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DEVELOPMENT ARTICLE

Effects of a concept mapping-guided virtual laboratory learning approach on students' science process skills and behavioral patterns

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Abstract
Laboratory courses can help students learn in a meaningful way. In the past, students encountered difficulties in chemistry laboratory courses due to limited access to equipment and space for practicing experimental operations. In recent years, virtual laboratories have allowed students to repeatedly practice in order to achieve their experimental goals. However, even when students follow the experimental protocol, some still cannot fully understand the principles and meaning of the experimental procedures. Therefore, when they encounter unexpected situations in experiments, they may not know how to handle them. Thus, this study incorporated a concept mapping-guided learning approach to facilitate students' understanding of the concepts of the experimental process and the relationship between experimental procedures before virtual laboratory practice. Using a quasi-experimental approach, 51 middle school students aged 12 to 13 years were assigned to an experimental group ($M=12$, $F=14$) using the concept mapping-guided virtual laboratory learning approach, and a control group ($M=12$, $F=13$) using the conventional virtual laboratory learning approach. The experimental group improved their science process skills, problem-solving awareness, and creative thinking tendency. Teachers can employ guided virtual laboratory learning approaches to help students experiment and understand concepts.

Keywords Concept map · Virtual laboratory · Chemistry education · Experimental procedure · Secondary education

Introduction

One of the objectives of chemistry education is to facilitate meaningful learning so that students can correctly grasp the basic concepts of chemistry to solve problems in new situations (Ghani et al., 2017). Norris and Philips (2012) stated that chemistry education emphasizes the ability of students to think critically and reflectively in the process of learning chemistry. Scholars (Anderson, 1983; Hong et al., 2018; Sariscsany & Pettigrew, 1997; Stevenson, 1998) have pointed out that the main categories of chemistry are declarative knowledge and procedural knowledge. Declarative knowledge is domain

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specific and consists of meaningful links between facts, theories, names, relationships, and representative concepts, while procedural knowledge includes the effective implementation of skills and strategies. In the past, chemistry teachers taught through lectures to help students remember and understand descriptive knowledge. Furthermore, procedural knowledge learning is based on descriptive knowledge and is trained through experimental training skills (Hong et al., 2018). Chemistry experiments can develop students' understanding of science content process skills and increase their self-confidence, problem-solving skills, and higher-order cognitive skills (Ural, 2016; Wahyuni & Analita, 2017). Garnett et al. (1995) considered that experimental operations would help improve students' conceptual understanding, application skills, and techniques, and their ability to analyze intervariable relationships and chemical analysis-synthesis. Mandasari et al. (2021) found that higher proficiency in laboratory process skills was associated with higher achievement in academic achievement, so laboratory skills are correlated with achievement. Baseya and Francis (2011) noted that the use of appropriate experimental teaching strategies could develop students' science process skills and understanding of scientific principles.

Ural (2016) claimed that the traditional laboratory type is known as the "expository laboratory," "cookbook style laboratory," or "verification laboratory." Donaldson and Odom (2001) indicated that in a traditional laboratory students' ability to follow instructions is considered, rather than their ability to ask questions, design, implement, and analyze experiments. Laboratory work is an inseparable component of understanding the chemistry curriculum (Tatli & Ayas, 2013). Previous studies have mentioned that laboratory work could not be adequately integrated into the traditional chemistry curriculum due to safety issues and the time and effort required to perform accurate experiments (Durmus & Bayraktar, 2010; Tatli & Ayas, 2013). Consequently, virtual laboratories are considered educational environments for real-life experimental alternatives (Wu et al., 2019). In addition, virtual laboratories can provide students with opportunities to enrich their learning experiences, to conduct experiments as if they were in a real laboratory, and to improve their experiment-related skills such as manipulating materials and equipment, collecting data, interactively completing experimental procedures, and preparing experimental reports (Subramanian & Marsic, 2001; Usman & Huda, 2021). Previous studies have reported that virtual environments increased students' motivation for courses through peer support and discussion platforms for students and instructors (Geban et al., 1992; Kubala, 1998). Hofstein and Lunetta (2004) identified that laboratory operations are necessary for science teaching, and noted that there was insufficient hands-on guidance from teachers, and therefore students did not have a good grasp of the experimental procedures during the experiments. This implies the need to provide additional assistance or tools to enable students to have a global view of experimental procedures when learning with virtual laboratories.

Concept maps (CM) have been identified as an effective cognitive tool for helping learners organize knowledge and perceive learning content or tasks from a macro view (Cui & Yu, 2019; Zhao et al., 2022); they have both expository (Wong & Lim, 2021) and procedural characteristics (Nakiboglu, 2017). Declarative knowledge requires explanation, while procedural knowledge comprises organized procedures, and these steps organize concepts in a hierarchical structure (Ismono et al., 2019). Makransky et al. (2019) showed that learners' cognitive overload may hinder effective learning in virtual environments (Winkelmann et al., 2017). Therefore, providing instructional support can manage this cognitive load more effectively and can assist learners when needed (Chan et al., 2021). Therefore, in this study, a concept mapping-based virtual laboratory (CM-VL) approach is proposed to guide students to practice experimental procedures. Moreover, an experiment was conducted to explore the effects of the CM-VL approach in a chemistry course to respond to the following research questions.

(1) Is the CM-VL learning approach significantly different in terms of student learning achievement compared to the conventional VL learning approach?
(2) Is the CM-VL learning approach significantly different in terms of students' science process skills compared to the conventional VL learning approach?
(3) Is the CM-VL learning approach significantly different in terms of students' problem-solving awareness compared to the conventional VL learning approach?
(4) Is the CM-VL learning approach significantly different in terms of students' creative thinking tendency compared to the conventional VL learning approach?
(5) What are the differences between the learning behaviors of the students learning with the CM-VL learning approach and the conventional VL learning approach?

Literature review

Science process skills and virtual laboratories

Laboratory learning is an essential part of science education. Laboratories can motivate students and spread the practice of science (Chou & Feng, 2019). Scholars have indicated that students are likely to incorrectly perform experimental procedures owing to the lack of practicing opportunities and receiving feedback from the teacher for making reflections in traditional school settings (An et al., 2019). Such a learning environment would discourage students from expressing their opinions, engaging in problem solving, and developing their problem-solving competences (Kirn & Benson, 2018). Virtual environments have been shown to boost students' motivation for courses by providing peer support and discussion platforms for both students and instructors (Ekici & Erdem, 2020). Sugiharti and Limbong (2018) noted that virtual laboratories (VL) could be used to familiarize students with experimental techniques and procedures prior to experimentation to help them be better prepared to perform the same or similar experimental laboratories in actual chemistry. Moreover, the virtual learning environment allows students to repeat events multiple times without hesitation, zoom in and out, and watch in slow motion (Alebous, 2021). Virtual laboratories offer several advantages, including the ability to operate without constraints of time and space, as well as their low cost, high safety, and ease of use, making them attractive for students and educators looking to enhance their laboratory experiences (Desnita & Susanti, 2017).Virtual chemistry laboratories can elevate the process of chemical laws to a whole new level to enhance student engagement, communication skills, and creativity (Nechypurenko & Selivanova, 2019; Nechypurenko et al., 2020).

Several studies have compared physical and virtual manipulation in science learning (Lee et al., 2020). Yesiloglu et al. (2021) noted that virtual laboratories lack the developmental skills of providing real situations for learners to learn by doing, when compared to real laboratories. Similarly, Mutlu and Şeşen (2020) found that learners can effectively improve their learning achievements in both real and virtual laboratory environments, but learners tend to prefer learning in real laboratories due to the lack of realistic experience in virtual laboratories. However, virtual laboratory learning can be optimized with proper teaching intervention and support. Yesiloglu et al. (2021) emphasized the importance of such intervention, as it may be difficult for students to fully comprehend experimental concepts without guidance. Additionally, Makransky et al. (2019) found that cognitive overload can hinder effective learning in virtual environments, as noted by Winkelmann et al. (2017). These studies highlight the need for effective instructional strategies and support in virtual laboratory learning to optimize student learning outcomes. While virtual laboratories may lack some aspects of physical laboratories, they offer unique benefits and can be highly effective with appropriate instructional support. By utilizing the strengths of virtual laboratory learning and addressing its limitations, educators can provide students with a rich and engaging science learning experience.

Science process skills (SPS) play an important role in the completion and solution of various problems by students (Abdurrahman & Jalmo, 2018; Harahap et al., 2016). According to Sukarno and Hamidah (2013), learning skills cannot be separated from learning concepts in learning process skills. The mastery of science process skills is a fundamental requirement that students need to examine when learning certain chemical concepts. Therefore, the best way to solve problems is to conduct experiments in which scientific information from different sources is considered (Saputro et al., 2018). Teachers can use appropriate types of laboratories to teach science process skills; virtual laboratories are one such type (Gunawan et al., 2019). For example, Serevina (2018) developed a digital module based on PBL (problem-based learning) where students learn in a virtual laboratory that can effectively improve their SPS.

Furthermore, Ratnasari et al. (2017) found that students' conceptual understanding of science affects their SPS and therefore suggested enhancing students' conceptual understanding of science. In this study, concept maps were used to intervene in students' learning in a virtual laboratory. Therefore, concept mapping was expected to help students' understanding and further improve their SPS. It is important for SPS to be recorded, because it can confirm whether the learners are correct in their operation process, and plans for the future can be proposed. For example, Nezu et al. (2014) set up several cameras in a laboratory to record and analyze students' scientific process skills in chemical experiments, and concluded that in the future, more appropriate laboratory risk assessment methods can be proposed. The virtual laboratory proposed in this study can record learners' operation behaviors for further analysis and discussion.

Virtual laboratories simulate real laboratory environments and processes so that students gain knowledge by conducting experiments and translating theoretical knowledge into practice (Sugiharti et al., 2019). Researchers have developed a virtual chemistry laboratory activity to provide students with support for virtual laboratory research related to real-world settings, linking chemistry-learning concepts with virtual laboratory operations, thereby enhancing students' understanding of chemistry concepts (Davenport et al., 2018). Virtual laboratories provide students with meaningful virtual experiences and present important concepts, principles, and processes. Through virtual laboratories, students have the opportunity to repeat any incorrect experiments or deepen the intended experience (Rivera, 2016). For example, Tatli and Ayas (2013) adopted a POE (Predict-Observed-Evaluation)-based teaching strategy combined with a virtual laboratory learning model to enhance hands-on laboratory skills. In addition to the independence required for students to use virtual laboratories, they also need a great deal of instruction to guide them through the process. If students use these virtual laboratory devices without guidance, they may easily react negatively. Yesiloglu et al. (2021) mentioned in the study that without proper teaching intervention in virtual laboratory learning, it will be impossible to understand the concepts in the experiment. This study therefore employed a concept map to facilitate virtual laboratory operations.

