Development of Collaborative Chemistry Experiment Environment Using VR

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Abstract. In recent years, the importance of distance learning has been reaffirmed, but there are some subjects where learning is ineffective owing to the difficulty of interaction. For chemistry experiments, some researchers have tried to conduct remote experiments using head-mounted display (HMD)-based virtual reality (VR). However, in these attempts, there is a concern that collaborative learning, which is important in science education, is lacking. In this study, we proposed a new environment for remote chemistry experiments using network services and HMD-based VR. Specifically, we conducted VR experiments of flame color reaction and metal ion separation and identification, which are often taught in high school chemistry, and then evaluated the effectiveness of the proposed environment using exams and questionnaires. The results confirmed effective learning in the chemistry experiment using HMD-based VR, suggesting that collaborative learning was possible in VR spaces.

Keywords: VR · CSCL · Chemical experiment · E-learning · E-education · Synchronous learning

1 Introduction

1.1 Background

Devices such as personal computers and smartphones, which have become ubiquitous in modern society, can communicate remotely and are expected to become even more widespread in the future. Against this backdrop, Japan's Ministry of Education, Culture, Sports, Science and Technology is aiming to promote distance education [1]. Accordingly, they are improving the information and communication technology (ICT) environment in schools from 2018 to 2022 [2]. However, for subjects that require face-to-face lessons, such as physical education, technology, and chemistry experiments, it is expected that effective learning might be difficult in distance lessons.

Among such subjects, this study focuses on chemistry experiments, in which dangerous equipment and materials are handled. The primary approach in distance

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learning is video demonstration experiments by instructors. However, students cannot interact with such demonstrations, and therefore there is a concern that the students will miss learning opportunities.

In recent years, to address such problems, there have been attempts to conduct science experiments remotely by using head-mounted display (HMD)-based virtual reality (VR) and augmented reality (AR) [3–5]. These attempts were aimed at individuals, but in the science section of the Ministry of Education, Culture, Sports, Science and Technology's curriculum guideline [6], school education is required to include work with others to solve problems. Therefore, collaborative learning is important. In this respect, the previous remote learning attempts were inadequate, and we are also concerned that the advantages of in-person collaborative classes, such as exposure to a variety of opinions and ideas, the development of communication and social skills, and the deepening of one's own understanding through discussion and debate with friends, will not be achieved.

1.2 Purpose of This Paper

From the current situation of distance learning as described above, it is considered necessary to have a distance learning environment in which students can interact and collaborate. Therefore, in this study, we develop a collaborative learning system for chemistry experiments using VR with network services and evaluate its effectiveness.

2 HMD-Based VR and Collaborative Learning

2.1 Trends in HMD-Based VR

In a 2019 survey [7] conducted on 206 people aged between 15 and 69, 91% recognized the term VR, and 21% had actually experienced VR. Of those who had experienced it, 85% responded that they were satisfied with the sensation of reality and presence.

In 2020, an affordable stand-alone HMD-based VR device that does not require a high-spec computer was released [8], which is expected to make VR more widespread in the future and enable its use in the educational field.

2.2 Example of Using HMD-Based VR for Education

Nakamura et al. [3] focused on the gyro sensor of smartphones and tried to develop e-learning materials to teach physics to students experientially. By using the gyro sensor of a smartphone and operating the camera in the virtual space according to the direction a student is facing, the student can freely observe and move in the virtual space to obtain a high sense of immersion. This synchronous e-learning teaching material has the following advantages:

- It is possible to reproduce an environment that is not possible in reality, such as an object with zero mass or a space with zero friction.
- Experiments are easy to repeat
- Experiments such as those dealing with explosives or fragile objects are possible without risk.

Nakamura et al. dealt with physics experiments, but the above advantages might be possible in chemistry experiments as well. However, Nakamura et al. expressed concern that the learning opportunities of the stuis possible to reproduce an environment that dents may not be sufficient because the learning is based on demonstration experiments.

