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Effect of virtual analytical chemistry laboratory on enhancing student research skills and practices

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This article aims to determine the effect of a virtual chemistry laboratory on university student achievement. The article describes a model of a laboratory course that includes a virtual component. This virtual component is viewed as a tool of student pre-lab autonomous learning. It presents electronic resources designed for a virtual laboratory and outlines the methodology of e-resource application. To find out how virtual chemistry laboratory affects student scientific literacy, research skills and practices, a pedagogical experiment has been conducted. Student achievement was compared in two learning environments: traditional – in-class hands-on – learning (control group) and blended learning – online learning combined with in-person learning (experimental group). The effectiveness of integrating an e-lab in the laboratory study was measured by comparing student lab reports of the two groups. For that purpose, a set of 10 criteria was developed. The experimental and control student groups were also compared in terms of test results and student portfolios. The study showed that the adopted approach blending both virtual and hands-on learning environments has the potential to enhance student research skills and practices in analytical chemistry studies.

Keywords: tertiary education; e-resources; blended learning; student achievement; computer simulation

Introduction

Information technology (IT) is being increasingly used and integrated in all areas of secondary and tertiary education. The use of technology can facilitate more student-centred and inquiry-based learning, and allow for a flipped classroom where content is covered outside of class and application and/or feedback occurs during class time (Bowen 2012; Esson 2016; Fitzgerald and Li 2015; Kubicek 2005). One of the ways in which IT has been employed in chemical education is using various technology tools for engagement and assessment, for example, Wiki, Moodle, Web 2.0, Blackboard (Ballesta-Claver *et al*. 2011; Biasutti and El-Deghaidy 2014; Farrell and Krause 2014; Franklin and Smith 2015; Morton and Uhomoibhi 2011), allowing to organise both asynchronous and synchronous modes of interaction. Electronic tools are feasible when designing interactive course textbooks (Nilsson *et al*. 2010), optimising different computational procedures (Young 2011), assessing learning outcome achievement and providing feedback.

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Laboratory course is an essential component of the university chemistry study. To which extent can technology be used when organising laboratory exercises, investigation and experiments? Laboratory work is a typical form of experiential learning. The role of experience in learning is well known. It is especially important in learning of the sciences. Learning models based on experience date back to the ideas of British empiricism and John Locke; John Dewey's philosophy of pragmatism; Jean Piaget's theory of cognitive development; David Kolb's experiential learning, etc. These models imply a concrete experience, an active laboratory experimentation, in which the learner 'touches all the bases' (Kolb, Boyatzis, and Mainemelis 2001, p. 22) and has a tactile contact with the object of study. Effective learning is seen when the learner progresses through a cycle of four stages: of (1) having a concrete experience followed by (2) observation of and reflection on that experience which leads to (3) the formation of abstract concepts (analysis) and generalisations (conclusions) which are then (4) used to test hypothesis in future situations, resulting in new experiences (Kolb, Boyatzis, and Mainemelis 2001).

At the same time, the organisation of chemical laboratory course at the university level and the design of laboratory experiments that are able to fulfil students' expectations and faculty goals pose some questions. These issues have been extensively discussed in publications of the Towns Research Group (Purdue University Department of Chemistry) and Bretz Research Group (Miami University). Numerous works have been devoted to the study of chemical laboratory course framed by Ausubel's assimilation theory of cognitive learning (Novak 1993, 2010) and meaningful learning (Bretz 2001). These studies revealed inconsistency between faculty goals, student expectations and learning outcomes across three domains of meaningful learning: affective (attitudes and emotions), psychomotor (physical skills) and cognitive (content knowledge growth) (Brandriet, Ward and Bretz 2013; Bruck, Towns and Bretz 2010; DeKorver and Towns 2016; Galloway and Bretz 2015a, 2015b).

An alternative learning environment, a virtual laboratory, seems to contribute to occurrence of meaningful learning. It is gaining popularity in many ways: there are numerous educational applications, computer-assisted physical and chemical simulations, copying natural phenomena and conditions of an experiment (Basher and Isa 2006; González-Gómez *et al.* 2015; Seeling 2010; Tatli and Ayas 2013).

The main tangible and intangible benefits of a virtual lab in addition to a physical one are the following.

First, the general view is that simulations and virtual labs are learner-centred and inquiry-based, which promotes higher levels of thinking and retention. It also allows students to receive immediate feedback and correct their faulty understanding of a concept (Smetana and Bell 2012; Stone 2007). However, the fact that physical labs can also reflect inquiry-based learning, for example, through applying the Science Writing Heuristic (SWH) approach (Burke, Greenbowe, and Hand 2006; Greenbowe *et al.* 2007; Rudd *et al.* 2001), cannot be overlooked.

Second, virtual laboratories are seen as a low cost solution for laboratory experiments. Experiments that would be too expensive (either cost of instrumentation or supplies), complicated or even dangerous to work with can be recreated safely in the virtual environment, thus bridging the gaps found in traditional laboratories (Achuthan and Murali 2015; Basher and Isa 2006). In addition, experimentation time significantly reduces and routine procedures of processing experimental results become less complex.

Third, remote labs are used as supplementary tools for complementing in-person laboratory education (Diwakar *et al.* 2016; Mejías Borrero and Andújar Márquez 2012), including virtual elements which interact with real ones, thus exposing students to blended learning. Students can work independently and at their own pace online, learn how to use chemicals and instruments and pre-plan an experiment before carrying it out in class (Borras-Linares *et al.* 2011).

Another benefit offers more possibilities to simulate and visualise quite a number of complex scientific concepts. Students increase their knowledge regarding unobservable molecular-level phenomena and acquire better conceptual understanding (Chiu, Dejaegher, and Chao 2015; Kollöffel and de Jong 2013; Shegog *et al.* 2012).

Finally, students become more positive towards using computers for learning. They find simulation of laboratory assignments motivating and creating a lot of experience. Simulation supports students in the accomplishment of cognitive tasks and enhances their learning processes (Josephsen and Kristensen 2006).

However, many comparison studies do not find any difference between physical and virtual experiments in terms of improved academic performance (De Jong, Linn, and Zacharia 2013; Jolley *et al.* 2016). Moreover, the use of e-labs in teaching and learning chemistry, analytical chemistry in particular, fails to meet the university needs, as most virtual chemical laboratories are created for secondary schools. Virtual labs that can be used for university courses are limited in number, mainly for teaching the so-called general chemistry (inorganic and organic).

Considering this limited application, e-labs cannot replace traditional laboratories but can respond to the existing challenges and optimise the learning process. Students can benefit from virtual laboratories when ‘learning about the real world’, as they acquire conceptual knowledge and develop science process skills (Finkelstein *et al.* 2005; Jaakkola, Nurmi, and Veermans 2011; Lampi 2013; Peffer *et al.* 2015; Yang and Heh 2007). Computer models and simulations, then, are treated as auxiliary cognitive tools to acquire experimental and analytical skills, and to develop an ability to interpret experimental results, especially during pre-lab lectures.