Concept mapping in science education

Concept mapping as an assessment tool can improve student learning outcomes and high order thinking ability in chemistry (Ghani et al., 2017; Ha et al., 2009). Martínez et al. (2013) found that learning engineering physics through concept maps has been effective in terms of improving learning achievement. Li et al. (2021) found that the use of concept maps in a food science digital game improved learning outcomes by helping learners connect concepts and recall them during testing. In chemistry, Wang et al. (2021) investigated the effects of different concept maps, such as translating a completed map, on learning achievement. Ismono et al. (2019) investigated the effects of creating complete concept maps on learning achievement. A concept map is a graphical diagram that can be used to help students organize and form ideas (Novak, 1990). In mathematics learning, Kusumadewi and Kusmaryono (2022) found that incorporating concept maps cultivated original ideas, promoted finding relationships between concepts, and enhanced creative thinking. Concept mapping is a practical strategy for teachers to use with students to help them recall, review, communicate, and solve problems. Hannasari et al. (2017) found that scientific inquiry learning through concept maps significantly enhanced scientific process skills. In addition, Abd El-Hay et al. (2018) demonstrated that concept maps can improve problem-solving abilities and maintain a positive attitude among students. They assist students in learning more effectively by recording information in an organized manner (Novak, 2002). It has also been found that the concept mapping strategy is not only to support students to develop, but also to organize their ideas (Vasconcelos et al., 2020). For example, Buran and Filyukov (2015) indicated that concept mapping could effectively lead to meaningful learning by intensifying learners' associative thinking in oral English courses.

Several researchers in the field of science education have investigated the role of concept mapping in improving students' higher-order thinking, in particular, in conducting chemistry experiments (Ghani et al., 2017; Ismono et al., 2019; Talbert et al., 2020). For example, Ghani et al. (2017) demonstrated that using concept maps as a rubric can enhance critical thinking by asking students to construct concept maps before and after chemistry experiments. Talbert et al.'s (2020) research revealed that students' conceptual understanding was improved through teachers' assignments in chemistry classrooms which required students to construct concept maps. Ismono et al. (2019) presented that concept mapping in chemistry learning isomorphs improved students' ability to perform higher-level analyses with varying degrees of credit.

Development of a concept mapping-guided virtual laboratory

According to cognitive elaboration theory (Hamm et al., 2017; Wittrock, 1978), during the learning process, it is important to engage students in organizing new concepts into the existing knowledge structure. Several scholars have also pointed out the benefits of using concept maps as a knowledge organizing tool (Piri et al., 2018; Rahimi et al., 2021). When conducting complex experiments, students should have a clear idea of what they will be doing in a chemistry experiment, and this would not only promote their laboratory skills but also prevent them from encountering hazards or accidents during the experiment (Demircioğlu & Yadigaroğlu, 2011). Therefore, this study proposed the Concept

Mapping-Guided Virtual Laboratory (CM-VL) learning approach, which enables students to not only experience complex experiments but also to have a thorough understanding of the experimental process and possible scenarios.

System framework

In this study, the CM-VL Learning System included two applications. MindMeister from Linksoft was used for the concept map, and the THIX for the Chemist virtual laboratory application was used for the virtual laboratory, as shown in Fig. 1. THIX for the Chemist is a unique virtual chemistry lab that can be accessed on a tablet or cell phone. It provides an interactive learning experience for students, educators, and researchers by enabling them to perform a wide range of chemistry experiments and explore chemical reactions and experimental equipment. Unlike other virtual chemistry labs, THIX for the Chemist stands out because it is designed to mimic real-life laboratory conditions. The app allows users to adjust the concentration of chemicals, measure pH values, and observe changes in temperature and pressure in real time. Furthermore, THIX for the Chemist also offers a comprehensive database of experiments covering various topics in chemistry, such as stoichiometry, acid–base reactions, and electrochemistry. The app provides step-by-step instructions for each experiment, along with safety guidelines, making it an ideal tool for students to learn and practice their experimental skills.

The content of the concept map was designed by the teacher through the concept map development module, and the learning materials were stored in the concept map material database. Students could complete concept maps through the interactive concept map module. The virtual laboratory app consists of the experimental equipment database to simulate the functions of the experimental equipment and chemicals and the virtual laboratory scene database to set the conditions of the experimental environment. The experimental procedures would be stored in the learning process database, and the teachers could analyze the experimental procedures through the learning process database.

The virtual laboratory learning app comprises 17 types of equipment, six indicators, and four major categories of chemicals, as shown in Fig. 2. The four categories of chemicals

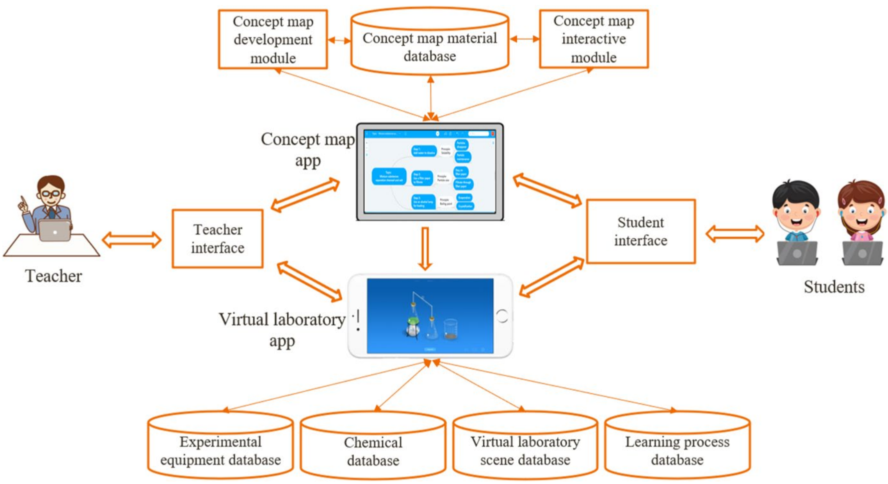

Fig. 1 CM-VL learning system framework

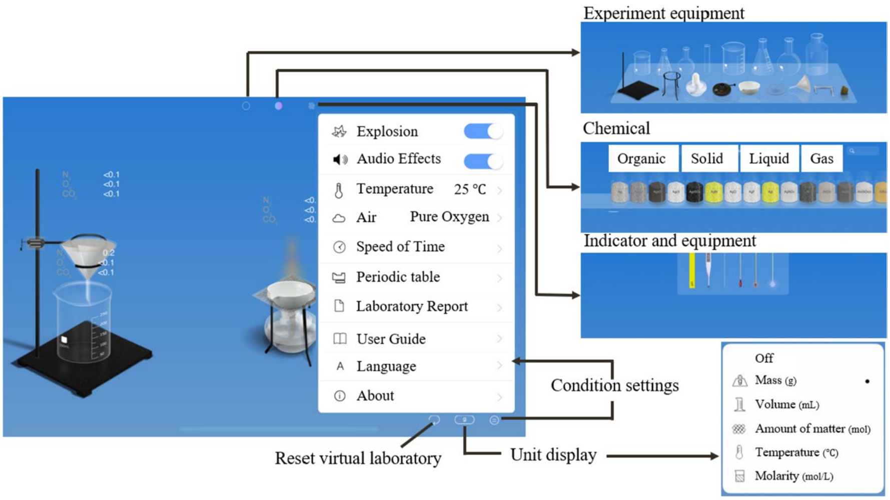

Fig. 2 Virtual laboratory learning app

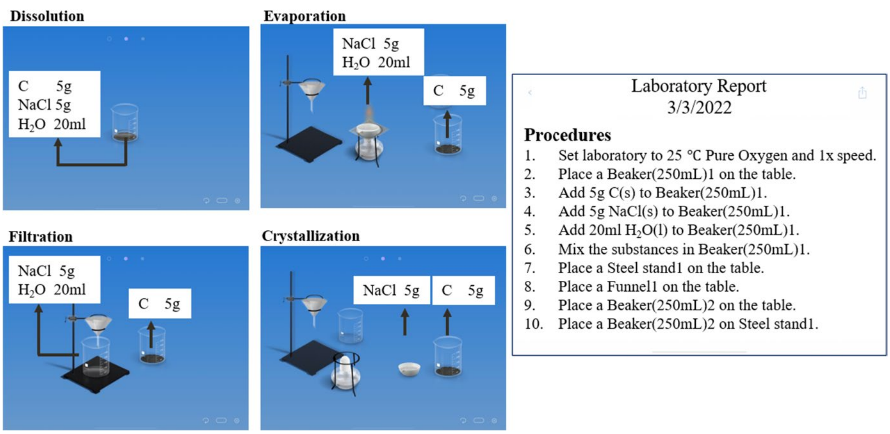

Fig. 3 Virtual laboratory learning app operation interface and laboratory report

are organic, solid, liquid, and gas. Figure 3 shows the operating interface of the virtual laboratory learning app and the laboratory report. The bottom right corner contains the laboratory options: "Reset," "Unit display," and "Condition settings." The "Reset" button indicates that all pieces of equipment on the screen can be cleared at once. Units are displayed to provide the units of the chemical in the container on the screen. The units displayed include mass (g), volume (ml), mole number (mol), temperature (°C), and molarity (M). Condition settings include the temperature and gas composition of the experimental environment experimental reports.

This study adopted a CM-VL learning approach to explore students' learning achievement, science process skills, problem-solving awareness, and chemical creative thinking tendency. The target unit of the study focused on separating a mixture of substances into pure substances. During the CM-VL learning process, students were guided to complete a blank concept mapping task, which aimed to help them understand the principles of the experimental operations and deduce the sequence and relationships of the experimental procedure, as shown in Fig. 4. Both experimental and control groups used computer and tablet devices for their virtual laboratory learning activities. During the study, the experimental group utilized concept maps on computers to study the experimental procedur xe, while the control group used traditional study sheets on computers.

