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EVALUATION AND CHEMICAL THINKING DEVELOPMENT

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Abstract

The successful mastering of chemical knowledge is closely related with the chemical thinking development and the elaboration of methods for it measuring. However, as an analysis of literary sources shows that the term "chemical thinking" is used extremely rarely, since it was believed that nature could not afford the luxury of creating special types of thinking for each activity. To assess success in chemistry is usually used either psychological methods that have nothing to do with chemical thinking or a block of chemical tasks, which allow to estimate the range of knowledge, but not the level of chemical thinking. Does chemical thinking exist? Is it possible to develop a Chemical Thinking Test and, if so, what is its reliability? Purpose of the study is to develop a tool for assessing chemical thinking and evaluate its psychometric characteristics. Participants aged 14 to 70 years old were invited to the study. They were asked to evaluate their general and chemical abilities, and then, to solve as quickly as possible the problems of generalization, classification and synthesis of (a) chemical objects and (b) non-chemical ones. The results of the psychometric evaluation of the Chemical Thinking Test (ChTT) indicated its high reliability. Chemical thinking is formed based on mental operations such as analysis, synthesis, comparison, classification, the establishment of identity-difference, the identification of cause-effect relationships and probabilistic evaluation as a result of the selection of elements of thought and their sequences that correspond to the qualitative-quantitative relationships chemical interaction

Keywords: Chemical Thinking Test, development, evaluation, DI-theory.

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1. Introduction

Development of methods for the evaluation of chemical thinking is linked closely to the fundamental problem solution that outstanding minds have been trying to solve throughout human history. This is the issue about the nature of thinking since the solution of this problem allows us to answer the question about the mechanisms of reasonable human behaviour.

The study of thinking in general and chemical thinking in particular can make a significant contribution to solving such theoretical problems as understanding the mechanisms of reasonable human behaviour when person interacting with the chemical nature of matter and the mechanisms that provide the generation of new knowledge of Chemistry.

Chemistry as an educational discipline has almost unlimited possibilities in terms of the development of intelligence and creativity. So for example, Mary M. Kirchhoff (2011) proposed to study chemistry for solving the problem of creativity crisis: "Chemistry is a marvellous way to teach creativity. Chemists are molecular designers, applying their skills and knowledge to create new products and processes" (p. 1). In previous works of the author, it was shown that the purposeful development of chemical thinking leads the development of intelligence, competence and creativity (Volkova, 2011a; Volkova, 2013b; Volkova, 2014; Volkova, 2015).

Educational activity in the field of chemistry has significant resources in terms of the provision of psychotherapeutic assistance, since it is a creative activity, which creates not only new substances, chemical processes, but also the person himself.

The study of the features of chemical thinking is associated with the development of intelligent systems of the newest generation, as well as means of increasing the mental abilities of people, which increases a person's resistance to "brainwashing", because smart people are hard to manipulate.

Misunderstanding the nature of chemical thinking and the laws of its development significantly reduces the effectiveness of chemical education:

- Substitution of all the wealth of a chemical experiment with its poor video copies;
- Using physical methods and means of solving chemical problems without understanding the specifics of chemical thinking;
- Learning without understanding the natural sequence of introducing new knowledge in chemistry, etc.

2. Problem Statement

The study of chemical thinking is associated with enormous difficulties. Firstly, they are caused by the difficulties of studying thinking as a subject of psychological research:

- Thinking in each sciences is interpreted, studied in different ways and then it is introduced into psychology, replacing the psychological aspect of thinking, which is so necessary in educational practice.
- Thought is fundamentally not observable either from the side of the external observer, or from the side of the person itself.

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- Thinking is associated both with processes occurring in the brain and with objects of thinking, but the properties of thinking cannot be formulated either in terms of physiological processes or in terms of the problem being solved.
- Thinking is an open psychological system that is influenced by many factors (the content of tasks, the system of knowledge, the emotional and motivational state of the person, the world around him, the situation of the testing, the personality of the researcher, etc.).
- Instead of the definition of thinking in the scientific and educational literature, its descriptive characteristics are given that do not reveal its nature, which is different from sensation and perception and determines the sources of its cognitive advantages.

Secondly, the difficulties in the study of chemical thinking are caused by the difficulties in highlighting the qualitative specificity of the thinking of chemists, different from the thinking of mathematicians, physicists, musicians, etc.