There is some evidence to suggest that only a balanced combination of physical and virtual laboratories can enhance science learning and encourage scientific practices (Chiu, Dejaegher, and Chao 2015; De Jong, Linn, and Zacharia 2013; Lei *et al.* 2015). Brinson (2015) reviews recent (post-2005) empirical studies that focus on comparing learning outcome achievement using traditional lab (TL; hands-on) and non-traditional lab (NTL; virtual and remote) participants as experimental groups. The findings show that 89% of the 50 reviewed studies demonstrate that student learning outcome achievement is equal or higher in NTL versus TL across all learning outcome categories (knowledge and understanding, inquiry skills, practical skills, perception, analytical skills and social and scientific communication).

The principal aim of this study is to determine the effect of a virtual chemistry laboratory on student achievement in the course entitled ‘Analytical Chemistry, Physical and Chemical Analysis’. The objectives of the article are as follows: It presents electronic resources designed for a virtual laboratory and outlines the methodology of e-resource application. Then the work assesses the effectiveness of virtual chemistry laboratory related to enhancing student scientific literacy, research skills and practices through a comparison with the traditional in-class format.

Methods

Course description

'Analytical Chemistry, Physical and Chemical Analysis' is a junior level undergraduate analytical chemistry course taught at the Ural State University of Economics (USUE) (Ekaterinburg, Russia). The course is required for bachelor-degree programs with majors in Commodities Management and Expertise; Food Processing Technology and Public Catering.

Sample

In total 50 students participated in our study. Participants were randomly assigned to two groups: experimental group ($n = 25$) and control group ($n = 25$). The experimental group was provided with a virtual lab-based inquiry learning environment created by the authors where students were able to perform experiments using the virtual chemistry laboratory before in-class experimental work. The control group was taught in a traditional – with instructor guidance only – format.

All students volunteered to participate in the experiment and the assessment process. They were curious to monitor their progress and receive feedback on their achievements. The experiment followed the procedures fully agreed upon with the participants including the issue of confidentiality.

E-learning resources design

The virtual lab included the use of computer-based learning environment that was developed through interdisciplinary project-based learning (IPBL) described in Stozhko *et al*. (2015) where IPBL is defined as activities performed by IT and chemistry students who were directly involved in the design of e-learning resources related to the simulation of chemical analysis procedures. However, the present article describes the application of IPBL in a different context: the students of the experimental groups were *not* participating in designing virtual laboratory exercises; they just used them as a learning resource.

Procedure

Students were provided with two learning environments: traditional in-class learning and blended learning – online learning combined with in-person learning. Traditional laboratory sessions are run as a series of prescriptive steps described in the manual which students have to follow in order to obtain some expected results. Laboratory sessions also include calculations, writing a lab report and final assessment.

The blended learning environment combines online learning and in-class instruction. The laboratory work includes a range of experience-based tasks. To accomplish these tasks, students have to apply their research skills under the guidance of the teacher. It is expected that students reflect upon their initial predictions, draw conclusions and make recommendations. Eventually these accomplishments will lead to some quantitative results and conclusions, which form new knowledge both for the student and the instructor. Following a prescribed layout, students then prepare a final report that is one of the assessment instruments. Other assessment tasks (interviews, tests), measuring student ability to run real research experiments, are performed either by the instructor or computer tested.

The virtual component is followed by a physical laboratory experiment. Students are expected to apply the skills they acquired during virtual experience. They set objectives, carry out measurements, receive and process the newly obtained results, come to conclusions and make recommendations in the same way as they did within the virtual environment. At the end of each in-class laboratory session, students are assessed by context-based tests.

Assessment and testing

The effectiveness of integrating an e-lab in the laboratory study was measured by comparing:

1. the lab reports of the experimental group students with the lab reports of the control group students;
2. in-class test results which aimed to assess student achievement of learning objectives (development of such skills as analysis of product quality, data interpretation and analysis, research skills);
3. student portfolios which were used to evaluate student learning progress and academic achievement over time.

All the data obtained (lab report assessment and test results) were managed with R-Studio and GraphPad Prism 7 software packages.

Experiment model

The model of the experiment was framed based on Piaget's theory of cognitive development and David Kolb' experiential learning and meaningful learning (Ausubel, Novak, Bretz). It also exploited the concept of a flipped class when the input was provided before the practical class. This input or preparedness for the laboratory exercise was different for the experimental and the control group.

The experiment aimed to provide answers to the following questions:

1. Is there a difference between the resulting applied knowledge and skills in the experimental group and in the control group?
2. Are there any differences in the content of students' laboratory reports in the experimental group and the control group?

The experiment has three stages: ascertaining, formative and summative. At the ascertaining stage, the two groups were put to a pre-lab test to compare students in terms of their relevant prior knowledge of chemistry and experimental (laboratory) experience. Then, all students performed traditional laboratory work and wrote lab reports. These results were important for comparing the two groups.

At the formative stage, the laboratory course was run in the traditional learning environment for the control group and in the 'blended' mode for the experimental group. Before each practical laboratory class, both experimental and control students were given equal time-on-task to get prepared for an in-class lab; thus, both groups exercised a ‘flipped classroom’, but with different content. The control group students studied the lab manuals; made notes on the main stages of the work and completed the tests from the manual. The experimental group was working with a virtual laboratory. On the one hand, the virtual element in the ‘blended’ mode is similar to students’ primary experience, providing the setting for a real experiment in the course of experiential learning. On the other hand, it is an intermediate step, when students’ expectations and the affective, psychomotor and cognitive learning goals may coincide. When the students of both groups came to the class, the lab instructor checked their preparedness for a physical experiment by interviewing students.

At the summative stage, both the control and experimental groups performed the same physical investigations. They presented their findings in laboratory reports which then were analysed by experts (instructors). Finally, context-based testing was used to assess both students groups in terms of analytical chemistry content knowledge and experiment skills.

Results and discussion

Laboratory course

The model of a virtual laboratory component of the experimental session is presented in Figure 1.

A virtual laboratory constitutes a component of a laboratory course for the experimental group students. By an e-lab, we understand software-based application designed for modelling real chemical processes, altering parameters and conditions under which a laboratory experiment is run. The virtual lab environment presents computer images of chemical reagents, glassware and instrumentation, which makes the virtual lab highly realistic. Students can work with this application independently in the out-of-class setting (e.g. at home) and try to accomplish a research task and come to some conclusions.