When students performed experiments in the virtual laboratory, they could base their experiments on the concept maps they had filled out. They were required to complete a virtual experiment on separating substances (see Fig. 5).

Methods

Participants

The experiment implemented a quasi-experimental design in two classes of a middle school chemistry course taught by the same teacher. The total number of students was 51, with 26 in the experimental group (12 boys and 14 girls) and 25 in the control group (12 boys and 13 girls). The students had no previous experience of conducting chemistry experiments. The content of the experimental module was based on the National Nature Curriculum, and the reference textbook is the National Secondary Nature Curriculum, Kang Xuan Edition, Grade 8, Book 1. Both the experimental group and the control group used the same virtual laboratory app, textbooks, class tasks, and additional materials, and were instructed by the same teacher.

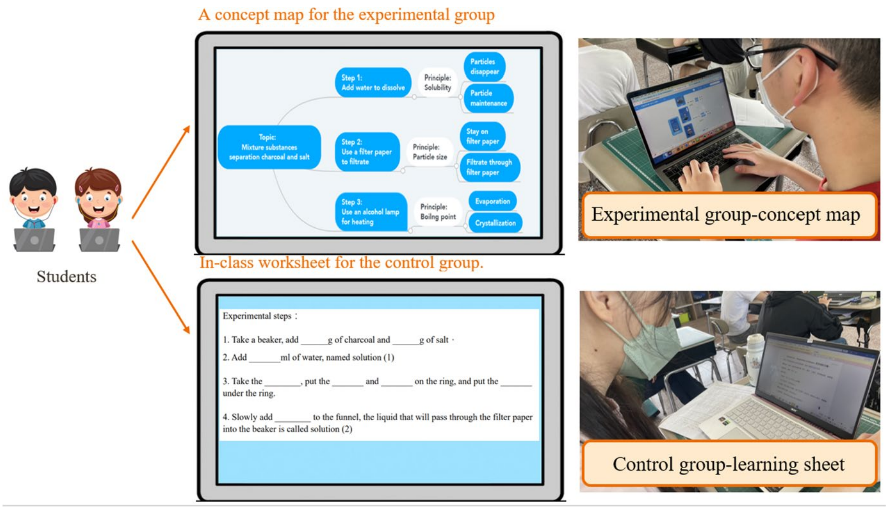

Fig. 4 The task of filling out the concept map

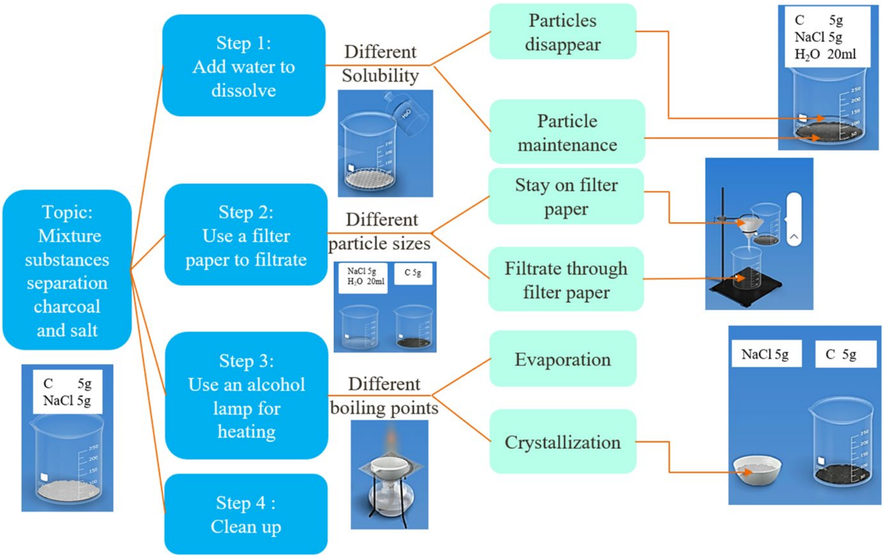

Fig. 5 Virtual experimental procedure

Measuring tools

The pre-test and post-test questions were adapted from the Natural Science Textbook of the National Institute for Translation and Compilation, and were designed by two teachers with 5 years of teaching experience. The purpose of the pretest was to assess whether the two groups of students participating in the experiment had equivalent basic knowledge of chemistry. The purpose of the posttest was to evaluate the two groups of students' understanding of the separation of mixtures and pure substances after the teaching and virtual experiment. There were 20 multiple-choice questions, with 5 points for each question, giving a total score of 100 points for the pretest and posttest. The Cronbach's α value was 0.83, indicating the relatively high internal consistency of the items.

The scoring rubric for science process skills (see Table 1) was adapted from Chen et al.'s (2013) scoring rubric for skills. There are four main procedures in the mixture separation experiment: "dissolution," "filtration," "evaporation and crystallization," and "cleanup," with a total of 17 steps. There are 6 points for Steps 1–16, and 4 points for the last step. Therefore, the perfect score is 100. Two teachers with 5 years of teaching experience rated the scores, and the Kappa value was 0.77, indicating substantial agreement.

The questionnaire of the problem-solving awareness measure was modified and based on Lai and Hwang (2014). The 5-point rating scale (5 = *strongly agree* and 1 = *strongly disagree)* was adopted to evaluate the students' views on problem-solving awareness. The purpose of the pre-questionnaire was to find out if the students clearly understood the experiment procedure and had the ability to complete the experiment in the past. The posttest was to find out whether the students were capable of completing the experimental process after the experiment. The Cronbach's α value on this scale was 0.80, indicating a relatively high internal consistency of the questionnaire.

The measure of creative thinking tendency was modified and based on Lai and Hwang (2014). It consisted of six items with a 5-point Likert rating scheme. The

Table 1 Scoring rubric for science process skills

Procedures	Steps	Score assessment conditions			
		6:Advanced	4:Proficient	2:Functional	0:Developing
Dissolution	Take a 250 ml beaker	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Add the correct mass of charcoal	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Add the correct amount of table salt	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Add the correct amount of water	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Stir the mixture	Successfully performs this task without supervision			Cannot complete the task
	Correct order	All in the correct order			The order is wrong
Filtration	Place the funnel and beaker in the correct position on the steel stand	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Pour all the solution into the funnel	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Separate charcoal and brine	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Correct order	All in the correct order			The order is wrong

Table 1 (continued)

Procedures	Steps	Score assessment conditions			
		6:Advanced	4:Proficient	2:Functional	0:Developing
Evaporation and crystallization	Pour the brine into the evaporating dish	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Take a tripod and an alcohol lamp	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Heat the evaporating dish with brine	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Evaporate water	Successfully performs this task without supervision	Successfully performs this task with minimal supervision	Successfully performs this task with moderate supervision	Cannot complete the task
	Extinguish lamp	Successfully performs this task without supervision			Cannot complete the task
	Correct order	All in the correct order			The order is wrong
Cleanup	Remove all equipment and chemicals one by one	N/A	Successfully performs this task without supervision	Successfully performs this task with moderate supervision	Cannot complete the task

Table 2 The coding scheme for science process skills

Code	Phase/content
PB	Place a beaker
PS	Place a steel stand
PF	Place a funnel
PE	Place an evaporating dish
PD	Place a tripod
PA	Place an alcohol lamp
AC	Add charcoal (C)
AN	Add salt (NaCl)
AH	Add water (H_2O)
MI	Mix the substance
PO	Pour substances
RB	Remove beaker
RS	Remove a steel stand
RF	Remove a funnel
RE	Remove an evaporating dish
RD	Remove a tripod
RA	Remove an alcohol lamp
RU	Remove all substances
LU	Light an alcohol lamp
PU	Put out an alcohol lamp

Cronbach's α value of the questionnaire was 0.88, indicating a relatively high internal consistency of the questionnaire. The students' behaviors were coded according to their steps in the virtual laboratory, such as picking up and placing equipment, adding and mixing chemicals, and heating. The coding scheme in Table 2 was adopted from Chen et al. (2013).

The interview questionnaire was modified from Hwang et al. (2009). The interview was designed to address learners' perceptions of virtual laboratory learning through the following questions.

(1) What aspects of this method have been most helpful in learning about separation of matter? Please list.
(2) How can the process of operating a virtual laboratory help learning?
(3) What are the benefits of this learning style?
(4) What can be improved in this approach (e.g., system functionality or interface design)? Please give a concrete example.
(5) Would you like to have the opportunity to study this way again in the future? What courses might use this approach? Why do you think these courses would suit this approach?

The interview questions were validated by two experts who had experience in developing measurement tools. Additionally, two experienced teachers reviewed the

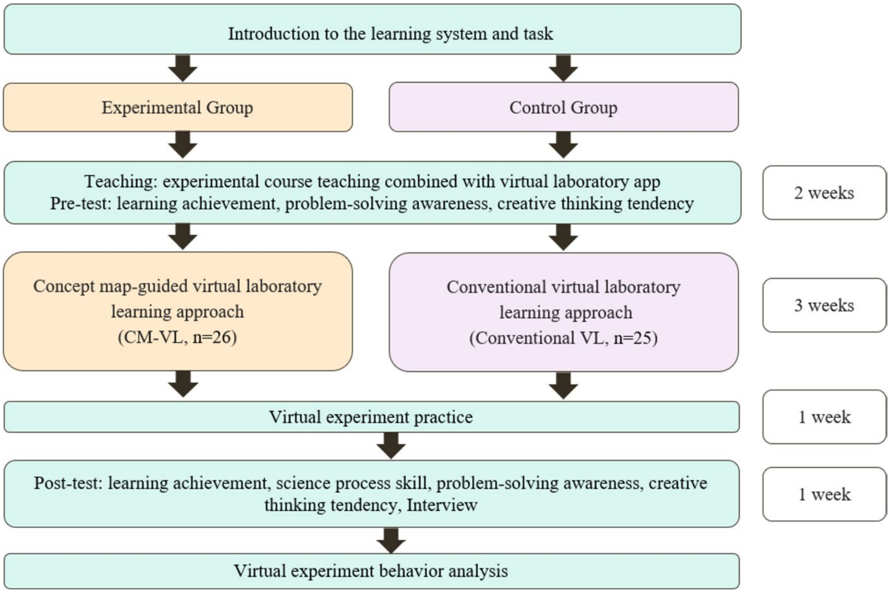

Fig. 6 Diagram of the experimental design

questionnaire and interview questions to ensure that the students understood the terms used in them. All students who participated in the study were interviewed.