- The idea of reducing chemistry to physics is being revived again and again, denying the specific features of chemistry and not allowing us to understand what specific features of chemistry are imprinted in the mind of a chemist and how the process-productive characteristics of his thinking is being changed. It should emphasized that thinking is always subject-and-specific.
- Chemical processes are the part of the complex processes of the universe, which makes it difficult to select stimulus material adequate to the nature of chemical thinking.
- The difficulties of distinguish gifted chemists and those who just know chemistry (in the structure of the abilities of the gifted chemists chemical thinking plays a core role, which allow ones to creatively realize himself in the field of chemistry and solve chemical problems not only quickly, but also accurately) (Volkova, 2011b).
- Pseudo-scientific creativity of teachers, authors of chemistry textbooks in interpreting chemical terms and selecting examples illustrating these terms (Popkov & Makarova, 2007).

2.1. Why do we need thinking?

Looking at the burning of candles on the table, we see how wax slowly melts and disappears, filling the room with warmth and comfort. In our perception, the total effects of the effects of the candle burning processes on our senses are given in undivided form (for example, our sensation of heat / cold depends on the temperature of our body), the total effects of various external forces acting simultaneously (Earth's gravity and table design resistance) and processes (melting wax and converting wax into carbon dioxide and water).

Within the framework of perception, it is impossible to completely separate the total effects of the interaction of various forces and processes, the subject and the object and come to a unique invariant definition of the properties of the object, depending only on them. In perception, even in the most generalized representations, the generic and species properties of objects are presented together at the same level, and in conceptual thinking - at different levels (Vekker, 1981). Between the representation of being at the level of perception and at the level of thinking, the fundamental difference is the lack of differentiation of perception as compared with a greater differentiation of thinking (Chuprikova, 2015; Rubinstein, 2003). At the level of perception, the burning of a candle is perceived as a holistic physical-and-chemical process,

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and only thinking allows us to discover individual processes, their characteristics and the relationships between them.

Thinking is an analytical-dissected form of cognition, qualitatively different from holistic-integrated representation of reality at the level of perception.

2.2. The structure of thought

The content of thoughts is infinitely diverse, but the structure of thought, whatever order it may be, includes three essential elements:

- Separation of objects;
- Comparing them with each other;
- Determining the direction of these comparisons (spatial or temporal adjacency, similarity, affiliation, causality, etc.) (Sechenov, 2001).

In thought, the ratio of the characteristics of isolated objects acts as a separate independent element, which is not at the level of perception. Thus, research methods of chemical thinking should allow us to evaluate:

- Ability to discover chemical objects and their characteristics;
- Ability to compare chemical objects and their characteristics with each other in various directions;
- Ability to determine the range of directions of this comparison depending on the conditions of the tasks.

2.3. Stages, patterns and mechanisms of development of the thought structure

To develop adequate quantitative indicators for assessing the development of chemical thinking, it should understand the patterns and mechanisms of thought structure development, or, in Hegel’s words, how a thought “takes away” from things their properties and relationships. It should be noted that thinking development and evolution of Chemistry are realized in the similar direction (Volkova, 2013a), namely, from global and undifferentiated forms to increasingly differentiated and hierarchically related forms (see Table 1).

Table 01. Stages of the thought structure development

Stages		**The emergence of a new ability**	**Consistent pattern**	**Consistent pattern in Chemistry**
1.	The lowest form of dismembered feeling	Ability to dismember the holistic sensory impressions	The selection of the largest elements corresponding to objects	Discovery the ability of a substance to change its properties under the influence of fire
2.	Sensory-automatic thinking	Ability to recognize of objects by their individual properties or characteristics	Selection of more fractional elements corresponding to the properties of objects	Discovery of methods to increase the temperature of combustion
3.	Concrete thinking	Ability to make judgments	The emergence of a three-term structure of thought	Cro-Magnons discovered a method for producing substances with new properties by heating two or more substances

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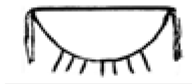
4.	Symbolic thinking	Ability to speech	Abstract content is associated with verbal signs, but signs continue to carry sensory content	 The symbol of gold (ancient Egypt), depicting the process of obtaining it (Loyson, 2011)
5.	Abstract thinking	Ability to operate with “pure signs" abstracted from sensory content	"Pure signs" abstracted from sensory content	Au

Both the child and the animal, which are capable of movement, are able to distinguish and recognize objects (Stage 1). Sensory-automatic thinking is not thinking in the true sense of the word, since there is no comparison of objects according to different signs and in different relations (Stage 2). Mechanisms for distinguishing sensory images are based on generalizing and dismembering work of the memory and dismembering role of the movement. The more specialized movements are, the more they contribute to the dismemberment of feelings. The mechanism of the emergence of concrete thought is the acts of comparing perceived objects with each other (Stage 3).

