Ph.D. Dissertation in Science Education

The Development of the Blended Laboratory and E-learning Instructional Design (BLEND) Model

: Lessons from University Instructors and Students Toward the Post-COVID-19 Laboratory Education

블렌디드 실험 및 이러닝 교수 설계 모형의 개발

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Abstract

The COVID-19 situation in 2020 and the so-called social distancing preventive policy necessitated the sudden shift of university laboratory courses from a conventional face-to-face format into an unfamiliar non-face-to-face one. Amidst the unexpected educational losses worldwide, science education scholars focused on the changes in laboratory education brought by remote laboratory course format and urged empirical studies on them.

The researcher had two research purposes throughout this study. First, it was to answer fundamental questions on the essence of laboratory education that were raised facing the unprecedented global implementation of remote laboratory courses. (Q1) What is the essence of the laboratory experience from the university to K-12 science education? If satisfactory learning outcomes are secured to some extent, can (remote) minds-on experience replace hands-on one? (Q2) Is spatio-temporal co-presence of instructors and students necessary? (Q3) How can we invite students to an inquiry about natural phenomena, which would be represented in their scientific writing in their lab report? (Q4) Do the answers differ according to the characteristics of interaction among instructors and students and in different cultures worldwide? (Q5) How can we design a laboratory course that is both effective and adaptive that can be implemented in both normal and emergency situations? The tentative answers were explored while reviewing theoretical backgrounds and more direct answers were given while discussing the specific results of this study.

Second, it was to investigate what happened in the university STEM education sites concerning remote labs necessitated by the COVID-19 in 2020 and provide implications for future University Remote Laboratories (URLs). More specifically, it was to rationalize how university instructors implemented their remote labs in the spring semester of 2020 facing the imminent pandemic (Study 1), investigate the consequence of those remote labs via university students' response (Study 2), and prescribe practical guidelines

for future remote lab design (Study 3). The research field of Hankuk University (pseudonym) initiated and enabled this overall research.

A framework to understand URL as the locus where the components of laboratory sessions and e-learning intersect was suggested. The reasons for implementing laboratory or e-learning courses lie in the purpose of laboratory or the promises and requirements of e-learning. As instructional programs, laboratory and e-learning should consider how the content is delivered, interactions between learners promoted, and assessment and feedback are provided. And those three factors in both programs naturally correspond to each other. The COVID-19 situation made the two strands of educational tradition meet, interplay, and blended in the various URL courses that emerged in 2020. The characteristics of the URL courses in 2020 were shaped according to each teaching and learning context, which includes sociocultural factors. And the lessons from URL instructors and students in 2020 (Study 1 and 2) led the researcher to an extended understanding of blended learning for laboratory education (see 2.3.4) and raised the need for an instructional design (ID) model for URLs (see 2.5 and Study 3).

For laboratory in science education, the purpose of laboratory, hands-on versus minds-on debate, interaction in laboratory, and lab report writing and feedback were contemplated. For e-learning and effective teaching strategies, the promises and requirements of e-learning, media presentation, aspects of online interaction, and assessment and feedback in e-learning were deliberated. For (re-)emergence of remote laboratory, studies before and after the COVID-19 were reviewed, and its meaning was revisited. Particularly, understanding remote laboratory as extended blended learning was suggested, which first blends the hands-on and minds-on laboratory experiences and second laboratory experiences and learning spaces.

Further, the instructor agency framework in science education was utilized to interpret the adaptive behavior of university STEM instructors while implementing their remote lab courses. The sociocultural perspective on Korean science instructors' agency elaborated the researcher's horizon of interpretation in macro-, meso- and micro- level structures. Also, the notion of design and development research in educational technology assured the utility of an ID model that is adaptive and flexible, which includes rapid prototyping (RP) when eliciting the course module for external validation.

In Study 1, the researcher compared four general remote labs, each for physics, chemistry, biology, and earth science, that were previously similar, and two major course labs at Hankuk University. The emergence of URL phenomena was interpreted from a sociocultural perspective, focusing on the structure posed by the COVID-19 pandemic and the educational authorities and the agency of university instructors. The macro-level context of Korea, the meso-level context of Hankuk University, and the micro-level context of each URL were closely interconnected with each other and the university instructors' agency. In the spring semester of 2020, instructors' agency was strongly shaped by the multi-level structures. However, the implemented URL in each discipline became quite various due to the endeavor instructors put in. The university instructors' concerns were about video materials, data characteristics, limited interactions between them and students, difficulties in evaluation, and what students could "gain" from the URLs without hands-on experience. Since the fall semester of 2020, instructors have adapted to the situation, revised their URLs, and suggested further improvements. Study 1 reveals that university instructors' agency led to the emergence of various remote laboratory course implementations in the context of an imminent emergency.