Procedure

Figure 6 illustrates the experimental procedure, which lasted 6 weeks. The pretest and pre-questionnaires of problem solving and creativity were administered to the experimental and control groups in the first 2 weeks. Subsequently, both groups learned with the virtual laboratory for 3 weeks. During the learning process, the experimental group used the CM-VL

Fig. 7 A student uses a tablet to operate the virtual laboratory

Table 3 ANCOVA of the posttest for learning achievement

Variable	Group	*N*	Mean	*SD*	Adjusted mean	*SE*	*F*	η^2
Learning achievement	Experiment	26	89.2	5.23	89.3	1.6	8.78**	0.16
	Control	25	82.6	10.62	82.5	1.63		

**$p < 0.01$

Table 4 The result of the *t* test for the science process skills of the two groups

Variable	Group	*N*	Mean	*SD*	*t*	*d*
Science process skills	Experiment	26	92.88	3.85	3.33*	0.87
	Control	25	88.76	5.49		

*$p < 0.05$

learning approach. On the other hand, the control group learned with the conventional VL learning approach; that is, they were guided by a worksheet, which guided them to conduct the experiment in the VL following a list of experimental steps, and to record the corresponding findings. After the experimental operation, posttests and virtual experimental behavior analysis were conducted. Figure 7 shows that both groups used tablet devices to perform virtual experimental manipulation. This allowed them to simulate a real laboratory setting and gain hands-on experience in a safe and controlled environment. By using tablets, students were able to adjust experimental parameters, record observations, and analyze data, all of which are crucial skills for experimental chemistry.

Results

Learning achievement

In this experiment, covariance analysis (ANCOVA) was used to analyze the difference between the chemistry tests of the two groups using the pretest scores as the covariate, the post-test scores as dependent variables, and the virtual laboratory approaches as an independent variable. The homogeneity test shows that the regression slopes of the chemistry tests were homogeneous ($F = 0.69$, $p = 0.41$), which implies the suitability of the data analysis for the use of ANCOVA for the experimental group and the control group.

Table 3 shows the ANCOVA results, which indicated that the posttest scores of the two groups were significantly different with $F = 8.78$ ($p < 0.01$). The students in the experimental group had significantly better scores (adjusted mean = 89.3) than those in the control group (adjusted mean = 82.53), implying that the CM-VL learning approach was helpful for the students in terms of improving their chemistry learning achievement.

Science process skills

In this experiment, an independent sample *t* test was conducted to investigate the science process skills of the two groups. The results are shown in Table 4. The *t*-test result was $t = 3.33$ ($p < 0.05$), showing a statistically significant difference in the two groups' science

Table 5 The ANCOVA result for problem-solving awareness of the two groups

Variable	Group	*N*	Mean	*SD*	Adjusted Mean	*SE*	*F*	η^2
Problem-solving	Experiment	26	4.58	0.34	4.57	.09	19.7*	.29
	Control	25	4.00	0.63	4.01	.08		

*$p < 0.05$

Table 6 The ANCOVA result for the creative thinking tendency of the two groups

Variable	Group	*N*	Mean	*SD*	Adjusted mean	*SE*	*F*	η^2
Creative thinking	Experiment	26	4.21	.41	4.22	.14	6.14*	.11
	Control	25	3.7	.95	3.71	.15		

*$p < 0.05$

process skill scores. Moreover, the means scores were 92.88 for the experimental group and 88.76 for the control group. This indicates that the CM-VL learning approach improved students' science process skills more than the conventional VL learning approach.

Problem-solving awareness

A one-way ANCOVA was used to measure the students' problem-solving awareness using their pre-questionnaire scores as a covariate, virtual laboratory approaches as an independent variable, and the post-questionnaire score as a dependent variable. The homogeneity of the regression was not violated ($F = 0.01$, $p = 0.22$), showing a common regression coefficient for one-way ANCOVA. Examination of the effectiveness of the CM-VL learning approach in terms of problem-solving awareness via the ANCOVA method showed that there was a significant difference between the problem-solving awareness ratings of the experimental group (adjusted mean = 4.57) and the control group (adjusted mean = 4.01) with $F = 19.7$ ($p < 0.05$), as shown in Table 5.

Creative thinking tendency

This study also examined the effectiveness of CM-VL in terms of the students' creativity. The assumption of the homogeneity of regression was not violated ($F = 1.44$, $p = 0.24$), implying the suitability of the data analysis for the use of ANCOVA. The one-way ANCOVA in Table 6 showed a significant difference between the two groups ($F = 6.14$, $p = 0.02$). The adjusted mean values were 4.22 for the experimental group and 3.71 for the control group. This means that the CM-VL effectively enhanced students' tendency for creative thinking compared to the conventional VL learning approach.

Table 7 Adjusted residual table (Z-score) of the experimental group

z-core	PB	PS	PF	PE	PD	PA	AC	AN	AH	MI	PO	RB	RS	RF	RE	RD	RA	RU	LU	PU
PB	.92	.44	− .56	.6	− 1.37	.91	14.17*	− 1.37	− 1.37	− 1.46	− .78	− 1.91	− 1.31	− 1.37	− 1.48	− 1.42	− 1.42	− 1.07	− 1.37	− 1.05
PS	1.05	− .86	16.42*	− 1.05	− .86	.15	− .96	− .92	− .92	− 2.08	− 1.55	− 1.28	− .88	− .92	− 1	− .96	− .96	− .96	− .92	− .71
PF	8.35*	− 0.86	− .92	− 1.05	− .92	− .96	− .96	− .92	− .92	− .92	5.71*	− 1.28	− .88	− .92	− 1	− .96	− .96	− .96	− .92	− .71
PE	− 1.17	− 0.98	− 1.05	− 1.19	5.11*	1.88	− 1.09	− 1.05	− 1.05	− 2.36	7.27*	− 1.46	− 1	− 1.05	− 1.13	− .1	− 1.09	− 1.09	− 1.05	− .81
PD	− 1.03	− 0.86	− .92	3.06*	− .92	10.18*	− .96	− .92	− .92	− 2.08	− .1	− 1.28	− .88	− .92	− 1	− .96	− .96	− .96	.23	.77
PA	− 1.07	− 0.9	− .96	− 1.09	10.18*	− 1	− 1	− .96	− .96	− 1.6	− 1.62	− 1.34	− .92	− .96	− 1.04	− 1	− 1	− 1	12.41*	− .74
AC	− 1.07	− 0.9	− .96	− 1.09	− .96	− 1	− 1	21.32*	− .96	− 1.04	− 1.62	− 1.34	− .92	− .96	− 1.04	− 1	− 1	1.15	− .96	− .74
AN	− 1.03	2.83*	− .92	− 1.05	− .92	− .96	2.38*	− .92	18.73*	− .92	− 1.55	− 1.28	− .88	− .92	− 1	− .96	− .96	− .96	− .92	− .71
AH	1.05	− 0.86	− .92	− 1.05	− .92	− .96	− .96	− .92	− .92	7.79*	.63	− 1.28	− .88	− .92	− 1	− .96	− .96	− .96	− .92	− .71
MI	− 1.27	6.7*	− 2.08	− 1.33	− 2.08	− 2.16	.08	− .92	− .92	13.7*	− .58	− 2.89	− 1.99	− .92	− 2.24	− 2.16	− 1.04	− 1.04	− .92	− .11
PO	− 0.43	0.86	− 1.55	.17	.63	− .22	− 1.62	− 1.55	− .1	− 2.04	− .79	1.6	− 1.49	− 1.55	.35	− 1.62	− .92	4.68*	1.35	− 1.2
RB	− 1.44	− 1.2	− 1.28	− .7	− 1.28	− 1.34	− 1.34	− 1.28	− 1.28	− 2.89	1.06	7.08*	1.69	5.56*	1	6.91*	− 1.34	− 1.34	− 1.28	− .99
RS	− 0.54	− 0.45	− .48	− .55	− .48	− .5	− .5	− .48	− .48	− 1.09	− .81	− .67	− .46	14.63*	− .52	− .5	− .5	− .5	− .48	− .37
RF	− 0.99	− 0.83	− .88	− 1	− .88	− .92	− .92	− .88	− .88	− 1.99	− 1.49	5.01*	14.19*	− .88	1.29	1.4	− .92	− .92	− .88	− .68
RE	− 1.03	− 0.86	− .92	− 1.05	− .92	− .96	− .96	− .92	− .92	− 2.08	− 1.55	1	− .88	− .92	5.46*	3.5*	9.07*	− .96	− .92	− .71
RD	− 1.01	− 0.85	− .9	− 1.03	− .9	− .94	− .94	− .9	− .9	− .85	− 1.52	− 1.26	− .87	− .9	8.9*	1.33	11.56*	− .94	− .9	− .7
RA	− 1.07	− 0.9	− .96	1.88	− .96	1.15	− 1	− .96	− .96	− 2.16	− 1.62	.31	1.4	7.95*	3.11*	5.44*	− 1	− 1	− .96	− .74
RU	− 1.07	− 0.9	− .96	− 1.09	− .96	− 1	− 1	− .96	− .96	1.2	.48	3.61*	− .5	− .96	− 1.04	− 1	2.22*	3.29*	− .96	− .74
LU	− 1.03	− 0.86	− .92	4.08*	1.39	− .96	− .96	− .92	− .92	− 1.5	− .83	− .43	− .88	− .92	− 1	− .96	− .96	− .96	− .92	6.7*
PU	− 1.05	− 0.66	− .71	− .81	− .71	− .74	− .74	− .71	− .71	− .11	− .26	1.21	− .37	− .71	− .77	− .74	− .74	− .74	− .71	− .55

*$P < 0.05$

Behavior analysis of the experimental and control groups

To understand students' science process skills in the CM-VL learning approach and the conventional VL learning approach, we used the GSEQ software (Bakeman & Quera, 1995) to analyze students' behaviors while conducting chemical experiments through lag sequential analysis. Table 7 shows the sequential analysis of the learning behaviors in the experimental group, of which 35 items are statistically significant.

Table 8 shows the sequential analysis of the learning behaviors of the control group, of which 37 items are statistically significant. The z score of these sequences is higher than 1.96 (Bakeman & Gottman, 1997). According to Table 7 and 8, the behavioral paths are constructed as shown in Figs. 8 and 9. For example, PB to AC indicates that the student takes the beaker and then adds the charcoal. AH to MI indicates that the student adds water and then starts stirring, and LU to PU means that the student lights the alcohol lamp and then extinguishes it.