An analysis of literary sources shows that the term “chemical thinking” is used extremely rarely, since it was believed that nature could not afford the luxury of creating special types of thinking for each activity. To assess success in chemistry is usually used either a block of psychological methods that have nothing to do with chemical thinking or a block of chemical tasks of different difficulty levels, which allow evaluating the level of knowledge, but not the level of chemical thinking. At the same time, many teachers note that when solving non-standard chemical problems, any slightest deviation from the beaten track leads most students to a stupor, turning into complete paralysis of mental activity. To teach chemical thinking is to teach how to distinguish chemical objects and their characteristics and compare them in different directions. It is impossible to master the laws of the chemical process with the help of mathematical or musical thinking. However, it is also impossible to agree fully with the opinion that all human abilities are specific and operate in a limited area of activity, and the G-factor is a myth, a statistical artefact. It is necessary to pay attention to the existence of intellectual thresholds for different types of activities; for chemistry, such a threshold is 110 IQ (Wechsler Adult Intelligence Scale). Studies show that chemical thinking is formed on the basis of such mental operations as analysis, synthesis, comparison, classification, establishment of identity-differences, identification of cause-effect relationships and probabilistic assessment as a result of the selection of those links of thought processes and their sequences that are more consistent qualitative and quantitative relations of chemical interaction.

3. Research Questions

Does chemical thinking exist? Is it possible to develop a Chemical Thinking Test and, if so, what is its reliability?

4. Purpose of the Study

Purpose of the study is to develop a tool for assessing chemical thinking and evaluate its psychometric characteristics.

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5. Research Methods

Participants aged 14 to 70 years old were invited to the study. They were asked to evaluate their general and chemical abilities, and then, to solve as quickly as possible the problems of generalization, classification and synthesis of (a) chemical objects and (b) non-chemical ones.

The Chemical Thinking Test (ChTT) was elaborated based on an analysis of the stages, patterns and mechanisms of development of the thinking (Table 1).

ChTT consists of three subtests:

- Categorical generalization of chemical objects;
- Conceptual synthesis of chemical objects;
- Classification of chemical objects.

5.1. Subtests 1. Categorical generalization of chemical objects

Instruction: Here are 10 triads of words. You should think about what is common between the words in each triad and call this essential attribute, if possible, in one word. You have 5 minutes to think and write down the answers (30 seconds for each triad of words). The answer should be recorded strictly in accordance with the number indicated in the list of answer (see Table 02).

Table 02. List of answer

No	Triads	Answers	Scores
1.	Fluorine, Chlorine, Bromine		
2.	Hydrogen Chloride, Methane, Hydrogen		
3.	Magnesium, Aluminium, Silicon		
4.	Aluminium Oxide, Zinc Hydroxide, Amino Acid		
5.	Benzene, Naphthalene, Styrene		
6.	SO_2, CH_3COOH, $AlCl_3$		
7.	Butine, Cyclobutene, Butadiene		
8.	P_4O_{10}, H_3PO_4, $Ca_3(PO_4)_2$		
9.	Esterification, Hydrolysis, Exchange		
10.	Water, Sulphuric Acid, Ammonia		
Total			

Consider the evaluation criteria for the example of triad 7 “Butine, Cyclobutene, Butadiene”:

- **0 points** - thematic generalization based on associative relations (chemistry lesson, dangerous); a generalization of only two words out of three (double bond);
- **1 point** - analytical generalization based on the allocation of a specific trait (4 carbons, complex compounds, combustible substances);
- **2 points** - categorical generalization using a strict generic category (unsaturated hydrocarbons);
- **3 points** - revealing the essence of the phenomenon, the allocation of generic-species relations (isomers).

Interpretation of results:

- **0 - 9 points** - respondents with weak chemical thinking.
- **10–20 points** - respondents with ordinary chemical thinking.
- **21–30 points** - respondents with strong chemical thinking

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5.2. Subtests 2. Conceptual synthesis of chemical objects

Instruction: Before you are three words. Try to establish semantic links between these words and write down in the form of one or two sentences, so that all three words are used simultaneously. In total, 3 triads of words will be presented. The work time with each triad of words is 2 minutes.