In Study 2, in step with Study 1, the researcher investigated how Hankuk University students perceived various remote laboratory course experiences in different content disciplines. Conducted as a mixed-methods study, online survey responses were collected from 338 students, and in-depth interviews were conducted with 18 students. ANOVA and Bonferroni post hoc tests of survey responses found that students' perceptions of their URL experiences were significantly different ($p < .05$) dependent on content discipline (physics, chemistry, biology, earth science, and other majors). In addition, student interviews revealed that these differences in perceptions resulted from the different emergent teaching strategies used in each course. Suggestions were made for clearly setting learning objectives, carefully designing videos of experiments, offering collaborative synchronous online sessions, providing guidance and feedback for lab report writing, and introducing supportive assessments as strategies for future implementation of remote labs.

In Study 3, the BLEND (Blended Laboratory and E-learning iNstructional Design) ID model for URL was developed and validated. To respond to the fluctuating instructional environment of the pandemic, an ID model was promptly constructed and applied in the authentic learning context, iteratively revising the model with participant feedback. The research context was an Analytical Chemistry Experiment (ACE) course for pre-service chemistry teachers. The initial BLEND model was based on a literature review and lessons from Study 1 and 2 in 2020. For internal validation, six stakeholders participated in the usability test, and 10 subject-matter experts from various science disciplines and three educational technology experts provided expert reviews. For external validation, the URL course module was developed and implemented from the ID model, and seven university students who took the course responded to online surveys and participated in follow-up interviews. After two rounds of validation, the BLEND model was confirmed to be internally efficient and externally effective. The interactions with the instructor and peers, in particular, were highly appreciated. The finalized BLEND model for URL emphasizes constant formative evaluation and feedback and structures and visualizes the URL instructional system at both the weekly and overall course levels. Study 3 is a rare case of applying a design and development research method to science education.

Some issues were not resolved in this study and need follow-up research: (1) The interplay between the requirements of remote lab format and the nature of each science discipline (i.e., physics, chemistry, biology, and earth science) should be scrutinized. (2) How the experiment video should be designed, shot, and edited remains crucial. (3) An ID model for open-ended inquiry laboratory is a plausible future research topic. Then, how to evaluate the open-ended inquiry module arises as an essential prerequisite, which is also an important research agenda.

The strength of this study lies in its unique research field - Hankuk University in 2020 and 2021. This study seems to have collected extensive data for various remote lab courses that emerged in the initial situation of the COVID-19. Therefore, Study 1 to Study 3 can be said the attempts that report the URL phenomena during the early stage of the COVID-19 comprehensively. However, ironically, the COVID-19 situation that shaped the strength of this study can also be a double-edged sword as time passes and the situation changes. Consequently, the status of remote teachings, especially of remote labs in the post-COVID-19 era, is hard to predict.

If we take an optimistic view, our experience of URLs will broaden our imagination to evolve our laboratory education towards a blended format incorporating various learning modes across time and space. Indeed, the extended understanding of the blended learning for laboratory courses could shed some light on the path that overcoming the old dichotomies such as hands-on versus minds-on, synchronous vs. asynchronous, physical versus virtual, and place-based versus remote, to proceed toward better laboratory education.

In contrast, if we take a pessimistic view, we can expect that even our serious contemplation on remote labs may disappear someday, as many teaching methods did in the history of education. Therefore, it is recommended to recall fundamental questions on the essence of laboratory sessions that are rediscovered while we experience remote labs due to the COVID-19 (Q1-Q5). The easiest way to answer those questions would be by relying on the peculiarity of the learning objectives in each laboratory course - however, it does not open the way to more profound contemplations toward the post-COVID-19 laboratory education.

Instead, more certain answers for the abovementioned questions (Q1-Q5) could be meaningfully derived from participants' voices throughout this study: (A1) The minimum firsthand experience should be secured to foster students’ experimentation skills and provide students chances to engage with unexpected phenomena relevant to tacit knowledge and the nature of science. Note that a blended learning format can be an

alternative that provides students with both hands-on and minds-on experiences. (A2) Instructors and students must have synchronous interactions in a temporal aspect. However, whether the spatial co-presence is necessary is not so manifest. (A3) If possible, a semester-long open-ended laboratory class would be the best chance to invite students to in-depth inquiry thinking. However, the gap between the theoretical prediction and the real experimental data seems to be the plausible locus where an inquiry may arise for cookbook-style labs in a practical sense. Therefore, the pre-lab activity, the characteristics of data, and peer discussions should be designed carefully. (A4) If the culture surrounding the laboratory education site favors the hand or mind as a cognitive channel or shapes the interaction between instructors and students vertically or horizontally, the answer would be yes. (A5) The notion of formative assessment of the instructional system may help make the laboratory courses more adaptive and flexible in various instructional situations, as in the BLEND model developed in Study 3.