In the experimental group, it was found that the student behavior pattern in the dissolution and filtration section was AC→AN→AH→MI→PS→PF→PO. Students in the experimental group mixed charcoal and salt and then added water to dissolve the mixture, followed by filtration. On the other hand, in the control group, it was found that the students' behavior pattern in the dissolution and filtration section was AN→PS→PF→PO, where the charcoal and salt were mixed, and then the filter paper was taken directly to the filtration. After the charcoal and salt, the control group students took the filter paper directly. Then they went straight to the filter. When the students poured the mixture into the filter paper and could not separate it, they reworked it and added water to dissolve it. Therefore, from this behavioral pattern, it is clear that the experimental group had a clear understanding of the concepts of dissolution and filtration due to the CM-VL learning approach; on the other hand, the control group students were not very clear about the concept of dissolution and filtration, which could lead them to the wrong sequence of experimental operations and hence failed to achieve the expected experimental outcomes.

The behavior pattern of the control group students during the evaporation and crystallization part of the operation was PA→LU→PE. This pattern indicated that the operation process was that the students ignited the alcohol lamp before taking the evaporating dish and then assembling the heating device, which would be dangerous in the experimental operation. The pattern of behavior of the students in the experimental group during the evaporation and crystallization part of the operation was PE→PO→LU. This represented the process of taking the evaporating dish, pouring the liquid into the evaporating dish, and assembling the heating device before lighting the fire. Therefore, it can be confirmed that the experimental group was able to identify the correct procedure of the experimental process due to the CM-VL learning approach.

Student interviews

In this study, interviews were conducted after the students had operated the virtual laboratories, and the students were interviewed about the virtual laboratory learning process. The interview questions were adapted from Hwang et al. (2009). Two researchers and experts analyzed the students' responses and identified the following relevant responses. Comparing the answers of the students in the experimental group and the control group after integration, there are two similar points, namely increasing learning motivation and improving learning efficiency. See Table 9.

Table 8 Adjusted residual table (Z-score) of the control group

z-core	PB	PS	PF	PE	PD	PA	AC	AN	AH	MI	PO	RB	RS	RF	RE	RD	RA	RU	LU	PU
PB	− 1.21	3.48*	2.76*	− .62	− 1.57	− 1.66	9.97*	.59	− 1.57	− 1.51	− 2.11	− 2.33	− 1.47	− 1.44	− 1.57	− 1.57	− 1.57	1.16	− 1.47	− 1.37
PS	13.78*	− 1	9.77*	− 1.18	− 1	− 1.06	− 1	− 1	− 1	− .96	− 1.64	− 1.48	− .94	− .92	− 1	− 1	− 1	− 1.77	− .94	− .87
PF	− .23	− 1	− 1	− 1.18	− 1	− 1.06	6.54*	− 1	− 1	− .96	7.41*	− 1.48	− .94	− .92	− 1	− 1	− 1	− 1.12	− .94	− .87
PE	− 1.38	− 1.18	− 1.18	.18	4.35*	1.37	− 1.18	− 1.18	− 1.18	− 1.14	9.38*	− 1.76	.85	− 1.09	− 1.18	− 1.18	− 1.18	− 2.1	− 1.11	− 1.03
PD	− 1.17	− 1	− 1	− 1.18	− 1	21.42*	− 1	− 1	− 1	− .96	− .94	− 1.48	− .94	− .92	− 1	− 1	− 1	− 1.77	− .49	− .87
PA	− 1.23	− 1.06	− 1.06	12.74*	3.03*	− 1.12	− 1.06	− 1.06	− 1.06	− 1.01	− 1.07	− 1.57	− .99	− .97	− 1.06	− 1.06	− 1.06	− 1.87	− .99	− .92
AC	− 1.17	− 1	− 1	− 1.18	− 1	− 1.06	− 1	23.77*	− 1	− .96	− 1.64	− 1.48	− .94	− .92	− 1	− 1	− 1	− 1.77	− .94	− .87
AN	− 1.17	− 1	− 1	− 1.18	− 1	− 1.06	2.23*	− 1	23.77*	− .96	− 1.64	− 1.48	− .94	− .92	− 1	− 1	− 1	− 1.77	− 94	− .87
AH	− 1.17	− 1	− 1	− 1.18	− 1	− 1.06	− 1	− 1	− 1	21.43*	− 1.64	− 1.48	− .94	− .92	− 1	− 1	− 1	− 1.77	− .94	− .87
MI	− 1.12	13.59*	− .96	− 1.14	− .96	− 1.01	− .96	− .96	− .96	3.73*	− 1.57	− 1.42	− .9	− .88	− .96	− .96	− .96	− 1.7	− .9	− .84
PO	1.71	− 1.64	− 1.64	− 1.94	.45	− 1.07	− 1.64	− 1.64	− 1.64	− 1.57	− 2.69	− 2.43	− .8	− 1.5	− 1.64	− 1.64	− 1.64	7.23*	2.89*	.94
RB	− 1.42	− 1.22	− 1.22	− 1.44	− 1.22	− 1.29	− 1.22	− 1.22	− 1.22	− 1.17	− 2	12.07*	− 1.14	4.73*	− .32	− 1.22	− 1.22	− 2.16	1.72	− 1.06
RS	− 1.02	− .87	− .87	− 1.03	10.13*	− .92	− .87	− .87	− .87	− .84	− .64	− 1.3	− .82	1.85	6.46*	− .87	− .87	− 1.55	− .82	− .76
RF	− 1.07	− .92	− .92	− .09	− .92	.14	− .92	− .92	− .92	− .88	− 1.5	− .54	22.67*	− .84	− .92	− .92	− .92	− 1.62	− .86	− .8
RE	− 1.02	− .87	− .87	− 1.03	− .87	− .92	− .87	− .87	− .87	− .84	− 1.43	− .32	.48	− .87	− .87	− .87	.35	− 0.82	− .82	− .76
RD	− 1.17	− 1	− 1	− 1.18	− 1	− 1.06	− 1	− 1	− 1	− .96	− 1.64	3.81*	− .94	− .92	3.31*	− 1	15.15*	− 1.77	− .94	− .87
RA	− 1.17	− 1	− 1	− 1.18	− 1	− 1.06	− 1	− 1	− 1	− .96	− 1.64	− 1.48	− .94	− .92	5.46*	10.85*	− 1	− 1.77	− .94	− .87
RU	− 2.07	− 1.77	− 1.77	− 2.1	− 1.77	− 1.87	− 1.77	− 1.77	− 1.77	− 1.7	.9	5.63*	− 1.66	4.75*	4.11*	− 1.77	− 1.77	− 1.77	− .97	− 1.55
LU	− 1.09	− .94	− .94	− .13	− .94	− .99	− .94	− .94	− .94	− .9	− .06	− 1.39	− .88	1.62	− .94	− .94	.21	− 1.66	− .88	5.67*
PU	− 1.02	− .87	− .87	− 1.03	− .87	− .92	− .87	− .87	− .87	− .84	− 1.43	− .44	− .82	− .8	− .87	10.13*	− .87	− .87	− .82	− .76

*$P < 0.05$

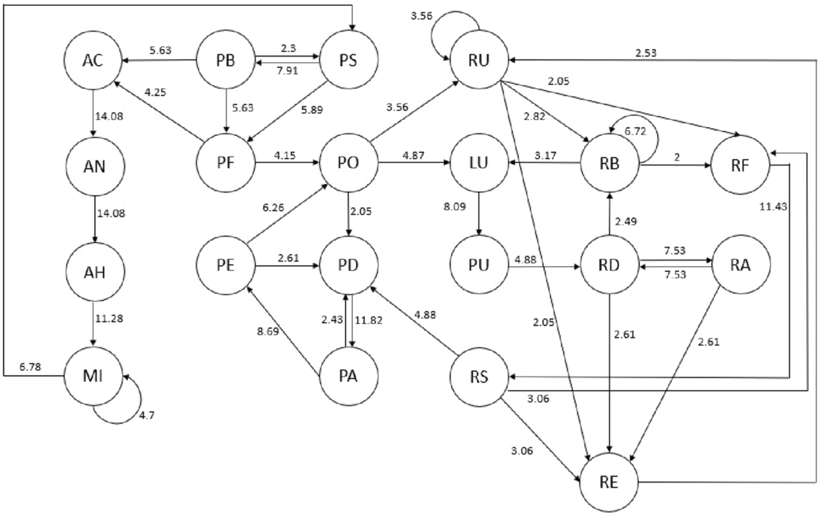

Fig. 8 The behavioral learning paths of the experimental group

In terms of increasing learning motivation, compared with past learning experiences, students expressed a positive attitude towards being able to conduct experimental operations through the virtual laboratory. In terms of improving learning effectiveness, students generally stated that virtual laboratories can greatly improve their learning effectiveness because they can conduct experiments without limitations of location, time and frequency.

The students in the experimental group operated the virtual laboratory after being taught with the concept map, so they had more to say in the interviews about how the teaching of the concept map helped them learn; this benefit was named "fostering learning reflection." The relevant comments from the experimental group interviews are summarized in Table 10.

The study of concept maps can help students reflect on the operation of the virtual laboratory, and the experimental process can accurately know the relationship between concepts between steps because of the concept maps. The operation process can continuously recall the entire concept map and process due to the learning of the concept map. Therefore, the study of concept maps can foster students' reflection.