The virtual stage of the laboratory session aims to attain the same goals and objectives (research, practical and pedagogical) as the laboratory in-class work. However, the virtual component is different as it includes assignments integrated within the virtual lab environment, which were designed to structure student experimentation processes. The virtual component assists students in collecting, systematizing and interpreting empirical data.

The e-lab coursework is structured in such a way that each step is followed by the aim of a laboratory task, detailed instructions on how the task should be completed, what chemical formulas should be used, how graphs should be plotted and how findings should be interpreted. These comments foster students’ understanding of the task, acquisition of empirical experience and data interpretation.

During in-class laboratory sessions, the experiment group students used real instruments and real samples (e. g. toothpaste, juice), applying their virtual experience. Conclusions and recommendations formed an essential element of the experimental group students’ final reports. The control group students also wrote lab reports as part of the assessment process. They used the same layout of the report as the experimental group.

The virtual lab is designed on the basis of the computer-assisted learning (CAL) system (Stozhko, Tchernysheva, and Mironova 2014). It integrates software modules

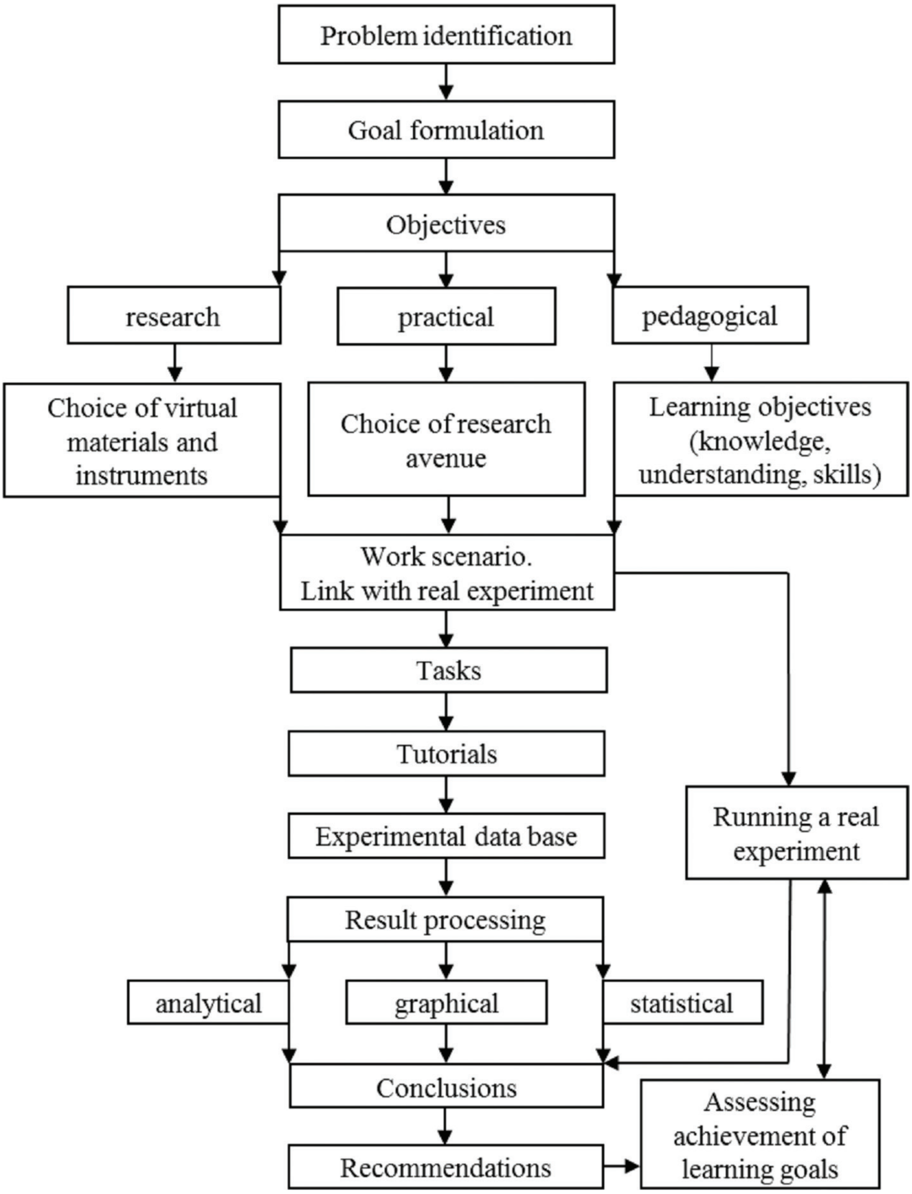

Figure 1. The model of a virtual component in the laboratory study.

designed for a range of purposes. Currently, there are over 30 modules, and their number is growing. Fourteen modules relate to the virtual laboratory. To illustrate how e-lab modules work, we will use three modules. The choice of these modules is attributed to at least two reasons. First, these modules deal with the products that are mass-consumed (toothpaste, candy, juice). Second, the methods of analysis used for these particular products are likely to be the most frequent methods students will encounter in their professional life.

Thus, the virtual component includes the following units:

- theoretical background (manuals with the description of analytical methods);
- preparation (calculation and weighing of samples, preparation of solutions and fixing of the exact concentration of titrant);
- instrumentation (work with virtual electronic scales and other instruments);
- operation (collection of empirical data);
- tabulation (construction of tables to show empirical data collected from virtual experiments);
- graphics (plotting on graphs);
- precision (measurement of precision);
- control (final test).

Animated images of instruments are developed with the use of detailed photos and video projections of real chemical instrumentation. Newsticker (or scrolling text) is used to control the sequence of operations during virtual titration. It displays digital and textual data explaining the values of the corresponding variables, for example, resistance (R) and volume (V) of the model object. Virtual tables show how the sample changes over time. Students use a 'mouse' to manipulate animated elements of the virtual lab.

Module 1. Using potentiometry for measuring mass fraction of fluoride ion in toothpastes

Students study the basic principles of potentiometry, familiarise themselves with the equipment and learn how to collect and process experimental data. Students study physical and chemical properties of toothpastes; learn what impact fluoride ions have on toothpaste features; and consider the problems associated with these features. Students get acquainted with a range of methods that can be used for chemical analysis of toothpastes; then compare these methods and justify their choice of the method; and formulate the purpose and objectives of the work. (Overall research, practical, and pedagogical objectives are stated in the manual).

Guided by the manual, students learn how to use laboratory instrumentation (electronic balance, pH meter-millivoltmeter) virtually and follow the procedure of the analysis. From a set of virtual samples, students choose an object of study, and conduct an experiment that simulates real chemical analysis. Then, they collect and process the data, and plot a calibrating curve (by using Microsoft Office Excel). Students analyse the obtained results and reach a conclusion. Finally, students write a report that should incorporate all the information. The virtual stage is completed with the test which enables to assess whether the student is able to conduct a real experiment. If the student has passed the test, he/she can now move on to a 'hands-on' experiment.