Okamoto et al. [4] conducted a solution experiment of inorganic chemistry using an HMD-based AR device and suggested the possibility of acquiring knowledge about inorganic chemistry. In their research, HMD-based AR equipment was used, but it is expected that the same learning effect can be obtained with HMD-based VR because VR can provide an immersive experience equal to or better than that of AR.

Hayashi et al. [5] used a hand-tracking controller within a VR chemistry experiment environment. They confirmed that chemical experiments involving body movements can be performed in virtual space.

In this study, we focus on collaborative learning, which was not considered the abovementioned studies.

2.3 Collaborative Learning

The Ministry of Education, Culture, Sports, Science and Technology states in its guidance on qualities and abilities to be cultivated in a topic, "What the new curriculum guideline aims for [9]" is "the ability to think, judge, and express oneself in order to share information with others, to understand the similarities and differences in diverse ways of thinking through dialogue and discussion, to sympathize with the ideas of others and to integrate diverse ideas, and to solve problems in cooperation (collaborative problem solving)" and "an attitude of respect for diversity and the ability to work together by making the best use of each other's strengths." In addition, "Thinking ability, judgment ability, expressive ability, etc., experience the scene of independent and collaborative problem finding/solving in which the above-mentioned thinking/judgment/expression is demonstrated in learning. The individual knowledge and skills that you have acquired will also be established by utilizing them in such learning experiences, and you will acquire them while being systematically associated with existing knowledge and skills, and eventually your life. It is expected to lead to a deep understanding of things and mastery of methods that can be utilized throughout."

In this way, collaborative learning is positioned as extremely important for learning in the coming era. In this study, we focused on "collaborative problem solving" and whether the knowledge and skills acquired by it can be systematized and acquired even in VR space.

CSCL. Computer-supported collaborative learning (CSCL) is a research activity that uses a computer to support collaborative learning in which multiple students learn while communicating with each other remotely. Nakahara [10] explains CSCL as follows:

> In conventional learning theory, learning is considered to be the accumulation of an individual student's knowledge, and the transfer of knowledge from the teacher's mind to the student's mind is learning and education. However, CSCL takes a situational cognitive approach that seeks to focus knowledge not only in the mind but also in relation to others and tools. This shift from traditional learning theory to a situational cognitive approach has brought about the following changes in beliefs about teaching and learning:
> - Change in students from "people who are satisfied with sharing the same knowledge" to "people who can cooperate with each other"
> - Change in teachers from "sources of knowledge" to "guides to advanced intellectual resources within the community"
> - Change in learning activities from "means for accumulation of knowledge" to "exercises of knowledge using tools and/or participation in the community"
> - Change in the learning objective from "the cultivation of competent individuals" to "the cultivation of individuals who can demonstrate their intellect when they cooperate while being dispersed in various groups."

In this way, with the progress of ICT and the importance of collaborative learning, the importance of CSCL is increasing and the form of learning is also changing. In this study, we tried to realize collaborative learning, which is important in science, in the form of CSCL.

3 System Overview

In this study, an HMD-based VR device was used by participants in order to conduct chemical experiments in VR space. The advantages of HMD-based VR are that it is highly immersive, it is possible to interact with objects as in an actual experiment, and the presence of others is greater than with an AR device when multiple people participate in a synchronized manner. The HMD-based VR device can transfer the movement of the body in real space to the virtual space by using infrared sensors. There are two types of movement methods: one is to actually walk in an area set in real space, and the other is to move back, forth, left, and right by operating the trackpad of a controller. One can also use the controller to lift objects and drop reagents from pipettes.

The Unity platform [11] was used to build the system, and Photon's PUN 2 package [12] was used as a network service for synchronization. PUN 2 is a multiplayer platform that enables highly reliable and rapid communication.

The experimental scene of this system is shown in Fig. 1. We prepared each subject's avatar and laboratory equipment with PUN 2's original network game object, and implemented it so that multiple people can conduct experiments remotely by sending and receiving object information via the Photon server.

