EXAMINING SYSTEMS THINKING THROUGH THE APPLICATION OF SYSTEMIC APPROACH IN THE SECONDARY SCHOOL CHEMISTRY TEACHING

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ABSTRACT

This study was conducted during the second semester of 2012/2013 school year, with the aim to investigate two possible applications of systemic synthesis questions, SSynQs: as instructional and assessment tools observing the construct of systems thinking in organic chemistry. In order to achieve this aim, the secondary school students were divided into two groups, one experimental (E: systemic classroom training) and one control (C: traditional classroom training). The final testing was conducting after instruction on three teaching themes: "Alcohols, phenols, ethers", "Carbonyl compounds" and "Carboxylic acids and their derivatives". The instrument for assessing students' systems thinking skills contained isomorphic and analogical SSynQs, while the results focused on E and C group students' percentage distribution through the four levels of systems thinking construct, as well as differences in their performances. Namely, the results obtained from both isomorphic and analogical SSynQs indicated that male and female students subjected to systemic classroom training developed systems thinking skills in more effective way than students from control group. Perceiving analogical SSynQs and gender as independent variable, the statistically significant difference appeared in E group within the most complex IV level of systems thinking, for the benefit of females. However, contrary to our previous research, E group male students were as much successful as female students in III level, and this finding led us to the conclusion that male students might benefit from longer lasting instruction with SSynQs. *[African Journal of Chemical Education—AJCE 7(3), Special Issue, October 2017]*

INTRODUCTION

In the science education literature it was noted that systems thinking is a very important higher-order thinking skill that students should develop, but simultaneously one of the most difficult to master [1]. Salisbury [2] defined systems thinking after observing the disadvantages of traditional science education. Science education at schools still concentrates on isolated concepts and facts [3] that are fragmented instead of linked with others and integrated in larger, meaningful wholes [4]. Thereby it is not possible to properly understand the new problem, or unit, by taking it apart and studding the characteristics of each concept individually. Hence, it was noted that such analytical approach should be complemented with synthetic approach and systems thinking [2].

Systems thinking has been mentioned in the many fields, and thereby received different meanings – from discipline to skill [5]. Salisbury [2] defined systems thinking as "discipline for seeing wholes". On the other hand, many authors agreed with the fact that systems thinking is a highly complex cognitive skill which includes the process of analyzing the system to its fundamental concepts, but also the synthesis of these concepts into a meaningful whole [1, 6]. For example, Burandt [5] considered systems thinking as a skill that allows individuals to better understand interdependencies and processes in the observed system.

Development of systems thinking with adequate instructional method is important [4] at each education level, but there is a need for valid and reliable instruments for its assessment too [3, 6]. In the literature, there are several different qualitative and quantitative tools for systems thinking assessment: video analysis, questionnaires, interviews [3, 7], drawings, and word associations [7]. Recently, systemic assessment questions, SAQs, were designed for this purpose [8-10], and applied in the empirical studies [see 6, 11-13].

Firstly, SAQs were proposed by Fahmy and Lagowski [14] within Systemic approach to teaching and learning chemistry (SATLC) as new objective test questions, or assessment schemas that belong to the broader group of concept mapping technique. Similarly, to concept maps, SAQs include two-dimensional spatial arrangement and representation of concepts and their interrelations [15]. However, there are some crucial differences between concept maps and SAQs. While concept maps have hierarchical structures, or arrangement of concepts, as the main characteristic [16], SAQs present closed, cyclic, interacting, and evolving conceptual structures – the "concept clusters", in which all existing relations between concepts are highlighted [6, 15, 17].

Depending on the number of concepts that are included in the assessment schema, SAQs were designed following several geometric shapes: triangular, quadrilateral, pentagonal, hexagonal, etc. Nodes correspond to the relevant concepts (Fig.1: Concepts A, B, C, D), while relations (Fig.1: labeled lines with x, y, z, w) between concepts are presented in clockwise or anticlockwise direction [8]. For example, concepts A, B, C and D could be organic compounds, while x, y, z, w (e.g. temperature, light, pressure, catalyst, reagent) explain relations between them [18].