Discussion and conclusions

This study used the CM-VL learning approach to help students understand the relationship between the concept of the experimental process and the experimental steps before the virtual experiment. The experiment was used in the separation experiment of chemical mixtures. The study found that the CM-VL learning approach could enhance students' learning achievement because students could understand the concept of each process through the concept map, and therefore could effectively improve the learning achievement (Bridges et al., 2015; Jack, 2013; Qarareh, 2010). Li et al. (2021) found that the teaching strategy of adding a concept map-based two-tier test to a food science digital game significantly improved the learning effect because the concept map helped learners connect

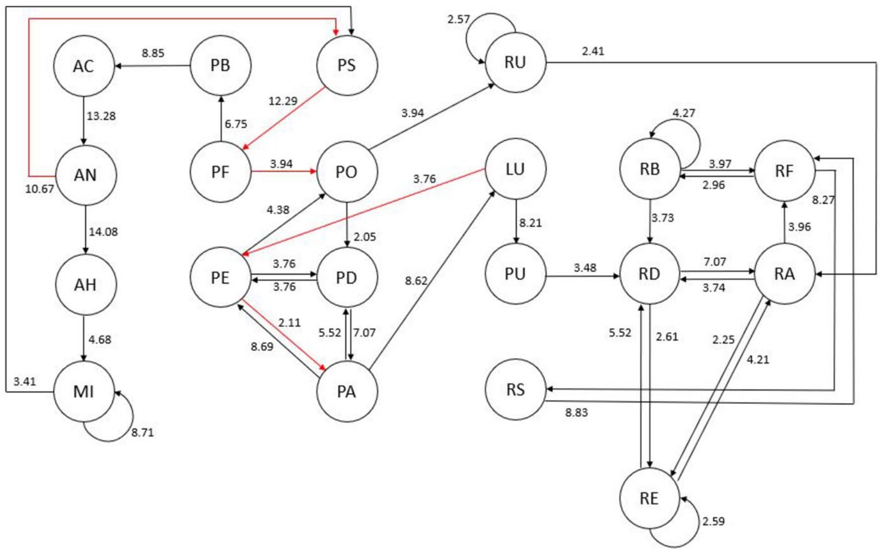

Fig. 9 The learning behavior paths of the control group

the relationship between concepts, and they recalled the concept map during the test. This result is also consistent with the interviews with the students in the experimental group. The students said that they could clearly understand the concept of each step of the experiment and the relationship between the concepts through the concept map.

Second, the CM-VL learning approach can enhance students' science process skills. Through concept mapping, students understand not only the concept of each step, but also the connection between the steps so that they can operate the experiment more smoothly when operating the virtual experiment. These findings are consistent with the study of Pernaa and Aksela (2010). They indicated that using concept mapping before conducting experiments in a physical laboratory helped students better understand procedural issues during the experiments, and made them run more smoothly. Indriani and Mercuriani (2019) revealed that students enhanced their science process skills through the use of concept maps. This result is similar to the results of the student interviews. The students said that they would recall the concept map during the operation of the virtual laboratory, know the important concepts of each step, and associate the sequence of steps that needed to be performed. From the perspective of behavior analysis, the learners in the experimental group had high accuracy in operating the virtual experiment, which means that they could clearly understand the concepts and procedures of the experimental steps due to the learning of the concept map.

Third, the CM-VL learning approach can enhance students' problem-solving awareness. The reasoning behind enhancing students' problem-solving awareness is that they have a holistic understanding of the concept map (Whitelock-Wainwright et al., 2020). As Cañas et al. (2017) stated, for each concept in the concept map, learners needed to understand the connection between the concept and the problem and think about how to solve the problem. Therefore, students were engaged in a problem-solving process when filling out the concepts in the concept map. Abd El-Hay et al. (2018) researched the use of concept maps in clinical nursing education, and found that students could maintain

Table 9 The experimental and control group students' similar interview comments

Category	Increasing learning motivation	Improving learning efficiency
Experimental responses	*S1: I can see a lot of chemicals and instruments that you can't usually see, it's very interesting*	*S1: I can operate the virtual laboratory more smoothly*
	S2: I can try any experiment that looks dangerous	*S2: I can understand the concept of the experimental procedure*
	S3: I can operate a virtual laboratory at home or at school	*S3: I was able to understand more deeply when doing charcoal and brine separation experiments*
	S4: I can see the reaction process, the results of the virtual laboratory, and the sound effects in the experiment, which are very realistic	*S4: Virtual experiments allow me to better understand chemical reactions*
	S5: I can practice as much as possible in the virtual laboratory	*S5: The concept map makes me learn chemistry experiments better*
Control responses	*SA: Equipment and chemicals I've never seen in my school lab can be seen in the virtual lab*	*SA: The virtual laboratory makes me learn better*
	SB:I can practice my chemistry experiments without being in a laboratory	*SB: There are more opportunities to practice, so that I can better understand chemical experiments*
	SC: I can access virtual laboratory exercises anytime	*SC: I can complete the experiment by myself according to the steps*
	SD: I think the virtual laboratory is great and fun	*SD: The virtual laboratory allows me to see how the reaction happens*
	SE: The equipment, chemicals and chemical reactions are very close to the real thing, so I would be willing to try different experiments	*SE: The virtual laboratory is easy to operate, so it lets me understand the experiment better*

Table 10 Experimental group comments on the concept map

Category	Fostering learning reflection
Experimental responses	*S1: When operating a virtual laboratory, I have the whole concept map in mind*
	S2: I can understand the principles of experimental steps and demonstrate sequence, relationships and clear concepts
	S3: When I encounter problems operating the virtual laboratory, I think of the concept map
	S4: The concept map is what allowed me to successfully conduct virtual experiments
	S5: The concept map allows me to connect all the experimental steps together, and I can see the context of the entire experiment

a positive and engaged attitude, which allowed them to think better. It could therefore significantly improve their problem-solving ability. This result is consistent with the interview results of the students in the current study. The students said that when operating the virtual laboratory, they would recall the entire concept map and the steps and relationships in the diagram. When operating the virtual laboratory, they could know exactly how to proceed in the next step.

Fourth, the CM-VL learning approach can enhance students' creative thinking tendency. Creative thinking is the ability to find new relationships, see topics from new perspectives and form new combinations of concepts (Ülger, 2016). Kusumadewi and Kusmaryono (2022) added concept map guidance to mathematics learning. Learners need to find relationships between concepts, cultivate original ideas and achieve new understandings, thus enhancing learners' creative thinking. Seechaliao (2017) showed that learners' use of concept maps combined with digital storytelling models in blogs enhanced students' creative thinking. Miranti and Wilujeng's (2017) study suggested that students could develop their creative thinking tendencies by exploring the links between concepts in concept maps. Their result is consistent with the results of the student interviews in the current study, as the students said that when learning the experimental steps, they would use the virtual laboratory to try various operations in order to find the relationship between the steps. The CM-VL learning approach in this study enabled students to fill in the conceptual blanks in concept mapping, while at the same time, the virtual experiment could be paired with various exploration possibilities to help students develop creative thinking.

In the post-study interviews, the experimental group students stated that they were able to accurately perform the experimental operations of dissolution, filtration, evaporation, and crystallization because they knew the concepts and principles of the experimental steps through the concept mapping-guided learning approach. In addition, they could understand the relationship between and sequence of concepts through the concept maps, so they could know the flow and sequence of experiments, which helped them achieve the experimental objectives and results quickly. This is consistent with previous studies, such as Markow and Lonning (1998), who found that having students construct concept maps prior to the experiments helped them understand the concepts in the experiments they conducted. Laboratory learning typically involves using procedural knowledge to support the learning of laboratory processes according to modeling techniques (Pernaa & Aksela, 2010). In particular, since experiments have a flow and sequence, concept mapping facilitated students' understanding of the relationship and sequence between concepts and finally their performance of accurate operations. Hannasari et al. (2017) found that in scientific learning, scientific inquiry learning in the form of concept maps can significantly improve learners' scientific process skills. Ismono et al. (2019) mentioned that the learning of conceptual constructs is suitable for learning with declarative and procedural knowledge. Students conducted hands-on learning in a virtual laboratory where the focus was on the process of experimentation rather than on the equipment or drugs (Tatli & Ayas, 2010). Therefore, this study used concept mapping to guide learning in virtual laboratories, and it was through concept mapping that the operational processes of virtual laboratories guided the learning.

In terms of behavior analysis, it was found that the experimental group had a good understanding of the concepts in the process of operating the virtual laboratory after the learning guided by the concept map, and laboratory safety could be achieved due to the correct operation process. The behavior of the students in the control group who tried many times during the operation of the virtual laboratory actually represented that they did not fully understand the principles and concepts of the experiment, and the use of equipment in the wrong order may lead to a laboratory safety crisis. This study adopted the CM-VL learning approach to improve students' learning achievement, science process skills, problem-solving awareness, and creative thinking tendency. Meanwhile, this study also analyzed how concept mapping influenced students' experimental procedures.

However, there are some limitations that should not be overlooked. The sample size for this study is quite small, so it is less likely that the findings can be extrapolated to other groups or settings. Nonetheless, previous studies have also been conducted on small samples. For example, Alroobaea and Mayhew (2014) selected five samples to investigate the effectiveness and satisfaction of the Internet and related technologies to achieve the research effect. In addition, Chao et al. (2016) used virtual laboratories to improve students' understanding of microscopic and macroscopic concepts in physics. The sample size of their experimental group was small ($N=16$). Thus, the results of a small sample can be to some extent representative (Smith & Little, 2018). A small number of students were not good at using the concept map app, which can cause negative reactions. Some students operated the virtual laboratory app on their cell phones. The buttons in the virtual laboratory were too small, so the students mentioned that they could not operate it smoothly. Students are recommended to use tablets or laptops to practice these applications. It is suggested that teachers can help students clarify the relationship between the concepts behind the experiments and the operation procedures through the concept mapping-guided learning approach when teaching experimental courses and then conducting experiments, which can enhance students' learning effectiveness and experimental operation skills. Teachers can conduct experiments in a virtual laboratory to help students experiment and understand abstract concepts in science experiments despite the epidemic.

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Data availability The datasets generated and analyzed during the current study are not publicly available due to privacy and ethical considerations concerning student data. However, the manuscript provides a comprehensive account of the data used, the methodologies employed in data collection, and the analytical processes applied. Researchers interested in replicating the study or inquiring further into the data may contact the corresponding author. Access to the data will be granted following an assessment of the request and ensuring compliance with privacy regulations and institutional policies.

Declarations

Conflict of interest The authors would like to declare that there is no conflict of interest in this study.

Consent to participate The participants were protected by hiding their personal information during the research process. They knew that the participation was voluntary and they could withdraw from the study at any time.