The instructors and students at Hankuk University in 2020 were genuine agents who struggled to implement and take URL courses. And their lessons enabled the development of the BLEND model and the contemplation of the essence of laboratory sessions toward the post-COVID-19 laboratory education.

Keyword: remote laboratory course, university science education, e-learning, teacher agency, design and development research, COVID-19

Student Number: 2016-25832

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Chapter 1. Introduction

1.1 Study Background

The word ‘crisis’ has its etymological meaning of “judgment, result of a trial, selection” from the Greek word κρίσις (krisis), which in turn has the meaning of “decisive point in the progress of a disease,” and also “vitally important or decisive state of things, point at which change must come, for better or worse.”[1] Therefore, when we face the crisis of something, we shall diagnose its state as like it being interrogated to be sentenced in court or checked up before major surgery, which would decide its destiny to face essential changes. Therefore, a crisis that comes with the ‘new normal’ calls for a historical contemplation of what past it has undergone, its present status, and the necessary changes for the future.

The COVID-19 pandemic outbroke in late 2019 in Wuhan, China, and has swept the globe rapidly. As the respiratory disease is characterized by its high contagiousness, essentially all the countries in the world have been swayed since 2020. The influence of COVID-19 reached almost all aspects of our living world, including politics, economy, society, culture - and especially education. The so-called social distancing policy ordered schools from kindergarten to university to be closed at least temporarily. For instance, according to United Nations Educational, Scientific and Cultural Organization (UNESCO) (2022), more than 1.29 billion K-12 students from 151 countries, about 81.8% of total enrolled students, were affected by the school closure as of April 20th, 2020. Consequently, previously assumed face-to-face (FTF) teaching and learning practices were

[1] https://www.etymonline.com/word/crisis (retrieved May 6th, 2022)

mandated to shift to non-face-to-face (NFTF) ones, which most educators around the globe were not prepared to implement in early 2020.

The initial response from educators worldwide was desperate. Most scholars predicted that the remote teaching environment coerced by the pandemic would lead to educational losses - i.e., a decrease in students' academic performance (Reimers & Schleicher, 2020). The prediction was correct to some extent. For instance, in Korea, the National Assessment of Education Achievement data revealed that the ratio of middle students that showed the lowest achievement level increased in 2020 compared to 2019 (KMOE, 2021). After that, endeavours to remedy this situation followed throughout levels of educational agents - international (e.g., UNESCO, OECD, World Bank), national, organizational, and individual. Most of those were briefing on the current situation, presenting specific ways to implement remote teaching, and/or calling for innovation in teaching and learning methods during the crisis (Reimers & Schleicher, 2020; World Bank, 2020; Korkmaz & Toraman, 2020).

In the science education field, soon after the beginning of the pandemic in 2020, articles began to appear that investigated the influence of COVID-19 in several categories: (1) editorials in journals related to science education that have urged researchers to engage in the pandemic situation as research context, as it inhibited the usual science teaching in class (e.g., Siry, 2020; Verma, 2020; Erduran, 2020); (2) suggestions that public understanding of the science concerning mask-wearing and vaccination was misled because false information provoked people's fear and that the history, philosophy, and sociology of science would help to overcome this crisis (Reiss, 2020; Erduran, 2021); and (3) reports of the changes in science teaching and learning in various situations followed.

Although there have been some case studies from secondary schools (Levrini et al., 2021; Lee & Kim, 2021a; 2021b), many others have focused on the shift of university-level laboratories from FTF to NFTF format (Jang et al., 2020; Lee & Hong, 2021b).

A hands-on laboratory had been one of the most prominent teaching and learning methods in the previous ‘normal’ science education. The idea of a laboratory in school science education may be dated back to the 17th century when John Amos Comenius (1592-1670) emphasized the integration of the sensory experience and the theoretical understanding of the nature and introducing real objects into the classroom (Lee & Hong, 2021a). Henry Edward Armstrong (1848–1937) followed this idea and suggested his heuristic teaching method (Lee & Hong, 2021a). And since the 1980s and until before the COVID-19, science educators have considered hands-on laboratory the most distinguished learning process in the discipline (Hofstein & Lunetta 1982; 2004).