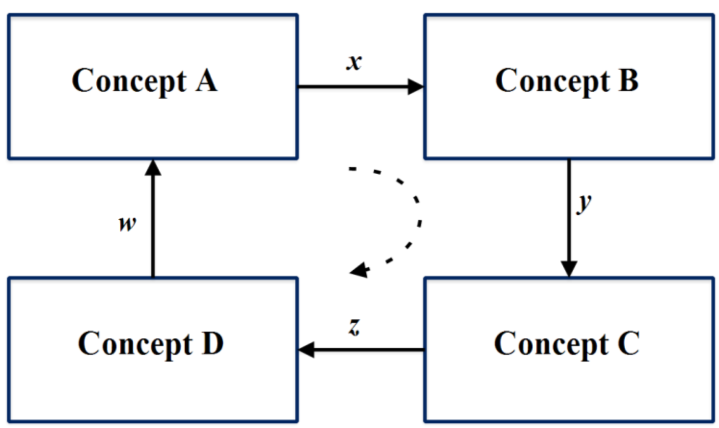

Fig. 1: SAQ with quadrilateral geometric shape and clockwise direction of relations (adjusted from [18, 19])

Fahmy and Lagowski [8] have proposed several types of SAQs: systemic true/false questions, STFQs, systemic multiple choice questions, SMCQs, systemic matching questions, SMQs, systemic sequencing questions, SSQs, systemic synthesis questions, SSynQs, and systemic analysis questions, SAnQs. In our studies, we have applied one specific type of SAQs: SSynQs. However, the differences between original version and our SSynQs can be observed in the request of the question:

i. In the original version, concepts that are parts of a particular SSynQ are mentioned in the request of the question, and students should build diagram by positioning these concepts in the right fields, and highlight relations among them [9];
ii. (ii) In our SSynQs students are required to perceive defined relationships and initial concept in unfilled, or partially filled SSynQ, to be able to identify concepts that are missing [18, 19]. Example of SSynQ is provided in "Methodology" section (Fig. 2 and 3).

Since the beginning of our research with SSynQs, our interest centered on developing and applying SSynQs as valid and reliable instructional and assessment tools for high school organic chemistry. Firstly, our focus was on students' meaningful understanding of organic chemistry [18, 19, 20], and recently we have paid more attention on systems thinking [12, 13]. In this particular study, the following main research question was defined:

- Are there statistically significant differences in students' achievements at defined four levels of systems thinking construct, observing groups (experimental/control) and gender (males/females) as independent variables?

METHODOLOGY

Participants

This study included 119 participants, 61 males (51.26%) and 58 females (48.74%), who were high school students (11th school year, 17-18 years old). Our experiment was conducted in four classes, in one urban high school in Novi Sad, Serbia.

In order to achieve the aim of this study, the experiment with two parallel groups: one experimental (E: systemic classroom training) and one control (C: traditional classroom training), was chosen. Namely, classes were divided into two experimental and two control classes, after equalization by students' average chemistry grades achieved at the end of first and second school years (E group: $M = 4.38$, $SD = 0.63$; C group: $M = 4.42$, $SD = 0.70$). Since the data was not normally distributed (Shapiro-Wilk test, E group: $W = 0.830$, $p = 0.000$; C group: $W = 0.790$, $p = 0.000$), a non-parametric Mann-Whitney test was applied to compare medians of the E and C groups. The results showed that there was no significant difference in average chemistry grades between the two groups (E group: $MR = 58.77$, $SR = 3820.00$; C group: $MR = 61.48$, $SR = 3320.00$, $U = 1675.00$, $p = 0.653$). Thus, formed E group consisted of 65 students and C group consisted of 54 students.