Module 2. Using photoelectrocolorimetry for measuring sugar content in candies

The experiment kit of a conductivity (photometric) plant includes a portable digital LCR-meter (to measure inductance, capacity and resistance), a photoelectrocolorimeter, a conductivity cell and a magnetic stirrer. The procedure is similar to the procedure in Module 1.

Module 3. Using potentiometric titration for measuring acidity in drinks

The module includes virtual digital scales, a potentiometric device (pH-meter-millivoltmeter), a potentiometric cell, a magnetic stirrer and a titrator. The procedure is as follows: the calculation and weighing of the primary standard sample (amber acid); preparation of virtual solutions (sodium hydroxide, amber acid); use of prepared solutions in virtual potentiometric titration; collecting empirical data during virtual titration of amber acid solutions and sample drinks (e.g. juices) with sodium hydroxide solution; and computer-based processing of the results of both virtual and physical experiments.

Results of the ascertaining stage

At the ascertaining stage, the students of the control and experimental groups had a pre-test aiming to measure students' prior knowledge of general chemistry. The pre-test had 25 multiple-choice questions. Students were required to choose two correct answers out of four to six alternatives, which, in our opinion, significantly decreased the chance of pure guesswork. Each correct answer added one point. The total maximum score was 50 points. All test results were analysed using a Shapiro–Wilk's W_s test (a test of normality), an F test of equality of variances and a Student's t test for means comparison. The results are shown in Table 1.

Based on the results shown in Table 1, the obtained values for W_s and $p_s > 0.05$ allow acceptance of the null hypothesis that there is normal distribution of grades in each group. The F test is less than the critical value, which means dispersion equivalence. The below critical values of the t test and $p_t > 0.05$ allow us to conclude that in terms of students' prior knowledge of general chemistry the groups showed no difference (a stronger statement about establishing equivalency of the groups cannot be made due to limitation of statistical power (Lewis and Lewis 2005).

At the ascertaining stage, both experimental and control students were completing the same physical laboratory exercises where the virtual component was not present. During the practical class, students were informed that they had to work on

Table 1. Pre-test results of the control and experimental groups at the ascertaining stage.

Parameter	Control group ($n = 25, v = 24$)		Experimental group ($n = 25, v = 24$)
M	31.92		30.88
σ	5.94		5.90
m	2.57		2.50
W_s ($W_{s\ critical} = 0.9186$)	0.9725		0.9517
p_s	0.7089		0.2737
F ($F_{critical} = 1.71$)		1.01	
t ($t_{critical.} = 2.011$)		0.557	
p_t		0.5804	

Notes: M is the average score; σ is the standard deviation; m is the error of the mean; W_s is the Shapiro–Wilk test experimental value; $W_{s\ critical} = 0.9186$ is W_s critical value; p_s value is calculated probability of the occurrence of normal distribution in groups; F is the experimental value of an F test; $F_{critical} = 1.71$ is the F test critical value from the use of $\alpha = 0.05$ for the sample size ($n_1 = n_2 = 25$); t is the experimental value of an t test; $t_{critical.} = 2.011$ is the t test critical value for degrees of freedom in the samples $v = 48$; p_t value is calculated probability of the occurrence of group equivalence.

lab reports and they were instructed what requirements their reports should meet. The requirements for report writing in fact repeated 10 criteria that experts developed to evaluate the quality of student reports. They are as follows:

1. scientific validity of goals and objectives;
2. clearly formulated objectives;
3. relevant description of methods and instruments;
4. critical approach, depth and logic of theoretical background;
5. ability to make measurements;
6. ability to process obtained results (including graphics);
7. ability to critically analyse obtained results, to describe abnormal or unexpected results;
8. ability to perform metrology procedures;
9. validity and clarity of conclusions; and
10. practicality and clarity of recommendations.

The criteria are of a qualitative nature. Each criterion was assigned by a group of five raters (experts) with a variable on the four-level scale: 'not expressed', 'poorly expressed', 'fairly expressed' and 'well expressed'. Statistical analysis of inter-rater agreement found substantial agreement (McHugh 2012). The raters also took into consideration student autonomy and creative approach to report writing. To ensure greater objectivity of the evaluation, reports of both groups were shuffled and letter-encoded by support staff (non-experts). After the raters (experts) rated the reports, the non-experts decoded the reports from both groups and transferred the experts' grades to tables with student names.

These tables were used for further expert analysis. The experts were to compare the reports of the experimental group participants with the reports of the control group students, and to measure the effect of instructional methods (virtual vs. traditional) on learning outcomes, specifically acquisition of research skills and practices and scientific reasoning. Table 2 summarises the results of the analysis of the experts.

Following the data from Table 2, the null hypothesis (H_0) was proposed that there is no difference between students' report writing skills in the experimental and control groups. To test H_0 and to ensure statistical validity of comparing students' reports, normality of distribution of experts' mean ranks in each of 10 criteria was tested. The use of the Shapiro–Wilks test failed to give positive results; hence, the Kruskal–Wallis test with Dunn's posttest for multiple comparisons was applied, which enables to limit the chance of type I error. The results are presented in Table 3.

As can be seen from Table 3, for all criteria, p_w value is greater than 0.9999, that is, statistically significant differences are not observed. On the basis of the Kruskal–Wallis test with Dunn's posttest, H_0 is accepted as true, which means the absence of differences between the experimental and the control groups with regard to students' report writing skills.

Results of the summative stage

The results of comparing student laboratory reports from the experimental and control groups based on 10 criteria at the summative stage are presented in Table 4.

Table 2. Comparison of student laboratory reports from the experimental and control groups at the ascertaining stage.

Criteria	Experimental group ($n = 25$, $v = 24$)			Control group ($n = 25$, $v = 24$)		
	M_{exp}	σ_{exp}	m_{exp}	M_{cont}	σ_{cont}	m_{cont}
1. Scientific validity of goals and objectives	2.53	0.29	0.12	2.57	0.24	0.11
2. Clear formulation of objectives	2.72	0.35	0.15	2.84	0.26	0.11
3. Relevant description of methods and instruments	2.91	0.34	0.14	2.91	0.33	0.14
4. Critical approach, depth and logical presentation of the theoretical part	2.60	0.27	0.11	2.55	0.30	0.12
5. Ability to make measurements	2.44	0.29	0.12	2.46	0.35	0.15
6. Ability to process obtained results (including graphics)	2.43	0.32	0.13	2.42	0.26	0.11
7. Ability to critically analyse obtained results, to describe abnormal or unexpected results	2.75	0.35	0.15	2.86	0.28	0.12
8. Ability to perform metrology procedures	2.57	0.20	0.09	2.66	0.24	0.10
9. Validity and clarity of conclusions	2.42	0.24	0.10	2.46	0.24	0.10
10. Practicality and clarity of recommendations	2.16	0.36	0.15	2.08	0.29	0.12

Notes: M_{exp} and M_{cont} are the experimental and control group means; σ_{exp} and σ_{cont} are the standard deviations; m_{exp} and m_{cont} are the errors of the mean; n is the sample size; v is degrees of freedom.