Typically, a hands-on laboratory allows students to integrate what they have learned in theoretical classes into the experimental process, thus acquiring tacit knowledge, understanding of the nature of science (NOS), and practical skills (Lee & Hong, 2021b; Domin, 1999; Hofstein & Lunetta, 2004). Students must usually attend the lab, conduct experiments with colleagues, and write lab reports weekly in a hands-on laboratory. As preparing for the hands-on laboratory is burdensome for instructors and requires many resources (Hofstein & Lunetta, 2004), higher education sites have tended to be considered more appropriate for them than K-12 education (Lowe et al., 2013). Particularly for East Asian countries such as Korea, Japan, and China, where high school science education emphasizes science as a fixed product (or content), university laboratories are considered crucial for introducing science as a process (Rice et al., 2009). Consequently, students in STEM fields are usually required to take introductory physics, chemistry, biology, or earth science labs in their first year and later take major-level course labs, which can foster their scientific knowledge, skills, and attitudes that pertain to their own professional or vocational paths (Domin, 1999; Reid & Shah, 2007). This conventional notion of the hands-on laboratory has been typified in university STEM education and has not changed significantly over time (Reid & Shah, 2007; Lee & Hong, 2021b). However, the unpredicted COVID-19 pandemic has abruptly changed the world, which entailed a global educational crisis (Reimer & Schleicher, 2020), including science education and laboratory.

As the hands-on science laboratory collapsed during the pandemic, and it has been acutely problematic for science educators; Particularly university chemistry instructors have faced the difficult task of designing and implementing University Remote Laboratories (URLs) (Pertillion & McNeil, 2020; Blizak et al., 2020; Youssef et al., 2020; Jang et al. 2020). The loss of hands-on experiences during laboratory was generally unimaginable to science instructors before the COVID-19 because remote instruction seemed incompatible with the conventional practice of science laboratories in university — students gather their experimental data firsthand and interpret it in the light of relevant scientific theory to make assertions for the phenomena (Domin 1999; Lee & Hong, 2021b).

Manifestly, the COVID-19 situation in 2020 was a crisis for science educators, which demanded an immediate response to reshape their laboratory courses. They had to contemplate how they should implement laboratories without hands-on experience or even they could. Although some have suggested that the remote settings may lead us to the innovation of laboratory with cutting-edge technologies such as augmented/virtual reality (AR/VR) (Ray & Srivastava, 2020; Hu-Au & Okita, 2021), their visionary thoughts were not applicable in the exact time of hardship. Instead, the adaptive endeavors of individual university STEM instructors to implement their remote labs in the time of crisis are worth investigating (e.g., West et al., 2021; Lee & Hong, 2021b).

1.2 Purpose of Research

The researcher had two research purposes throughout this study. First, it was to answer fundamental questions on the essence of laboratory education that were raised facing the unprecedented global implementation of remote laboratories. The COVID-19 made science education researchers rethink substantial and lasting questions on laboratory education (Lee & Hong, 2021b), which envelope the specific research questions of the component studies in this dissertation (Study 1 to 3). Those questions that re-emerged with a new look due to the COVID-19 are as follows: (Q1) What is the essence of the laboratory experience from the university to K-12 science education? If satisfactory learning outcomes are secured to some extent, can (remote) minds-on experience replace hands-on one? (Q2) Is spatio-temporal co-presence of instructors and students necessary? (Q3) How can we invite students to an inquiry about natural phenomena, which would be represented in their scientific writing in their lab report? (Q4) Do the answers differ according to the characteristics of interaction among instructors and students and in different cultures worldwide? (Q5) How can we design a laboratory course that is both effective and adaptive that can be implemented in both normal and emergency situations? The tentative answers will be explored in the 2. Theoretical Framework and more direct answers would be given while discussing the specific results of this study.

Second, it was to investigate what happened in the university STEM education sites concerning remote labs necessitated by the COVID-19 in 2020 and provide implications for future URLs. More specifically, it was to rationalize how university instructors implemented their remote labs in the spring semester of 2020 facing the imminent pandemic (Study 1), investigate the consequence of those remote labs via university students' response (Study 2), and prescribe practical guidelines for future remote lab design (Study 3).