Study context and design

This study was conducted in the second semester of the 2012/2013 school year and students followed the organic chemistry course: "Organic compounds with oxygen". Three teaching themes were chosen as the material for this experiment:

- "Alcohols, phenols and ethers"
- "Carbonyl compounds"
- "Carboxylic acids and their derivatives".

Separate studies were conducted within each teaching theme, and each individual study contained two main phases. In the first phase, the two groups were treated equally, by the traditionally-oriented instructions of two chemistry teachers. The selected teachers both hold the Master's degree in Teaching of Chemistry, and have had approximately 10 years of experience working with high school students.

During the second phase, the E group students were taught in the systemic manner (application of SSynQs), in order to revise and practice what they have learned in the first phase. The authors of this paper prepared learning sheets with SSynQs for each teaching theme (examples are provided in [12, 20]), which required students to recognize relations highlighted on the arrows, as well as initial concepts, in unfilled and/or partially filled SSynQs. The teacher used a PowerPoint presentation, so that all the students might see the correct answer, which was presented by a video projector on white board.

At the same time, during the second phase, C group continued with traditionally-oriented instruction, solving conventional, linear questions (e.g. open-response, completion type, matching, and multiple-choice), in which only two concepts (e.g. two classes of organic compounds) might be linked.

After finishing the second phase of each particular study, the students were subjected to the testing. The results of assessing students' systems thinking skills were previously published for "Carbonyl compounds" [13] and "Carboxylic acids and their derivatives" [12]. However, at the end of this complex study, E and C groups students were subjected to the final testing in June 2013, and the results of the final testing will be presented in this paper.

Instrument for assessing students' systems thinking

The final test of knowledge contained nine questions: six linear questions (open-response, completion type, matching, and multiple-choice) and three SSynQs. However, in this paper, one isomorphic and two analogical SSynQs were observed as the instrument for assessing students' systems thinking skills.

At the beginning, it is worth mentioning that students from both E and C groups were familiar with SSynQs, as they were solving this type of questions during assessment process for mentioned three teaching themes: "Alcohols, phenols and ethers", "Carbonyl compounds", and "Carboxylic acids and their derivatives". Hence, there was no need for additional instructions before final testing, and students of both groups had 45 min (one school class) to solve the test.

Isomorphic SSynQ was identical with previously applied SSynQ, which was part of the instrument for assessing students' systems thinking skills for one specific teaching theme "Carboxylic acids and their derivatives" (presented in [12], p. 1462). This enabled us to conserve the strict isomorphism between the questions (SSynQs) from previous and final assessment instruments. An important fact to mention regarding the construction of the analogical SSynQs is that they were modified from their original version (version of the questions included in the previous assessment instruments), after students' first encounter with them. For example, SSynQ presented in Fig. 2 and 3 is analogical with SSynQ included in assessment instrument for "Carbonyl compounds" (presented in [13], p. 179). Thereby, the following changes were made:

- Selected representatives of ketones (original version: propanone; modified version: 3-methyl-2-butanone);
- Number of main fields, or concepts (original version: 6; modified version: 5; exclusion of one unstable product);

- Number and nature of relations (links between alkene and alkyne).

The analogical SSynQs were included in the assessment instrument in order to investigate if E and C groups students were able to more actively explore underlying and relatively new problems (SSynQs), and/or to more effectively identify concepts and relations that are relevant to question solutions, if they have some previous knowledge and experience in that sub-domain (according to [21]).