Table 3. Results of the Kruskal–Wallis test with Dunn's posttest for multiple comparisons with $\alpha = 0.05$ at the ascertaining stage.

Criteria[a]	MR_{exp}	MR_{cont}	MR diff	Significance	Adjusted p_w
1	237.6	252.9	−15.3	No	>0.9999
2	318.7	365.7	−47.0	No	>0.9999
3	381.6	376.2	5.4	No	>0.9999
4	254.6	238.7	15.9	No	>0.9999
5	213.5	203.7	9.8	No	>0.9999
6	189.3	191.6	−2.3	No	>0.9999
7	317.7	351.7	−34.0	No	>0.9999
8	235.1	292.7	−57.6	No	>0.9999
9	187.1	205.1	−18.0	No	>0.9999
10	109.3	87.2	22.1	No	>0.9999

Note: [a]The descriptions of criteria are given in Table 2; MR_{exp}, MR_{cont} are the mean ranks in the experimental and control group; MR diff is the difference between mean ranks.

Table 4. Comparison of student laboratory reports from the experimental and control groups at the summative stage.

Criteria[a]	Experimental group (n = 25, v = 24)			Control group (n = 25, v = 24)		
	M_{exp}	σ_{exp}	m_{exp}	M_{cont}	σ_{cont}	m_{cont}
1	3.59	0.25	0.11	3.15	0.31	0.13
2	3.74	0.23	0.09	3.63	0.26	0.11
3	3.58	0.25	0.10	3.21	0.27	0.11
4	3.69	0.25	0.10	3.58	0.34	0.14
5	3.59	0.27	0.11	3.34	0.30	0.12
6	3.61	0.25	0.11	3.45	0.25	0.10
7	3.56	0.29	0.12	3.49	0.34	0.14
8	3.57	0.26	0.11	3.30	0.29	0.20
9	3.60	0.28	0.11	3.30	0.30	0. 12
10	3.66	0.25	0.10	3.36	0.29	0.12

Notes: [a]The descriptions of criteria are given in Table 2.

M_{exp} and M_{cont} are the experimental and control group means; σ_{exp} and σ_{cont} are the standard deviations; m_{exp} and m_{cont} are the errors of the mean; n is the sample size; v is degrees of freedom.

Table 5. Results of the Kruskal–Wallis test with Dunn's posttest for multiple comparisons for $\alpha = 0.05$ at the summative stage.

Criteria[a]	MR_{exp}	MR_{cont}	MR diff	Significance	Adjusted p_{w}
1	288.7	112.5	176.2	Yes	0.0001
2	356.0	305.9	50.1	No	>0.9999
3	280.1	124.5	155.6	Yes	0.0011
4	334.4	288.7	45.7	No	>0.9999
5	292.2	178.6	113.6	Yes	0.0469
6	295.2	222.4	72.8	No	0.7005
7	276.0	249.9	26.1	No	>0.9999
8	278.6	161.0	117.6	Yes	0.0343
9	292.2	163.0	129.2	Yes	0.013
10	318.8	191.3	127.5	Yes	0.0152

Note: [a]The descriptions of criteria are given in Table 2; MR_{exp}, MR_{cont} are the mean ranks in the experimental and control group; MR diff is the difference between mean ranks.

As evident from Table 4, the students from the experimental group showed better results than the control group students on each criterion. The data related to statistical validity of these differences based on the Kruskal–Wallis test with Dunn's posttest for multiple comparisons can be found in Table 5.

It is apparent from Table 5 that the groups show statistically significant differences in some parameters. Students in the experimental group have outperformed students in the control group in terms of research skills and practices. Statistically significant differences were observed for criteria 1, 3, 5, 8, 9 and 10. Thus, the null hypothesis that there is no difference in laboratory report writing skills in the experimental and control groups was rejected and the alternative hypothesis that the experimental and control students are different in terms of report writing skills was proposed.

Table 6. The excerpts from laboratory[a] reports of the experimental and control student groups by selected criteria.

Criteria	Control group	Experimental group
Scientific validity of goals and objectives	*Goal:* to study the general concept of the method of potentiometric titration used for determining acidity in juices *Objectives:* (1) to determine titrate acidity in juice samples with different storage conditions (2) to compare the obtained results with maximum permissible concentrations	*Goal:* to study opportunities of the potentiometric method using titrable acidity of juices *Objectives:* (1) to identify the impact of storage conditions on juice acidity (2) to measure the quality of sampled juices in terms of safe-to-consume aspect
Relevant description of methods and instruments	pH-50 pH-meter-millivoltmeter; glass and silver chloride electrodes	pH-50 pH-meter-millivoltmeter, consisting of pH-150 current transducer, power supply unit and electrode system (glass and silver chloride electrodes) Measurement inaccuracy: - for the electrode system: ±5 mV - for the current transducer: ±0.02 - for pH meter: 0.05
Validity and clarity of conclusions	1. The method of potentiometric titration has been studied 2. Dependence of juice acidity on temperature and storage dates has been found	1. It has been found that the method of potentiometric titration allows to measure acidity of a variety of juices with the degree of precision that meets the existing standards 2. A degree of juice acidity grows with higher temperature within the studied range from 10° C to 30° C and similar storage dates

[a] The laboratory experiment title: Potentiometric titration: Determination of acidity in food products.

These differences are statistically significant with regard to the following specific abilities: clearly formulate research goals and objectives; describe methods and instruments; critically analyse obtained results; make valid conclusions; and offer practical recommendations. Table 6 provides some excerpts from students' lab reports, illustrating the differences found.

At the summative stage, context-based testing was used as an assessment tool of context-based learning. The latter aims to help students gain a better understanding of the world of science, appreciate the importance of chemistry in the modern world and see how it relates to people's lives (Bennett and Lubben 2006).

Thus, the tests included tasks that aimed to show how students can apply gained knowledge in their future professional experience, for example:

> *Choose the relevant method to analyse a product.*
> *Summarise key concepts behind analytical methods.*
> *Describe specifications of an instrument.*
> *Describe the procedure and the use of instruments.*
> *Calculate statistical errors.*
> *Determine key figures using the graph.*
> *Summarise conclusion and give recommendation.*

Similar to pre-tests at the ascertaining stage, these posttests consisted of 25 multiple-choice questions with 4–6 options, 2 of which are correct. The total maximum score is 50 points. Examples of tasks are given in Table 7.