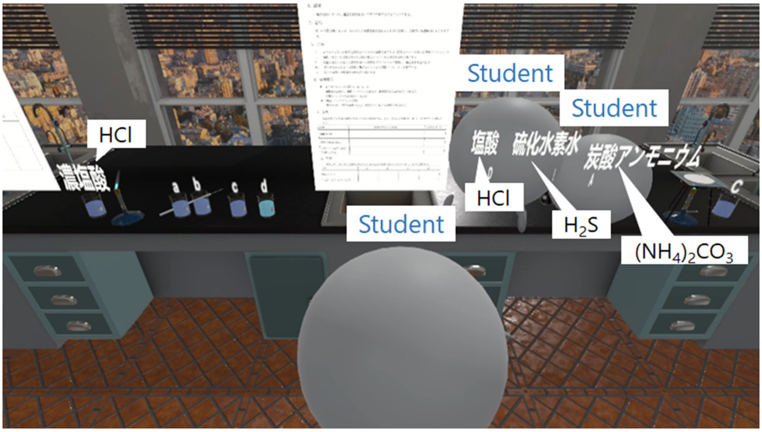

Fig. 1. Experimental scene with multiple people

3.1 Learning Content

This study deals with the flame reaction and metal ionization tendency of inorganic chemical compounds. For the flame reaction, students learn the change in the flame color of a gas burner depending on the sample introduced to it, and for the ionization tendency of the metal, students learn the identify of metal ions by introducing separation reagents into the system. These experiments were selected because they are frequently performed in junior high and high schools, and it is difficult and hazardous for a student to deal with gas burners and dangerous reagents without supervision. Because this system can conduct experiments in a non-hazardous situation, we thought that it would be effective even when students study outside of class hours.

Flame Reaction Experiment. When an alkali metal or alkaline earth metal is heated with a gas burner flame, the flame turns a color that is peculiar to the metal. Using this feature, we conducted experiments aimed at identifying the type of metal. In this experiment, first samples of salt ($NaCl$), potassium chloride ($NaCl$), strontium chloride ($SrCl_2$), and copper sulfate ($CuSO_4$) are dissolved in water. We randomly label and arranged them so that students do not know what solution is in any specific beaker. Students first clean the tip of a platinum wire with concentrated hydrochloric acid. Next, the tip of the platinum wire is dipped in a sample solution (Fig. 2), the tip is inserted into the flame of a gas burner (Fig. 3), and the student observes the flame color. This procedure is repeated for each solution. By looking at the color of the flame, the students determine whether the metal contained in the sample is Na, K, Sr, or Cu.