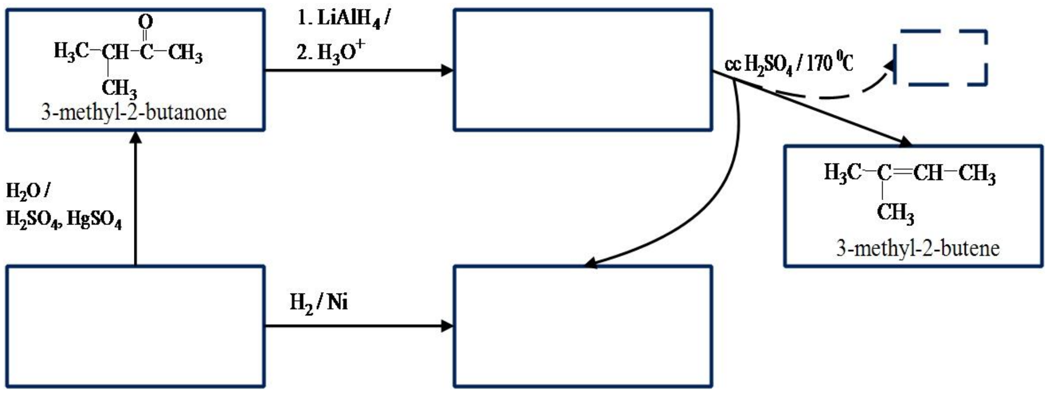

Fig. 2: SSynQ included in the assessment instrument as analogical question

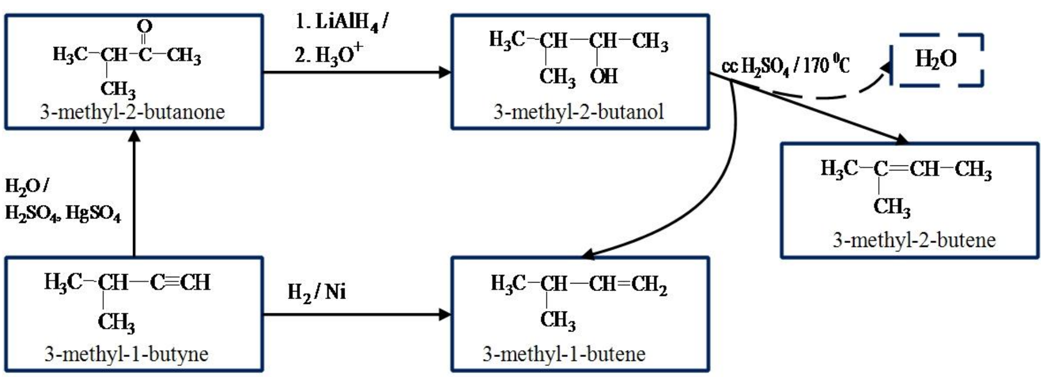

Fig. 3: Solution of SSynQ included in assessment instrument as analogical question

Scoring rubric for SSynQs is based on systems thinking construct. Contrary to original three-step scoring rubric with five systems thinking levels (proposed by Vachliotis et al. [11]), modified scoring rubric considered four levels [13], described in Table 1. According to the Table

1, each student could obtain maximally 4 points for isomorphic and 4 points for analogical SSynQs.

Table 1. Scoring rubric for SSynQs (adjusted from [13])

Level	Scores	Description
0	0	Lack of scientific knowledge; black fields in SSynQs, or irrelevant answers
I	1	Identifying the relevant, but unrelated concepts as individual parts of the sub-system, and/or system
II	2	Identifying semantically correct relations between two concepts of the systems (sub-systems)
III	3	Organizing (relating) more than two systems concepts in the larger conceptual sub-system
IV	4	Recognizing all concepts, relations and sub-systems by forming a meaningful whole – a system

RESULTS AND DISCUSSION

In order to examine students' performances at four levels of systems thinking, percentage distribution by group and gender was observed, separately for isomorphic (Fig. 4) and analogical SSynQs (Fig. 5). At the beginning, perceiving isomorphic SSynQ, it should be highlighted that all E group students managed to reach I level of systems thinking – identifying individual and conceptually unrelated concepts (Fig. 4). On the other hand, observing analogical SSynQs, the same could be said for E group female students, while 16% of male E group students did not reach I level of systems thinking in these questions (Fig. 5).