The results of post-lab context-based testing are presented in Table 8. The data were analysed using Shapiro–Wilk's W test, F test and Student's t test.

It is apparent from Table 8 that W_s and $p_s > 0.05$ allow us to accept the null hypothesis about normal distribution of grades in each group. F is less than the critical value, which means dispersion equivalence. A greater than critical t value and $p_t < 0.05$ indicate that the two samples are different in terms of knowledge of analytical chemistry at the summative stage of the experiment.

Additional evidence for an advantageous use of an e-lab as an interactive learning tool was provided from student portfolios. A student portfolio is a collection of student work and includes different forms of educational evidence such as completed tests, lab reports and final assessments. As the staff members of the USUE Department of Physics and Chemistry have been working on developing e-learning resources including virtual chemical labs for many years, they use student portfolio to monitor how students grow, mature and improve over the whole 4-year bachelor-degree program. Our observation showed that those students who experienced chemistry blended learning (virtual environment + traditional environment) had more evidence of academic or scientific accomplishment such as research articles and projects, conference presentations, in their portfolios (e.g. projects 'What kind of water do we drink?' and 'Eco-analytical monitoring of snow in Ural cities' presented at 2014 Eurasia Green Contest; projects 'Life without oxidative stress', 'Secrets of tea chemical composition', 'New methods of measuring the quality of mineral waters' and 'Analysing vegetables for nitrate ions with the use of analytical software' presented at the International Contest of Young Researchers' and Students' Projects (2013, 2014, 2015 and 2017). This monitoring allows us to make some arguments for a positive impact of portfolio on students' research skills.

Online resources may incentivise students to study chemistry and other natural sciences, and professional subject areas, such as metrology and standardisation, commodities management and food processing technology. Virtual learning environment can also contribute to better (compared to their peers who study in a traditional way) assessment results, and enhanced written and oral communication skills. As inquiry-based labs provide students with exposure to authentic science, they might get more willingly involved in real research projects that require application of the analytical chemistry knowledge and target the biggest issues of today: environmental, technological and social (quality of life).

It is worth noting that exposure to e-resources could improve student facility in using virtual workspaces and information and communication technology literacy. This might help students overcome the problems they often encounter when

Table 7. Samples of context-based test tasks.

<table>
<tr><th>Task</th><th>Options[a]</th></tr>
<tr><td>Which two methods should be used to measure antioxidant properties of food products (fruits, vegetables, teas, juices, wines, etc.) considering the ability of antioxidants to enter into a redox reaction with ROS?</td><td>1. Radiochemical
2. *Potentiometric*
3. Chromatographic
4. *Coulometric*
5. Spectroscopic</td></tr>
<tr><td>To analyse toothpastes for fluoride ions, 0.5 g of two samples of two toothpastes were dissolved in a small volume of diluted sulphuric acid, and heated in a water bath for 1 h. Then the volume was increased to 100 mL. The concentration of fluoride ions measured with potentiometry was 19 mmol/L (Sample 1) and 38 mmol/L (Sample 2). Choose two statements that conform to the state standard (GOST 7983-99) requirements for the value of fluoride ions in toothpastes (i.e. range from 0.005% to 0.15% of weight per moral mass).</td><td>1. *Sample 1 meets the standard*
2. *Sample 2 meets the standard*
3. Sample 1 does not meet the standard
4. Sample 2 does not meet the standard</td></tr>
<tr><td>To identify the type of mineral water (carbonate or hydrocarbonate) potentiometric titration against HCl solution is used with the record of all titration steps. How many titration steps are observed in carbonate and hydrocarbonate mineral water? Choose two correct answers.</td><td>1. None in hydrocarbonate water
2. None in carbonate water
3. *One in hydrocarbonate water*
4. One in carbonate water
5. Two in hydrocarbonate water
6. *Two in carbonate water*</td></tr>
<tr><td>Which two-electrode system is used to measure acidity (pH) in juices with potentiometry?</td><td>1. *Glass*
2. Glassy-carbon
3. Gold
4. Platinum
5. *Silver chloride*</td></tr>
<tr><td>Potentiometry was used to determine thermal stability of the milk sample by Ca^{2+} concentration, using the following tabulated data:
<table>
<tr><th>Milk quality</th><th>Ca^{2+} mg%</th></tr>
<tr><td>Highly thermally stable</td><td><9.5</td></tr>
<tr><td>Average thermally stable</td><td>9.5–10.5</td></tr>
<tr><td>Thermally unstable</td><td>>10.5</td></tr>
</table>
The obtained Ca^{2+} concentration was 9.4 mg%. To validate the obtained results, a small volume of alcohol was added to the milk sample. After stirring, the absence of white flakes was observed. Analyse the received result. Complete the conclusion choosing two appropriate words from the alternatives:
Conclusion:
This milk sample is highly thermally stable which ………….. by the alcohol test that ……….. be used for determining thermal stability of milk.</td><td>1. *is justified*
2. is not justified
3. *can*
4. cannot</td></tr>
</table>

[a]Correct answers are *italicised.*

Table 8. Posttest results of the experimental and control groups at the summative stage.

Parameter	Control group ($n = 25$, $v = 24$)	Experimental group ($n = 25$, $v = 24$)
M	34.8	39.2
σ	5.20	5.02
m	2.20	2.17
W_s	0.9576	0.9510
$W_{s\ \text{critical}} = 0.9186$		
p_s	0.3679	0.2643
F	1.028	
$F_{\text{critical}} = 1.71$		
t	2.642	
$t_{\text{critical.}} = 2.011$		
p_t	0.011	

Notes: M is the average score; σ is the standard deviation; m is the error of the mean; W_s is the Shapiro–Wilk test experimental value; $W_{s\ \text{critical}} = 0.9186$ is W_s critical value; p_s value is calculated probability of the occurrence of normal distribution in groups; F is the experimental value of an F test; $F_{\text{critical}} = 1.71$ is the F test critical value from the use of $\alpha = 0.05$ for the sample size ($n_1 = n_2 = 25$); t is the experimental value of a t test; $t_{critical.} = 2.011$ is the t test critical value for degrees of freedom in the samples $v = 48$; p_t value is calculated probability of the occurrence of group equivalence.

developing strategies of working with virtual resources (Gal *et al.* 2015; Stozhko, Stozhko, and Shilovtsev 2016), and enable them to cross-apply their IT skills in other learning and research domains. Individual students, as mentioned above, participated in the development of e-resources for chemistry studies as part of IPBL.

Our initial observation suggests that a virtual laboratory environment may ensure more meaningful student learning. It could also provide students with the opportunity to develop their research skills and practices.

