.

The main disadvantage of this research is reflected in relatively small number of tasks on the test. Although studies with a similar number of tasks could be found in the literature, it is recommended that the number of tasks in the test should be greater. A small number of tasks might have affected the obtained statistical data to a certain extent, and therefore, for the next usage, the test should be extended with new tasks.

Henceforth, the main contribution of the constructed Table is to help teachers to create the tasks with different cognitive complexity levels, in order to affect the cognitive development of each student.

Regarding implications for future research, we suggest the application of new methods for assessing cognitive complexities, such as, for instance, the Knowledge space theory, which can additionally confirm the validity of the design Table.

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