Additionally, 42.4% of C group male students and 45% of C group female students have not managed to reach I level of systems thinking while solving isomorphic SSynQ (they remained on 0 level). Similar percentages of C group students (52.4% males and 46% females) were not able to reach basic level of systems thinking in solving analogical SSynQs neither. According to this, it might be said that only about half of the C group students of both genders developed abilities to identify and present individual, fundamental concepts (compounds) in organic chemistry conceptual system.

Furthermore, the highest percentage of E group male students was characterized by prominent ability to correlate multiple concepts. Namely, according to their performances in SSynQs, 40% (isomorphic question) and 36% (analogical questions) of E group male students retained on III level of systems thinking (Fig. 4 and 5). These findings were in accordance with Vachliotis et al. [11], who also noted high number of students who reached III level of systems thinking, connecting three or more concepts and forming larger conceptual sub-systems. However, significantly lower percentage of E group male students reached expected IV level of systems thinking, which was especially noticeable in analogical SSynQs (only 12% of E group male students reached this level). Contrary, 52.6% E group female students have managed to reach the highest level of systems thinking while solving isomorphic SSynQs, or 36.9% while solving analogical SSynQs.

The results also showed a percentage decrease of male and female students in the defined levels of systems thinking within the C group. Hence, high percentage of students of both genders was positioned within “0 level” (Fig. 4 and 5), as they were not able to provide any answer, or the provided answers were incorrect in both isomorphic and analogical SSynQs. The lowest percentage of male and female C group students was observed in III and IV levels of systems thinking. For example, only 4.8% of male and 5% of female C group students reached IV level of systems thinking (i.e. interconnection of all concepts and sub-systems), while solving analogical SSynQs (Fig. 5).

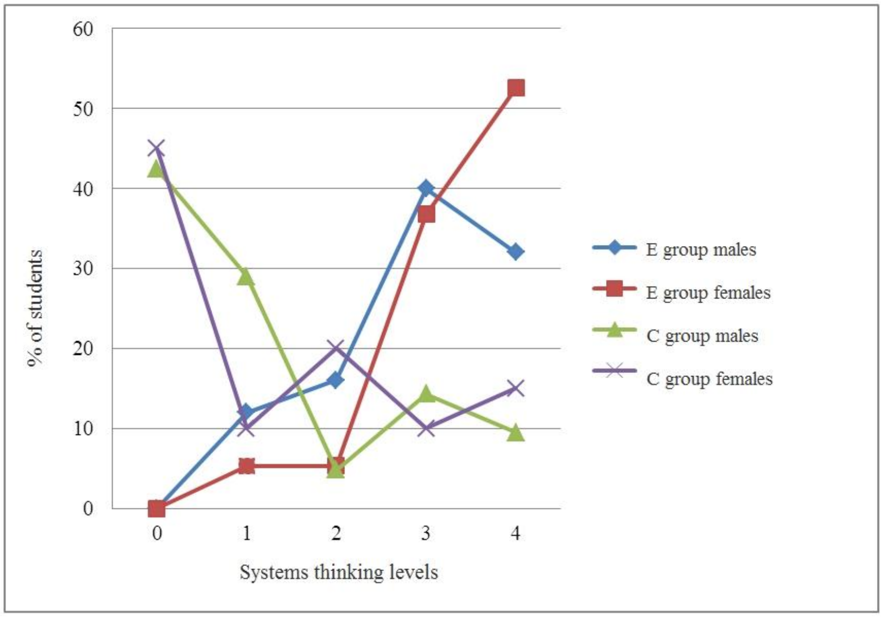

Fig. 4: Distribution of E and C group students through the systems thinking levels in isomorphic SSynQs