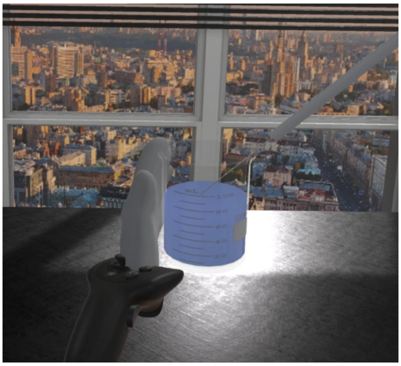

Fig. 2. Dipping the platinum wire into a solution

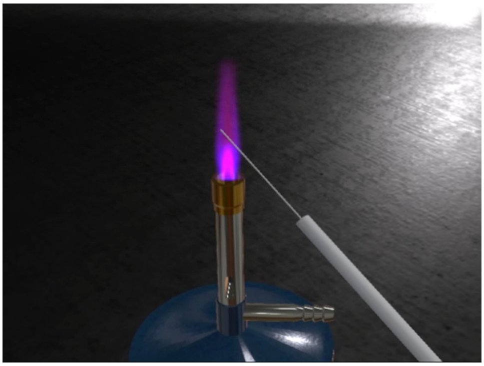

Fig. 3. Observing the flame reaction color

Metal Ion Separation Detection Experiment. Generally, cations can be divided into six groups by using appropriate separation reagents. In this experiment, students learn that cations of groups I to V can be precipitated, separated, and detected as each separation reagent is added. First, samples of silver nitrate ($AgNO_3$), sodium nitrate ($NaNO_3$), copper nitrate (II) [$Cu(NO_3)_2 \cdot 3H_2O$], and calcium nitrate [$Ca(NO_3)_2 \cdot 4H_2O$] are dissolved in water. We randomly label and arrange the solutions so that students do not know which sample is in any specific beaker. Students add hydrochloric acid (HCl) and hydrogen sulfide solution (H_2S_{aq}) to each beaker (Fig. 4). Then, a gas burner is used to expel hydrogen sulfide from the sample and then ammonium carbonate solution [$(NH_4)_2CO_3$] is added drop by drop, resulting in a white precipitate of silver chloride (Fig. 5), a black precipitate of copper sulfide, or a white precipitate of calcium carbonate. Students observe the results and consider which metal ion, Na+, Ag+, Cu2+, or Ca2+, is in each sample.

4 Evaluation Experiment

The evaluation experiment was performed according to the procedure shown in Fig. 6. Participants were randomly divided into an asynchronous system group, in which an individual uses the system, and a synchronous system group, in which multiple people perform synchronous communication to perform experiments together. First, we conducted a preliminary test (pre-test) on the instructional

Fig. 4. Dropping hydrochloric acid into a solution

Fig. 5. Change in color after the metal cation precipitates

content related to the flame reaction, the ionization tendency of the metal, and the equipment used in the experiment, and then we provided a basic explanation of the HMD-type VR device, such as how to use the controller. Next, in both groups, the experimental instructions existing in the VR space were first browsed, and then the subjects were observed as they carried out the chemical experiments. The synchronized system group used the voice call feature of the LINE app [13] to communicate by voice conversation. The content of the chemical experiments, as shown in Sect. 3.1, was the same for both groups. After that, participants answered a post-test with the same content as the pre-test and finally answered a questionnaire.

4.1 Evaluation Index

The purpose of the evaluation experiment is to determine whether effective collaborative learning can be achieved by multiple people sharing a VR environment with an HMD-type VR device. The evaluation indexes are the scores of a pre-test, post-test, and questionnaire. The questionnaire was composed of several sets of questions rated on a five-point scale (with 5 being positive) and a free-form comment section. The questions common to both groups included VR-related questions, system-related questions, and the comment section. An additional set of questions, also rated on a five-point scale, addressed the individual versus collaborative natures of the two different groups: one set investigated the environment in the asynchronous system (individual) group, and the synchronous system group was asked the other set of questions based on the collaborative learning environment design principles proposed by Mochizuki et al. [14]. Specifically, this environment consists of six design principles based on the division of labor in CSCL, which indicates collaborative learning supported by computers.

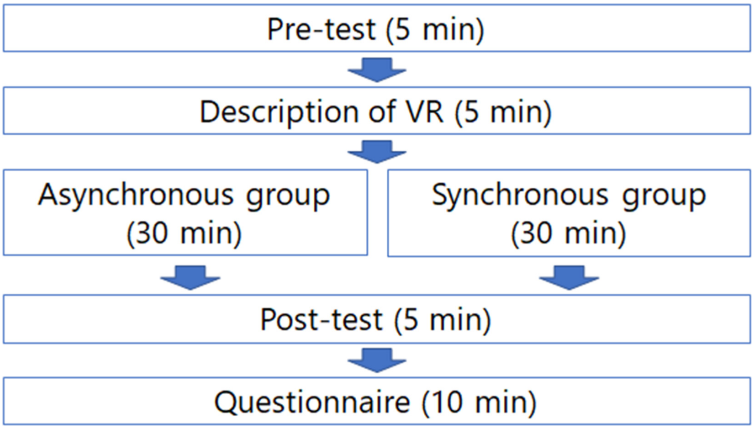

Fig. 6. Experimental flow

4.2 Results and Discussion

Results of Pre- and Post-tests. Eighteen university students participated in the evaluation experiment; nine were in the synchronous system group, and the other nine were in the asynchronous system group. In the synchronous group, the nine people were further divided into three subgroups. The test results are shown in Table 1.