Conclusions

It is a widely held view that an e-lab is an effective pre-physical laboratory training tool as it allows students to develop skills required for conducting hands-on experiments. There are some cases when the use of an e-lab is preferred or is the only possible way of teaching and learning, for example, distance learning and the impossibility to conduct a physical chemical experiment (lack of equipment, safety concerns, time constraints). In addition, an e-lab is an effective pre-class training tool that can be used prior to physical laboratory experiment as it allows students to practice necessary skills. These advantages of the virtual workshop have been reported and acknowledged.

Since the main aim of the present work was to determine the effect of a virtual chemistry laboratory on student achievement in the analytical chemistry course, it presented the use of original software-based resources in the virtual laboratory module format. Our research indicates that virtualised resources can be adopted as a supplementary and supportive element in tertiary education. We found out that a virtual laboratory experiment that is coordinated with practical laboratory assignments may certainly be a valuable teaching and student engagement tool. A virtual laboratory might contribute to developing student scientific literacy and an appreciation for chemistry's place in society. It might also provide hands-on experience with chemical phenomenon and build a fundamental understanding of chemical concepts. Combinations of virtual and physical laboratories offer advantages of attainting learning objectives.

However, the authors acknowledge that the present study has certain limitations. First, our experiment was conducted with only one set of control and experimental students. Second, our sample size is insufficient (due to the number of enrolled students, 50 = one academic group) to generalise the study's findings beyond the study groups. To overcome these limitations, future work is planned aiming to enlist more participants, to collect more evidence and to make findings more representative.

We also hope that sharing our research findings might trigger further study of the impact of virtual laboratories and their use in science education.

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References

Achuthan, K. & Murali, S. S. (2015) 'A comparative study of educational laboratories from cost & learning effectiveness perspective', *Advances in Intelligent Systems and Computing*, vol. 349, pp. 143–153.

Ballesta-Claver, J., *et al.*, (2011) 'Using web 2.0 tools to support university teaching in chemistry: the new way', *4th International Conference of Education, Research and Innovation (ICERI*), Madrid, Spain, pp. 27–32.

Basher, H. A. & Isa, S. A. (2006) 'On-campus and online virtual laboratory experiments with LabVIEW', *IEEE SoutheastCon*, Memphis, TN, pp. 325–330.

Bennett, J. & Lubben, F. (2006) 'Context-based chemistry: the Salters approach', *International Journal of Science Education*, vol. 28, no. 9, pp. 999–1015.

Biasutti, M. & El-Deghaidy, H. (2014) 'Interdisciplinary project-based learning: an online wiki experience in teacher education', *Technology, Pedagogy and Education*, vol. 24, no. 3, pp. 1–17.

Borras-Linares, I., *et al.*, (2011) 'Development of a virtual laboratory experiment for chemistry students', *3rd International Conference on Education and New Learning Technologies (EDULEARN*), Barcelona, Spain, pp. 3134–3139.

Bowen, J. A. (2012) *Teaching Naked: How Moving Technology Out of Your College Classroom Will Improve Student Learning*, Jossey-Bass, San Francisco, CA.

Brandriet, A. R., Ward, R. M. & Bretz, S. L. (2013) 'Modeling meaningful learning in chemistry using structural equation modeling', *Chemistry Education Research and Practice*, vol. 14, no. 4, pp. 421–430.

Bretz, S. L. (2001) 'Novak's theory of education: human constructivism and meaningful learning', *Journal of Chemical Education*, vol. 78, no. 8, p. 1107.

Brinson, J. R. (2015) 'Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: a review of the empirical research', *Computers & Education*, vol. 87, pp. 218–237.

Bruck, L. B., Towns, M. & Bretz, S. L. (2010) 'Faculty perspectives of the undergraduate chemistry laboratory: goals and obstacles to success', *Journal of Chemical Education*, vol. 87, no. 12, pp. 1416–1424.

Burke, K. A., Greenbowe, T. J. & Hand, B. M. (2006) 'Implementing the Science Writing Heuristic in the chemistry laboratory', *Journal of Chemical Education*, vol. 83, no. 7, p. 1032.

Chiu, J. L., Dejaegher, C. J. & Chao, J. (2015) 'The effects of augmented virtual science laboratories on middle school students' understanding of gas properties', *Computers and Education*, vol. 85, pp. 59–73.

De Jong, T., Linn, M. C. & Zacharia, Z. C. (2013) 'Physical and virtual laboratories in science and engineering education', *Science*, vol. 340, no. 6130, pp. 305–308.

DeKorver, B. K. & Towns, M. H. (2016) 'General chemistry students' goals for chemistry laboratory coursework', *Journal of Chemical Education*, vol. 92, no. 12, pp. 2031–2037.

Diwakar, S., *et al*., (2016) 'Complementing education via virtual labs: implementation and deployment of remote laboratories and usage analysis in South Indian villages', *International Journal of Online Engineering*, vol. 12, no. 3, pp. 8–15.

Esson, J. M. (2016) 'Flipping general and analytical chemistry at a primarily undergraduate institution', in *The Flipped Classroom Volume 2: Results from Practice*, eds J. Muzyka & C. Luker, pp. 107–125. ACS Symposium Series; American Chemical Society: Washington, DC

Farrell, S. & Krause, S. (2014) 'A virtual community of practice to support faculty efforts to adopt research-based instructional approaches', *2014 International Conference on Interactive Collaborative Learning, ICL 2014*, Dubai, United Arab Emirates, pp. 845–848.

Finkelstein, N. D., *et al*., (2005) 'When learning about the real world is better done virtually: a study of substituting computer simulations for laboratory equipment', *Physical Review Special Topics-Physics Education Research*, vol. 1, no. 1, pp. 010103(1–8).

Fitzgerald, N. & Li, L. (2015) 'Using presentation software to flip an undergraduate analytical chemistry course', *Journal of Chemical Education*, vol. 92, no. 9, pp. 1559–1563.

Franklin, R. & Smith, J. (2015) 'Practical assessment on the run: iPads as an effective mobile and paperless tool in physical education and teaching', *Research in Learning Technology*, [online] Available at: http://dx.doi.org/10.3402/rlt.v23.27986

Gal, Y., *et al*., (2015) 'Making sense of students actions in an open-ended virtual laboratory environment', *Journal of Chemical Education*, vol. 92, no. 4, pp. 610–616.

Galloway, K. R. & Bretz, S. L. (2015a) 'Measuring meaningful learning in the general chemistry and organic chemistry laboratories: a longitudinal study', *Journal of Chemical Education*, vol. 92, no. 12, pp. 2019–2030.