References

Abd El-Hay, S. A., El Mezayen, S. E., & Ahmed, R. E. (2018). Effect of concept mapping on problem solving skills, competence in clinical setting and knowledge among undergraduate nursing students. *Journal of Nursing Education and Practice, 8*(8), 34–46. https://doi.org/10.5430/jnep.v8n8p34

Abdurrahman, A., & Jalmo, T. (2018). The Effectiveness of students' worksheet of virtual laboratory practice on dynamic electricity to improve science process skill. *International Journal of Advanced Engineering, Management and Science, 4*(4), 319–328. https://doi.org/10.22161/ijaems.4.4.14

Alebous, T. (2021). The extent to which teachers of science subjects use virtual scientific laboratories during corona virus pandemic: The reality & hope. *Journal for the Education of Gifted Young Scientists, 9*(3), 193–206. https://doi.org/10.17478/jegys.972540

Alroobaea, R., & Mayhew, P. J. (2014). How many participants are really enough for usability studies?. In 2014 Science and Information Conference. 48–56. https://doi.org/10.1109/SAI.2014.6918171

An, J., Poly, L. P., & Holme, T. A. (2019). Usability testing and the development of an augmented reality application for laboratory learning. *Journal of Chemical Education, 97*(1), 97–105. https://doi.org/10.1021/acs.jchemed.9b00453

Anderson, J. R. (1983). *The architecture of cognition*. Harvard University Press. https://doi.org/10.4324/9781315799438

Bakeman, R., & Gottman, J. M. (1997). *Observing interaction: An introduction to sequential analysis*. Cambridge University Press.

Bakeman, R., & Quera, V. (1995). *Analyzing interaction: Sequential analysis with SDIS and GSEQ*. Cambridge University Press.

Baseya, J. M., & Francis, C. D. (2011). Design of inquiry-oriented science labs: Impacts on students' attitudes. *Research in Science & Technological Education, 29*(3), 241–255. https://doi.org/10.1080/02635143.2011.589379

Bridges, S. M., Corbet, E. F., & Chan, L. K. (2015). Designing problem-based curricula: The role of concept mapping in scaffolding learning for the health sciences. *Knowledge Management & E-Learning: an International Journal, 7*(1), 119–133. https://doi.org/10.34105/j.kmel.2015.07.008

Buran, A., & Filyukov, A. (2015). Mind mapping technique in language learning. *Procedia-Social and Behavioral Sciences, 206*, 215–218. https://doi.org/10.1016/j.sbspro.2015.10.010

Cañas, A. J., Reiska, P., & Mollits, A. (2017). Developing higher-order thinking skills with concept mapping: A case of pedagogic frailty. *Knowledge Management & E-Learning: an International Journal, 9*(3), 348–365. https://doi.org/10.34105/j.kmel.2017.09.021

Chan, P., Van Gerven, T., Dubois, J. L., & Bernaerts, K. (2021). Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design. *Computers and Education Open, 2*, 100053. https://doi.org/10.1016/j.caeo.2021.100053

Chao, J., Chiu, J. L., DeJaegher, C. J., & Pan, E. A. (2016). Sensor-augmented virtual labs: Using physical interactions with science simulations to promote understanding of gas behavior. *Journal of Science Education and Technology, 25*(1), 16–33. https://doi.org/10.1007/s10956-015-9574-4

Chen, H. J., She, J. L., Chou, C. C., Tsai, Y. M., & Chiu, M. H. (2013). Development and application of a scoring rubric for evaluating students' experimental skills in organic chemistry: An instructional guide for teaching assistants. *Journal of Chemical Education, 90*(10), 1296–1302. https://doi.org/10.1021/ed101111g

Chou, P. N., & Feng, S. T. (2019). Using a tablet computer application to advance high school students' laboratory learning experiences: A focus on electrical engineering education. *Sustainability, 11*(2), 381. https://doi.org/10.3390/su11020381

Cui, J., & Yu, S. (2019). Fostering deeper learning in a flipped classroom: Effects of knowledge graphs versus concept maps. *British Journal of Educational Technology, 50*(5), 2308–2328. https://doi.org/10.1111/bjet.12841

Davenport, J. L., Rafferty, A. N., & Yaron, D. J. (2018). Whether and how authentic contexts using a virtual chemistry lab support learning. *Journal of Chemical Education, 95*(8), 1250–1259. https://doi.org/10.1021/acs.jchemed.8b00048

Demircioğlu, G., & Yadigaroğlu, M. (2011). The effect of laboratory method on high school students' understanding of the reaction rate. *Western Anatolia Journal of Educational Sciences*, 509–516. https://web.deu.edu.tr/baed/giris/baed/ozel_sayi/509-516.pdf

Desnita, D., & Susanti, D. (2017). Science process skills-based integrated instructional materials to improve student competence physics education prepares learning plans on teaching skills lectures. *Jurnal Penelitian & Pengembangan Pendidikan Fisika, 3*(1), 35–42. https://doi.org/10.21009/1.03105

Donaldson, N. L., & Odom, A. L. (2001). What makes swing time? A directed inquiry-based lab assessment. *Science Activities, 38*(2), 29–33. https://doi.org/10.1080/00368120109603607

Durmus, J., & Bayraktar, S. (2010). Effects of conceptual change texts and laboratory experiments on fourth grade students' understanding of matter and change concepts. *Journal of Science Education and Technology, 19*(5), 498–504. https://doi.org/10.1007/s10956-010-9216-9

Ekici, M., & Erdem, M. (2020). Developing science process skills through mobile scientific inquiry. *Thinking Skills and Creativity, 36*, 100658. https://doi.org/10.1016/j.tsc.2020.100658

Garnett, P. J., Garnett, P. J., & Hackling, M. W. (1995). Refocusing the chemistry lab: A case for laboratory-based investigations. *Australian Science Teachers Journal, 41*(2), 26–32.

Geban, O., Askar, P., & Ozkan, I. (1992). Effects of computer simulations and problem-solving approaches on high school students. *Journal of Educational Research, 8*(1), 5–10.

Ghani, I. A., Ibrahim, N. H., Yahaya, N. A., & Surif, J. (2017). Enhancing students' HOTS in laboratory educational activity by using concept map as an alternative assessment tool. *Chemistry Eeducation Rresearch and Ppractice, 18*(4), 849–874. https://doi.org/10.1039/C7RP00120G

Gunawan, G., Harjono, A., Herayanti, L., & Husein, S. (2019). Problem-based learning approach with supported interactive multimedia in physics course: Its effects on critical thinking disposition. *Journal for the Education of Gifted Young Scientists, 7*(4), 1075–1089. https://doi.org/10.17478/jegys.627162

Ha, L., Du, J., Holden, H., & Rada, R. (2009). Literature trends for mobile learning: Word frequencies and concept maps. *International Journal of Mobile Learning and Organisation, 3*(3), 275–288.

Hamm, J. M., Perry, R. P., Chipperfield, J. G., Murayama, K., & Weiner, B. (2017). Attribution-based motivation treatment efficacy in an online learning environment for students who differ in cognitive elaboration. *Motivation and Emotion, 41*(5), 600–616.

Hannasari, R., Harahap, M. B., & Sinulingga, K. (2017). Effect of scientific inquiry learning model using scientific concepts map and attitudes to skills process science students. *Journal of Education and Practice, 8*(21), 48–52.

Harahap, M. B., Manurung, S. R., Marbun, M. A., & Mihardi, S. (2016). Effect model inquiry training on students science process skill. *Advances in Social Sciences Research Journal, 3*(11), 38–42. https://doi.org/10.14738/assrj.311.2288

Hofstein, A., & Lunetta, V. N. (2004). The laboratory in science education: Foundations for the twenty-first century. *Science Education, 88*(1), 28–54. https://doi.org/10.1002/sce.10106

Hong, J., Pi, Z., & Yang, J. (2018). Learning declarative and procedural knowledge via video lectures: Cognitive load and learning effectiveness. *Innovations in Education and Teaching International, 55*(1), 74–81. https://doi.org/10.1080/14703297.2016.1237371

Hwang, G. J., Yang, T. C., Tsai, C. C., & Yang, S. J. H. (2009). A context-aware ubiquitous learning environment for conducting complex science experiments. *Computers & Education, 53*(2), 402–413.

Indriani, D., & Mercuriani, I. S. (2019). Experiential learning model with mind mapping on fungi: how to improve science process skills? *Biosfer: Jurnal Pendidikan Biologi, 12*(2), 223–237. https://doi.org/10.21009/biosferjpb.v12n2.223-237

Ismono, I., Poedjiastoeti, S., & Suyono, S. (2019). Train high order thinking skills at undergraduate students chemistry through concept map based learning. *In National Seminar on Chemistry, 2019*(19), 189–195. https://doi.org/10.2991/snk-19.2019.34

Jack, G. U. (2013). Concept mapping and guided inquiry as effective techniques for teaching difficult concepts in chemistry: Effect on students' academic achievement. *Journal of Education and Practice, 4*(5), 9–15.

Kirn, A., & Benson, L. (2018). Engineering students' perceptions of problem solving and their future. *Journal of Eengineering Eeducation, 107*(1), 87–112. https://doi.org/10.1002/jee.20190

Kubala, T. (1998). Addressing student needs: Teaching on the Internet. *The Journal, 25*(8), 71–74.

Kusumadewi, R. F., & Kusmaryono, I. (2022). Concept maps as dynamic tools to increase students' understanding of knowledge and creative thinking. *Premiere Educandum: Journal Pendidikan Dasar Dan Pembelajaran, 12*(1), 12–25. https://doi.org/10.25273/pe.v12i1.11745

Lai, C. L., & Hwang, G. J. (2014). Effects of mobile learning time on students' conception of collaboration, communication, complex problem-solving, meta-cognitive awareness and creativity. *International Journal of Mobile Learning and Organisation, 8*(3), 276–291.

Lee, V. W., Hodgson, P., Chan, C. S., Fong, A., & Cheung, S. W. (2020). Optimising the learning process with immersive virtual reality and non-immersive virtual reality in an educational environment. *International Journal of Mobile Learning and Organisation, 14*(1), 21–35. https://doi.org/10.1504/IJMLO.2020.103908

Li, F. Y., Hwang, G. J., Chen, P. Y., & Lin, Y. J. (2021). Effects of a concept mapping-based two-tier test strategy on students' digital game-based learning performances and behavioral patterns. *Computers & Education, 173*, 104293.