Table 1. Pre- and post-tests results

Test	Synchronous group		Asynchronous group	
	Mean	SD	Mean	SD
Pre-test	3.667	1.054	3.889	0.875
Post-test	4.444	0.831	4.889	0.875

In both groups, the post-test scores were higher than those of the pre-test. Two-way analysis of variance (ANOVA) with replication was performed on the results of Table 1. We set the synchronous system group and asynchronous system group in the specimen elements, set the pre-test and post-test scores in the column elements, with the significance level set to 0.05. The results are shown in Table 2.

Table 2. ANOVA between pre- and post-test results

Variable factor	P-value	Significant difference?
Specimen (between groups)	0.309	No
Column (between tests)	0.010	Yes
Interaction	0.733	No

There was a significant difference in the increase in scores between the pre- and post-tests, which is the column item ($p < 0.05$). However, no significant difference was found between the synchronous group and asynchronous group, which is the specimen item. In addition, no significant difference was found in the interaction. It is possible that the effect of collaborative learning was not fully exhibited because the technical content of the experiment was not very complicated. Therefore, it is necessary to employ experiments dealing with more complicated subjects and verify whether problems can be solved in collaboration.

Questionnaire Results

– About VR
The results of the questionnaire about the VR space are shown in Table 3.

Table 3. "About VR" questionnaire results

Q	Question content	Synchronous group		Asynchronous group	
		Mean	SD	Mean	SD
Q1	I was able to concentrate (become immersed) in the VR space	4.667	0.471	4.556	0.956
Q2	The chemistry experiment in VR space was done in the same way as an actual chemistry experiment	3.222	0.629	3.889	0.737

In Q1, both groups reported high levels of immersiveness, so it is probable that this system created an environment where it was easy to concentrate on the chemical experiments. However, responses to Q2 by the synchronization system group were moderate. One participant reported that "the physical behavior was strange." Therefore, it is necessary to aim for behavior that is closer to reality.

– About the System
The results of the questionnaire about the system are shown in Table 4.

Table 4. "About the system" questionnaire results

Q	Question content	Synchronous group		Asynchronous group	
		Mean	SD	Mean	SD
Q1	There was no discomfort in the flame and its color expressed in the VR space	4.444	0.685	4.333	1.247
Q2	The flame expressed in the VR space and its color change were easy to observe	4.667	0.471	5.000	0.000
Q3	There was no discomfort in the appearance of the liquid expressed in the VR space	3.778	1.227	3.333	1.414
Q4	I was able to observe the precipitation reaction expressed	3.444	1.499	3.667	1.247

From Q1 and Q2, the flame reaction exercise was highly rated overall, and we were able to obtain the opinion that "the color and reaction of the flame are easy to understand" in one of the comments. It was suggested that the flame reaction experiment using the HMD-type VR device was easy to understand and might be effective for learning.
Regarding the metal ion separation detection experiments in Q3 and Q4, the standard deviation was large and the rating was moderate. In addition, comments mentioned low realism of "the appearance of the liquid" and "the appearance of the precipitate." When conducting a metal ion detection experiment in VR space, it is considered necessary to improve the realism of liquid representation.

– Group-specific Survey
In the group-specific questionnaire, "synchronization" was investigated in the synchronous system group, and "environment" was investigated in the asynchronous system group.
The results of the "environment" questionnaire are shown in Table 5.

Table 5. "About environmental" questionnaire result

Q	Question content	Mean	SD
Q1	Work progressed without problems	3.778	1.133
Q2	I was able to work smoothly	3.667	1.054
Q3	I felt like I was performing the experiment with multiple people	4.222	0.916

From Q1 and Q2 in Table 5, it is considered that the content of the chemical experiments dealt with in this experiment were such that individuals could proceed smoothly even while working alone. Therefore, it is considered that there was no significant difference between the groups in Table 2. However, Q3 showed that they were interested in experiments with multiple people, suggesting that they are highly motivated for collaborative learning in chemistry experiments.