List of answer:

1. Alcohol - Acid – Water

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2. Speed - Equilibrium - Catalyst

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3. Litmus - Salt – Metal

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Criteria for evaluation:

- **0 points** - conceptual synthesis has no chemical meaning or contains errors (*The catalyst slowed my speed and I lost my balance*.); a conceptual synthesis of only two words out of three (*If you mix water and alcohol, you get vodka*);
- **1 point** - conceptual synthesis is established on the basis of a simple enumeration of chemical objects or their formal opposition (*I had medical alcohol, acid and water*);
- **2 points** - all three words are included in a certain specific situation (Ethyl alcohol, sulphuric acid and water are liquid substances);
- **3 points** - all three words are combined through a generalized categorical basis, using complex analogies, the development of causal relationships (Ethyl alcohol is the weaker acid than water. To increase the speed without shifting the equilibrium, I had to use a catalyst).

Interpretation of results:

- **0 – 3 points** - respondents with weak chemical thinking.
- **3–6 points** - respondents with ordinary chemical thinking.
- **7–9 points** - respondents with strong chemical thinking.

5.3. Subtests 3. Classification of chemical objects

Instruction: Here is a set of formulas of chemical compounds. Distribute these formulas into groups in the most convenient, logical and natural way, from your point of view. There is no one correct solution in this task, each person distributes the formulas in his own way. Groups can be any. Name each group. Performing time is 5 minutes.

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List of answer:

ZnO, $AlNO_3Cl_2$, Na_2KPO_4, HClO, H_3PO_4, BeO, CrO_3, $Cu_2(OH)_2CO_3$, H_2SiO_3, $Cu(OH)_2$, NH_4OH, SO_3, $Ba(OH)_2$, CO_2, Na_2HPO_4, $KMnO_4$, $CrCl(NO_3)_2$, BaO, H2CO$_3$, CrO, $Fe(OH)_3$, Cu(NO3)$_2$, $Na_2Cr_2O_7$, KOH, $Be(OH)_2$, FeO, $Al(OH)_2Cl$, HCOOH, Cr_2O_3, $FeCl_3$, $Al_2(SO_4)_3$, NH_4NO_3, $NaHCO_3$, $Zn(OH)_2$, CH_3COOH, KMgPO4, Fe_2O_3, HNO_3, $CaHPO_4$, $Fe(OH)_2$, P_2O_5, H_2SO_3.

Criteria for evaluation:

- The number of correctly selected groups.

Interpretation of results:

- **0 – 4 groups** - respondents with weak chemical thinking.
- **5–10 groups** - respondents with ordinary chemical thinking.
- **11–14 groups** - respondents with strong chemical thinking.

6. Findings

The testing of the Chemical Thinking Test (ChTT) was took place on a sample of students, students and teachers from Moscow, Taganrog, Tyumen, Yekaterinburg, and Saratov. The results of comparative analysis of the categorical generalization of chemical objects in respondents with different successfulness in chemistry are presented in Table 3.

Table 03. Comparative analysis of the categorical generalization of chemical objects in respondents with different successfulness in chemistry

No	Triads	More successful chemist	Less successful chemist
1.	Fluorine, Chlorine, Bromine	halogens	simple substances
2.	Hydrogen Chloride, Methane, Hydrogen	hydrogen compounds	fuel
3.	Magnesium, Aluminium, Silicon	III period	metals
4.	Aluminium Oxide, Zinc Hydroxide, Amino Acid	ampholytes	oxygen
5.	Benzene, Naphthalene, Styrene	aromatics	chemicals
6.	SO_2, CH_3COOH, $AlCl_3$	compounds react with alkalis	something sour
7.	Butine, Cyclobutene, Butadiene	unsaturated hydrocarbons	syllable “boo”
8.	P_4O_{10}, H_3PO_4, $Ca_3(PO_4)_2$	phosphorus compounds (V)	PO_4
9.	Esterification, Hydrolysis, Exchange	exchange reactions	formation of new substances
10.	Water, Sulphuric Acid, Ammonia	contain unshared electron pairs	H
Total		27	10

The results of assessing the chemical thinking were compared with similar indicators of thinking obtained by the methods of M.A. Kholodnaya “Conceptual Thinking”. Chemists that are more successful have higher rates of both general and chemical thinking, but indicators of their chemical thinking is higher than general one. The growth of indicators of chemical thinking was observed as the age-related development and learning of chemistry. However, the indicators of thinking in general and chemical thinking in particular remained low.

7. Conclusion

- The results of the psychometric evaluation of the Chemical Thinking Test (ChTT) indicated its high reliability
- A very disappointing conclusion was obtained. Our young generation was not taught to think what could make them an easy victim of the manipulation of politicians and recruiters into terrorist gangs. Consequently, learning to think should be the most important task not only to improve the quality of education, but also to improve the safety of life.

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