Makransky, G., Borre-Gude, S., & Mayer, R. E. (2019). Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments. *Journal of Computer Assisted Learning, 35*(6), 691–707. https://doi.org/10.1111/jcal.12375

Mandasari, F., Iwan, I., & Damopolii, I. (2021). The relationship between science process skills and biology learning outcome. *Journal of Research in Instructional, 1*(1), 23–32. https://doi.org/10.30862/jri.v1i1.9

Markow, P. G., & Lonning, R. A. (1998). Usefulness of concept maps in college chemistry laboratories: Students' perceptions and effects on achievement. *Journal of Research in Science Teaching: THe Official Journal of the National Association for Research in Science Teaching, 35*(9), 1015–1029.

Martínez, G., Pérez, Á. L., Suero, M. I., & Pardo, P. J. (2013). The effectiveness of concept maps in teaching physics concepts applied to engineering education: Experimental comparison of the amount of learning achieved with and without concept maps. *Journal of Science Education and Technology, 22*(2), 204–214. https://doi.org/10.1007/s10956-012-9386-8

Miranti, M. G., & Wilujeng, B. Y. (2017). Creative thinking skills enhancement using mind mapping. *Advances in Social Science, Education and Humanities Research, 112*, 39–42. https://doi.org/10.2991/iconhomecs-17.2018.9

Mutlu, A., & Şeşen, B. A. (2020). Comparison of inquiry-based instruction in real and virtual laboratory environments: Prospective science teachers' attitudes. *International Journal of Curriculum and Instruction, 12*(2), 600–617.

Nakiboglu, C. (2017). Use of graphic organizers in secondary chemistry lessons. *The Eurasia Proceedings of Educational and Social Sciences, 7*, 72–75.

Nechypurenko, P., Evangelist, O., Selivanova, T., & Modlo, Y. O. (2020). Virtual chemical laboratories as a tools of supporting the learning research activity of students in chemistry while studying the topic" solutions". *CEUR Workshop Proceedings, 2732*, 984–995.

Nechypurenko, P., & Selivanova, T. (2019). Using the virtual chemical laboratory vlab in teaching chemistry of 9th grade students. *Technology Transfer: Innovative Solutions in Social Sciences and Humanities*. https://doi.org/10.21303/2613-5647.2019.00932

Nezu, Y., Hayashi, R., & Oshima, Y. (2014). Case study of experimental behavior analysis in an academic chemical laboratory using fixed-point observation via web cameras. *Journal of Environment and Safety, 5*(2), 99–105. https://doi.org/10.11162/daikankyo.E14RP0601

Norris, S. P., & Phillips, L. M. (2012). Reading science: How a naive view of reading hinders so much else. *Metacognition in Science Education, 40*, 37–56. https://doi.org/10.1007/978-94-007-2132-6

Novak, J. D. (1990). Concept mapping: A useful tool for science education. *Journal of Rresearch in Sscience Tteaching, 27*(10), 937–949. https://doi.org/10.1002/tea.3660271003

Novak, J. D. (2002). Meaningful learning: The essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of students. *Science Eeducation, 86*(4), 548–571. https://doi.org/10.1002/sce.10032

Pernaa, J., & Aksela, M. (2010). Future chemistry teachers use of knowledge dimensions and high-order cognitive skills in pre-laboratory concept maps. *In Concept Maps: Making Learning Meaningful Proceedings of the Fourth International Conference on Concept Mapping.* 137–140.. http://hdl.handle.net/10138/24432

Piri, M., Mesrabadi, J., & Azizi, H. (2018). The effectiveness of concept map based instruction on concept retention and comperhension in science and social lessons in the elementry sixth grade. *Research in Curriculum Planning, 14*(55), 91–99.

Qarareh, A. O. (2010). The effect of using concept mapping in teaching on the achievement of fifth graders in science. *Studies on Home and Community Science, 4*(3), 155–160. https://doi.org/10.1080/09737189.2010.11885314

Rahimi, A., Ahmadi, H., & Rostami, I. (2021). The effectiveness of concept map on elementary students' creativity in science lessons. *Iranian Evolutionary and Educational Psychology Journal, 3*(3), 366–376. https://doi.org/10.52547/ieepj.3.3.366

Ratnasari, D., Sukarmin, S., Suparmi, S., & Aminah, N. S. (2017). Students' conception on heat and temperature toward science process skill. *Journal of Physics: Conference Series, 895*(1), 1–7. https://doi.org/10.1088/1742-6596/895/1/012044

Rivera, J. H. (2016). Science-based laboratory comprehension: An examination of effective practices within traditional, online and blended learning environments. *Open Learning: THe Journal of Open, Distance and e-Learning, 31*(3), 209–218. https://doi.org/10.1080/02680513.2016.1208080

Saputro, A. D., Rohaeti, E., & Prodjosantoso, A. K. (2018). Promoting critical thinking and problem solving skills of preservice elementary teachers through process-oriented guided-inquiry learning (POGIL). *International Journal of Instruction, 11*(4), 777–794.

Sariscsany, M. J., & Pettigrew, F. (1997). Effectiveness of interactive video instruction on teacher's classroom management declarative knowledge. *Journal of Teaching in Pphysical Education, 16*(2), 229–240. https://doi.org/10.1123/jtpe.16.2.229

Seechaliao, T. (2017). Instructional strategies to support creativity and innovation in education. *Journal of Education and Learning, 6*(4), 201–208. https://doi.org/10.5539/jel.v6n4p201

Serevina, V. (2018). Development of E-module based on problem based learning (PBL) on Heat and temperature to improve student's science process skill. *Turkish Online Journal of Educational Technology-TOJET, 17*(3), 26–36.

Smith, P. L., & Little, D. R. (2018). Small is beautiful: In defense of the small-N design. *Psychonomic Bbulletin & Rreview, 25*(6), 2083–2101. https://doi.org/10.3758/s13423-018-1451-8

Stevenson, J. (1998). Performance of the cognitive holding power questionnaire in schools. *Learning and Instruction, 8*(5), 393–410. https://doi.org/10.1016/S0959-4752(97)00029-7

Subramanian, R., & I. Marsic. (2001). ViBE: virtual biology experiments. In *proceedings of the 10th International World Wide Web Conference*, 316–325. https://doi.org/10.1145/371920.372076

Sugiharti, G., Hamid, A., & Mukhtar, M. (2019). The implementation of learning model and virtual lab toward learning outcome of chemistry education. *Journal Pendidikan Kimia, 11*(3), 79–86.

Sugiharti, G., & Limbong, E. R. (2018). Application of learning model with virtual lab and motivation in learning chemistry. *Journal Pendidikan Kimia, 10*(1), 362–366. https://doi.org/10.24114/jpkim.v10i1.9676

Sukarno, S., & Hamidah, I. (2013). The profile of science process skill (SPS) student at secondary high school (case study in Jambi). *International Journal of Scientific Engineering and Research, 1*(1), 79–83.

Talbert, L. E., Bonner, J., Mortezaei, K., Guregyan, C., Henbest, G., & Eichler, J. F. (2020). Revisiting the use of concept maps in a large enrollment general chemistry course: Implementation and assessment. *Chemistry Education Research and Practice, 21*(1), 37–50. https://doi.org/10.1039/C9RP00059C

Tatli, Z., & Ayas, A. (2010). Virtual laboratory applications in chemistry education. *Procedia-Social and Bbehavioral Ssciences, 9*, 938–942. https://doi.org/10.1016/j.sbspro.2010.12.263

Tatli, Z., & Ayas, A. (2013). Effect of a virtual chemistry laboratory on students' achievement. *Journal of Educational Technology & Society, 16*(1), 159–170.

Ülger, K. (2016). The relationship between creative thinking and critical thinking skills of students. *Hacettepe University Journal of Education, 31*(4), 695–710. https://doi.org/10.16986/HUJE.2016018493

Ural, E. (2016). The effect of guided-inquiry laboratory experiments on science education students' chemistry laboratory attitudes, anxiety and achievement. *Journal of Education and Training Studies, 4*(4), 217–227. https://doi.org/10.11114/jets.v4i4.1395

Usman, M., & Huda, K. (2021). Virtual lab as distance learning media to enhance student's science process skill during the COVID-19 pandemic. *Journal of Physics: Conference Series*. https://doi.org/10.1088/1742-6596/1882/1/012126

Vasconcelos, C., Ferreira, F., Rolo, A., Moreira, B., & Melo, M. (2020). Improved concept map-based teaching to promote a holistic earth system view. *Geosciences, 10*(1), 8. https://doi.org/10.3390/geosciences10010008

Wahyuni, T. S., & Analita, R. N. (2017). Guided–inquiry laboratory experiments to improve students' analytical thinking skills. *AIP Conference Proceedings, 1911*. https://doi.org/10.1063/1.5016010

Wang, Z., Adesope, O., Sundararajan, N., & Buckley, P. (2021). Effects of different concept map activities on chemistry learning. *Educational Psychology, 41*(2), 245–260. https://doi.org/10.1080/01443410.2020.1749567

Whitelock-Wainwright, A., Laan, N., Wen, D., & Gašević, D. (2020). Exploring student information problem solving behaviour using fine-grained concept map and search tool data. *Computers & Education, 145*, 103731. https://doi.org/10.1016/j.compedu.2019.103731

Winkelmann, K., Keeney-Kennicutt, W., Fowler, D., & Macik, M. (2017). Development, implementation, and assessment of general chemistry lab experiments performed in the virtual world of second life. *Journal of Chemical Education, 94*(7), 849–858. https://doi.org/10.1021/acs.jchemed.6b00733

Wittrock, M. C. (1978). The cognitive movement in instruction. *Educational Psychologist, 13*(1), 15–29. https://doi.org/10.1080/00461527809529192

Wong, S. S. H., & Lim, S. W. H. (2021). Deliberate errors promote meaningful learning. *Journal of Educational Psychology*. https://doi.org/10.1037/edu0000720

Wu, B. J., Wong, S. K., & Li, T. W. (2019). Virtual titration laboratory experiment with differentiated instruction. *Computer Animation and Virtual Worlds*. https://doi.org/10.1002/cav.1882

Yesiloglu, S. N., Gençer, S., Ekici, F., & Isik, B. (2021). Examining pre-service teachers' views about online chemistry laboratory learning experiences amid the COVID-19 Pandemic. *Journal of Turkish Science Education, 18*, 108–124. https://doi.org/10.36681/tused.2021.75

Zhao, L., Liu, X., Wang, C., & Su, Y. S. (2022). Effect of different mind mapping approaches on primary school students' computational thinking skills during visual programming learning. *Computers & Education, 181*, 104445. https://doi.org/10.1016/j.compedu.2022.104445

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