In the synchronous group, we investigated the collaborative learning environment design principle advocated by Mochizuki et al. The results of the questionnaire are shown in Table 6. However, for Q7, some students thought that there were no inconsistencies or mistakes in the work, and the experiment was completed without any problems, so the number of valid responses to the questionnaire was six.

Table 6. "About synchronization" questionnaire result

Q	Question content	Mean	SD
Q1	I was able to share the work and carry out the experiment	3.889	0.994
Q2	I was able to carry out the experiment smoothly by sharing the work	3.222	0.916
Q3	I was able to grasp my work situation	3.667	0.943
Q4	I was able to grasp the work status of others	3.667	1.054
Q5	I was able to understand that others understood my work situation	3.111	0.875
Q6	I was able to share the work situation of myself and others and coordinate with them	3.444	0.956
Q7	When dividing labor, there is a contradiction in the work situation of the other party or your own work situation and I noticed a mistake	4.000	1.000

The three items Q2, Q5, and Q6 were rated relatively low, and an associated comment was "I couldn't distinguish avatars." It is possible that the experiment did not proceed smoothly because the similar appearance of student avatars led to communication problems. We also received the comment that "I want to be able to share information not only on the phone but also on VR." By taking fuller advantage of VR, it will be possible to realize smoother progress by presenting information on the progress of the experiment within the VR environment.

Because we were able to obtain a high overall evaluation for all items regarding the collaborative learning design principle, it is considered that collaborative learning was realized in this system. It will be important in the future to build an environment that facilitates collaborative learning by presenting information that visualizes the appearance of avatars and the progress of experiments.

5 Conclusion

5.1 Summary

In this study, we focused on chemical experiments, which are considered difficult to carry out in distance learning. Experiments are considered to be very important for teaching chemistry, but in distance learning, it is not possible to operate laboratory equipment, so students can only watch presentations by teachers or forego remote learning (i.e., go to school to perform experiments hands-on). In recent years, attempts have been made to carry out chemical experiments remotely by using HMD-type VR devices. However, these attempts were aimed at individuals and did not carry out collaborative learning, which is important in science. Therefore, in this study, we proposed an environment in which students can interact with each other and learn collaboratively on a network system using HMD-based VR, and evaluated its effectiveness. We developed a system in which students can carry out flame reaction experiments and metal ion separation and detection experiments remotely and collaboratively, and conducted the experiments by dividing participants into a synchronous group (remote collaborative learning) and an asynchronous group (remote individual learning). Based on the collaborative learning environment design principle [14] proposed by Mochizuki et al., the results indicating whether collaborative learning was realized suggested that collaborative learning of chemistry experiments using HMD-based VR was established. In addition, it was suggested that it is effective in improving the effectiveness of learning, regardless of whether it is collaborative.

5.2 Future Issues

In the collaborative learning environment design principle [14], as implemented in this study, it was not possible for students to distinguish the avatars of other students, so there was a discrepancy in the sharing of progress and communication when experiments were performed with a division of labor. It is necessary to improve the appearance of avatars, and then verify whether this change makes collaborative learning progress more smoothly and achieve a higher learning effect. It was also suggested that the realism of the chemistry needs to be improved. Improving the realism of the appearance and physical behavior of liquids may enhance the immersive feeling and allow more focus on the experiment. In this study, it was confirmed that collaborative learning using an HMD-based VR device was realized, but the content of the experiments could also be carried out by individuals. For this reason, it is considered that there was no significant difference in the learning effect between the pre- and post-tests between the synchronous system group and the asynchronous system group. This suggests that the verification of learning effects in collaborative learning remains insufficient. Therefore, it is necessary to design experiments with more complicated content and verify the learning effect of collaboration.

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