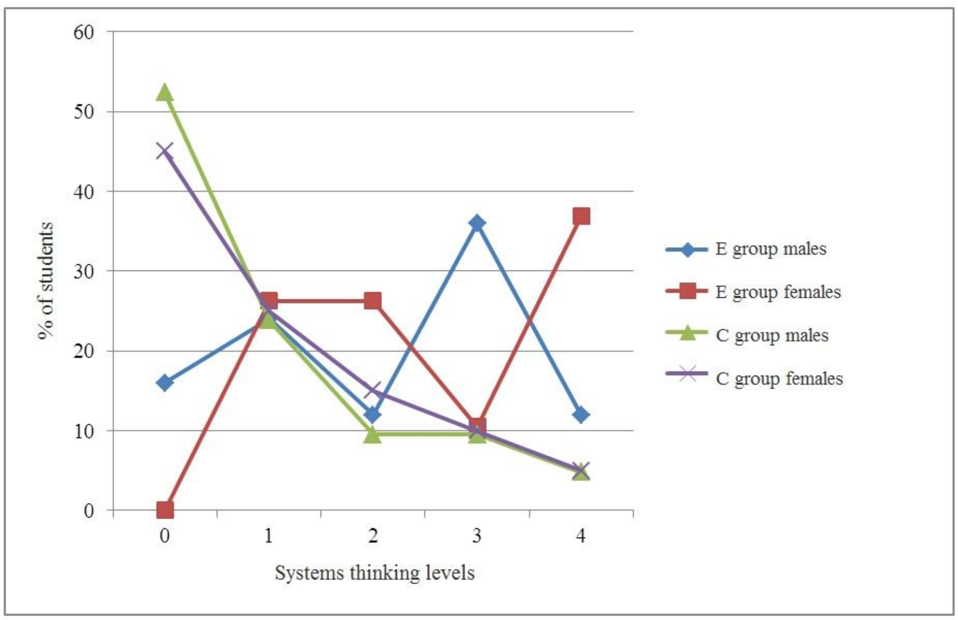

Fig. 5: Distribution of E and C group students through the systems thinking levels in analogical SSynQs

In order to statistically compare the E and C group students' performances in four levels of systems thinking the nonparametric Mann-Whitney test was done. The results for isomorphic SSynQ are presented in Table 2, while for analogical SSynQs in Table 3.

Observing students' performances at I, II, and III level of systems thinking, the results of conducted test showed the significant differences between E and C groups, for both genders. These results were found perceiving both isomorphic (Table 2) and analogical SSynQs (Table 3). Additionally, statistically significant difference did not appear between males and females neither within E, nor within C group students. According to this, it might be said that systemic approach in teaching and learning organic chemistry (i.e. solving SSynQs on classes) provided better opportunity for both male and female E group students to develop I, II and III level systems thinking skills, than traditional instructional method for both male and female C group students.

Furthermore, the results of E and C group students' performances on IV level of systems thinking are consistent with those previously analyzed (for I, II, and III levels), however only within isomorphic SSynQs. Within analogical SSynQs, it was found that E group females developed higher IV level systems thinking skills than E group males (Table 3: $U = 178.50$, $p = 0.044$, $p < 0.05$). While 36.9% of E group females managed to perceive complex interrelations among all the concepts (Fig. 5), only 12% of E group males were successful at this level of systems thinking. What more, statistically significant difference in IV level of systems thinking did not appear between E and C groups males (Table 3: M(Em)=12%, M(Cm)=4.8%, $U = 243.50$, $p = 0.391$, $p > 0.05$). These results are logical sequence of our previous study about application of SSynQs as instructional and assessment tools for students' systems thinking skills, observing "Carbonyl compounds" as teaching theme [13]. However, in our previous study, E group female students outperformed males in two levels of systems thinking: III level (identification of multiple, dynamic relations between concepts) and IV level (identification of most complex, cyclic relations between concepts) [13]. Perhaps, what is needed for male students in order to achieve greater benefit from systemic approach could be provided by longer lasting instruction with SSynQs. This might be reflected even in reaching the most desired and most complex IV level of systems thinking.