Galloway, K. R. & Bretz, S. L. (2015b) 'Measuring meaningful learning in the undergraduate chemistry laboratory: a national, cross-sectional study', *Journal of Chemical Education*, vol. 92, no. 12, pp. 2006–2018.

González-Gómez, D., *et al*., (2015) 'A comprehensive application to assist in acid-base titration self-learning: an approach for high school and undergraduate students', *Journal of Chemical Education*, vol. 92, no. 5, pp. 855–863.

Greenbowe, T. J., *et al*., (2007) 'Using the Science Writing Heuristic in the general chemistry laboratory to improve students' academic performance', *Journal of Chemical Education*, vol. 84, no. 8, pp. 1371.

Jaakkola, T., Nurmi S. & Veermans, K. (2011) 'A comparison of students' conceptual understanding of electric circuits in simulation only and simulation-laboratory contexts', *Journal of Science Education and Technology*, vol. 48, no. 1, pp. 71–93.

Jolley, D. F., *et al*., (2016) 'Analytical thinking, analytical action: using prelab video demonstrations and e-quizzes to improve undergraduate preparedness for analytical chemistry practical classes', *Journal of Chemical Education*, vol. 93, no. 11, pp. 1855–1862.

Josephsen, J. & Kristensen, A. K. (2006) 'Simulation of laboratory assignments to support students' learning of introductory inorganic chemistry', *Chemistry Education Research and Practice*, vol. 7, no. 4, pp. 266–279.

Kolb, D. A., Boyatzis, R. E. & Mainemelis, C. (2001) 'Experiential learning theory: previous research and new directions', *Perspectives on Thinking, Learning, and Cognitive Styles*, vol. 1, pp. 227–247.

Kollöffel, B. & de Jong, T. (2013) 'Conceptual understanding of electrical circuits in secondary vocational engineering education: combining traditional instruction with inquiry learning in a virtual lab', *Journal of Engineering Education*, vol. 102, no. 3, pp. 375–393.

Kubicek, J. P. (2005) 'Inquiry-based learning, the nature of science, and computer technology: new possibilities in science education', *Canadian Journal of Learning and Technology*, vol. 31, no. 1, [online] Available at: http://cjlt.csj.ualberta.ca/index.php/cjlt/article/view/149/142

Lampi, E. (2013) *The Effectiveness of Using Virtual Laboratories to Teach Computer Networking Skills in Zambia*, Doctoral dissertation, Virginia Polytechnic Institute and State University, Virginia, [online] Available at: https://vtechworks.lib.vt.edu/bitstream/handle/10919/22013/Lampi_E_D_2013.pdf?sequence=1

Lei, Z., *et al*., (2015) 'A DC motor position control system in a 3D real-time virtual laboratory environment based on NCSLab 3D', *International Journal of Online Engineering,* vol. 11, no. 3, pp. 49–55.

Lewis, S. E. & Lewis, J. E. (2005) 'The same or not the same: equivalence as an issue in educational research', *Journal of Chemical Education*, vol. 82, no. 9, pp. 1408–1412.

McHugh, M. L. (2012) 'Interrater reliability: the kappa statistic', *Biochemia Medica*, vol. 22, no. 3, pp. 276–282.

Mejías Borrero, A. & Andújar Márquez, J. M. (2012) 'A pilot study of the effectiveness of augmented reality to enhance the use of remote labs in electrical engineering education', *Journal of Science Education and Technology*, vol. 21, no. 5, pp. 540–557.

Morton, W. & Uhomoibhi, J. (2011) 'E-laboratory design and implementation for enhanced science, technology and engineering education', *Campus-Wide Information Systems*, vol. 28, no. 5, pp. 367–377.

Nilsson, G., *et al*., (2010) 'A web-based spectroscopy tutorial for the inorganic chemistry laboratory', *Journal of Chemical Education,* vol. 87, no. 7, pp. 758–759.

Novak, J. D. (1993) 'Human constructivism: a unification of psychological and epistemological phenomena in meaning making', *International Journal of Personal Construct Psychology,* vol. 6, no. 2, pp. 167–193.

Novak, J. D. (2010) 'Learning, creating, and using knowledge: concept maps as facilitative tools in schools and corporations', *Journal of e-Learning and Knowledge Society*, vol. 6, no. 3, pp. 21–30.

Peffer, M. E., *et al*., (2015) 'Science classroom inquiry (SCI) simulations: a novel method to scaffold science learning', *PLoS One*, vol. 10, no. 3, [online] Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0120638

Rudd, J. A., *et al*., (2001) 'Using the Science Writing Heuristic to move toward an inquiry-based laboratory curriculum: an example from physical equilibrium', *Journal of Chemical Education*, vol. 78, no. 12, pp.1680–1686.

Seeling, P. (2010) 'Work in progress: portable student labs implementation', *Proceedings-- Frontiers in Education Conference (FIE)–* Arlington, VA, pp. F2F1–F2F3.

Shegog, R., *et al*., (2012) 'Virtual transgenics: using a molecular biology simulation to impact student academic achievement and attitudes', *Research in Science Education*, vol. 42, no. 5, pp. 875–890.

Smetana, L. K. & Bell, R. L. (2012) 'Computer simulations to support science instruction and learning: a critical review of the literature', *International Journal of Science Education*, vol. 34, no. 9, pp. 1337–1370.

Stone, D. (2007) 'Teaching chromatography using virtual lab exercises', *Journal of Chemical Education*, vol. 84, no. 9, pp. 1488–1496.

Stozhko, D. K., Stozhko, K. P. & Shilovtsev, A. V. (2016) *Social Security of the Person in the Information Society: Theoretical and Methodological Aspect*, [in Russian], Ural State Agricultural University, Ekaterinburg.

Stozhko, N., *et al*., (2015) 'Interdisciplinary project-based learning: technology for improving student cognition', *Research in Learning Technology*, vol. 2, p. 27577, [online] Available at: http://dx.doi.org/10.3402/rlt.v23.27577

Stozhko, N., Tchernysheva, A. & Mironova, L. (2014) 'Computer assisted learning system for studying analytical chemistry', *Chemistry*, vol. 23, no. 4, pp. 607–613.

Tatli, Z. & Ayas, A. (2013) 'Effect of a virtual chemistry laboratory on students' achievement', *Educational Technology & Society*, vol. 16, no. 1, pp. 159–170.

Yang, K. Y. & Heh, J. S. (2007) 'The impact of internet virtual physics laboratory instruction on the achievement in physics, science process skills and computer attitudes of 10th-grade students', *Journal of Science Education and Technology*, vol. 16, no. 5, pp. 451–461.

Young, V. Y. (2011) 'Using Texas instruments emulators as teaching tools in quantitative chemical analysis', *Journal of Chemical Education*, vol. 88, no. 10, pp. 1442–1443.