Table 2. Results of Mann-Whitney test for comparing performances of E and C groups students in defined levels of systems thinking observing isomorphic SSynQs

Systems thinking level	Performance					
	E(m)/E(f)		C(m)/C(f)		E(f)/C(f)	E(m)/C(m)
I	*M*(m)=100% *M*(f)=100%	*U*=237.50 *p*=1.000	*M*(m)=57.1% *M*(f)=55%	*U*=205.50 *p*=0.891	*U*=104.50 *p*=0.001*	U=150.00 *p*=0.000*
II	*M*(m)=88% *M*(f)=94.7%	*U*=221.50 *p*=0.447	*M*(m)=28.6% *M*(f)=45%	*U*=175.00 *p*=0.281	*U*=95.50 *p*=0.001*	U=106.50 *p*=0.000*
III	*M*(m)=72% *M*(f)=89.5%	*U*=196.00 *p*=0.159	*M*(m)=23.8% *M*(f)=25%	*U*=207.50 *p*=0.930	*U*=67.50 *p*=0.000*	U=136.00 *p*=0.001*
IV	*M*(m)=32% *M*(f)=52.3%	*U*=188.50 *p*=0.175	*M*(m)=9.5% *M*(f)=15%	*U*=198.50 *p*=0.597	*U*=118.50 *p*=0.014*	U=203.50 *p*=0.039*

Table 3. Results of Mann-Whitney test for comparing performances of E and C groups students in defined levels of systems thinking observing analogical SSynQs

Systems thinking level	Performance					
	E(m)/E(f)		C(m)/C(f)		E(f)/C(f)	E(m)/C(m)
I	*M*(m)=84% *M*(f)=100%	*U*=199.50 *p*=0.071	*M*(m)=47.6% *M*(f)=55%	*U*=194.50 *p*=0.641	*U*=104.50 *p*=0.001*	*U*=167.00 *p*=0.010*
II	*M*(m)=60% *M*(f)=73.7%	*U*=205.00 *p*=0.348	*M*(m)=23.8% *M*(f)=30%	*U*=197.00 *p*=0.659	*U*=107.00 *p*=0.007*	*U*=167.50 *p*=0.015*
III	*M*(m)=48% *M*(f)=47.4%	*U*=236.00 *p*=0.967	*M*(m)=14.3% *M*(f)=15%	*U*=208.50 *p*=0.949	*U*=128.50 *p*=0.031*	*U*=174.00 *p*=0.016*
IV	*M*(m)=12% *M*(f)=36.9%	*U*=178.50 *p*=0.044*	*M*(m)=4.8% *M*(f)=5%	*U*=209.50 *p*=0.972	*U*=129.50 *p*=0.015*	*U*=243.50 *p*=0.391

CONCLUSIONS

This study presented the results of the final testing of the experiment that lasted for the entire second semester of 2012/2013 school year, within secondary school organic chemistry. Observing systems thinking as four levels construct, the results of this study indicated that SSynQs might be applied in secondary school organic chemistry teaching as effective instructional and assessment tools.

Firstly, it is important to note that E group students, who were subjected to systemic classroom teaching, outperformed C group (traditional classroom teaching) in all four levels of systems thinking. These results are different from those published in [13], where all the students who participated in the study performed relatively high on the I level of systems thinking. One of the more important facts, which did not appear in our previous research [13], is that instruction with SSynQs could lead to the development of higher systems thinking skills (e.g. organizing and relating multiple systems concepts in the larger conceptual sub-system) within male students also, if they are provided with longer lasting systemic oriented instruction. Namely, statistically significant difference between E group males and females appeared only at the highest level of systems thinking (i.e. recognizing all concepts, relations and sub-systems by forming a meaningful whole – a system) in analogical SSynQs, where females outperformed males. Hence, longer lasting instructions with SSynQs that might result in development of higher-order thinking skills such as systems thinking, creative thinking, critical thinking, posing questions, formulating arguments [22] within both genders, are worth future investigation.

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