The theoretical framework of this dissertation was set considering those questions. As explicated later, this study understood the remote laboratory courses as "laboratory teaching and learning implemented in e-learning" (Lee & Hong, 2021b). This enabled illuminating the students' laboratory experience, aspects of interaction, and lab report as a product of remote lab as an instructional program in lights of science education and e-learning theories. To consider laboratory teaching and learning context (cf. Song & Cho, 2004), the agency of instructors who designed and implemented remote labs in 2020 will be investigated from the sociocultural perspective. Also, the utility of an instructional design model, as suggested in the educational technology field, would suggest a method to develop design guides for efficient and effective course modules. Note that tentative answers to the abovementioned questions (Q1-Q5) will be given (in)directly throughout the 2. Theoretical Framework - meanwhile, more significant answers will be discussed in 6. Summary and Conclusion, after hearing the voices of instructors and students who participated in this study.

While seeking the answers to those questions, theoretical and practical implications for university laboratory education were elicited. These will be integrated into the Blended Laboratory and E-learning iNstructional Design (BLEND) model for URL courses, which is the final product of this research (Study 3). As its name presents, the BLEND model intends to blend laboratory courses in science education with effective e-learning strategies. It is anticipated that the BLEND model to be used by university instructors within various teaching and learning contexts worldwide who aspire to innovate their laboratory courses by broadening students' learning opportunities spatiotemporally in the post-COVID-19 era.

1.3 Research Field

The start and progress of this research were situated in the COVID-19 situation at Hankuk University (pseudonym) in Seoul, Republic of Korea. In May 2020, the researcher realized that the formerly similar general laboratory courses - viz. the physics, chemistry, biology, and earth science labs - have become remote labs with diverse characteristics in Hankuk University, which became the research field. As the researcher had a plausible prior understanding of how those courses had been implemented similarly within and between courses throughout the years (or possibly decades), the sudden diversification of course implementations seemed unnatural and required explanations. Also, through preliminary conversations with first-year chemistry education students who took the remote labs in 2020, he could assume that the outcomes of the various remote labs in 2020 must become different. The researcher could conjecture that investigating the emergence and consequence of remote labs at Hankuk University in 2020 could bring unprecedented insights into how university STEM instructors implement their laboratory courses and how university students perceive their learning experiences during those. Therefore, the researcher dived into the research field in June 2020, before the peculiar teaching and learning experiences within the initial responses to the COVID-19 situation vanished.

1.3.1 The Republic of Korea in the COVID-19 situation

As with many East Asian countries, Korea has a governmental system that is more centralized than many Western countries. After liberation from the Japanese Empire in 1945, an authoritarian government was in place for decades until 1993. Although Korea has been a democratized country for more than 30 years, the centralized government and public administration power still remain. Not only the prescriptive and equalizing national K-12 curricular, but also policy, administrative, and fiscal authority regarding education are centralized around the Korean Ministry of Education (KMOE) by law. For example, the KMOE executes budgets that support the universities throughout the country, and these are cut when a university does not follow the directives of the KMOE and/or fails to satisfy criteria. As many universities largely depend on financial support from the Ministry, it has a vast influence over them. Therefore, it is necessary to consider how the educational authority responded to the COVID-19 situation and directed schools and universities to implement adaptive online classes.

Not irrelevant to these, Korea’s success in limiting the spread of the COVID-19 pandemic can be attributed to (1) the centralized administrative system and people's adherence to public health guidelines and possibly (2) Korean people's uniformly fair scientific literacy regarding aspects of their daily lives.[2] For example, there has been essentially no report of protest or debate in Korea about mandating masks, unlike in some other countries. In either case, Korean people prefer a uniform perspective or approach to responding to imminent situations. Although this may help structure and consolidate society, it may limit individuals from utilizing their agency. Furthermore, this can have been one of the reasons that instructors at Hankuk University implemented remote labs in 2020 following the administrative decision concerning the spread of COVID-19 rather than sticking to the previous FTF course format.

1.3.2 Hankuk University in the Republic of Korea

This research was conducted at Hankuk University in Korea. About 3,000 students enter the university annually, and about half are enrolled in the STEM tracks. For graduation, they must take at least one introductory science course and its respective laboratory: physics lab, chemistry lab, biology lab, or earth science lab (Table 1) and a variety of major course labs. Hankuk University has conventional systems to implement massive courses for first-year students. Although they provide many classes with the same course name, each class is kept equivalent: The content is the same, and each TA teaches many classes based on the common course plan established by the TAs. Therefore, each student's learning experience within each introductory laboratory session is supposed to be identical. Most of the

[2] Although there were hundreds of confirmed cases of COVID-19 in Korea at the start of 2020, the daily rate of infection has remained under 1,000 per day up to the present (June 2021), which is very low compared to other countries with equivalent populations. (Retrieved on June 08, 2021 from https://kosis.kr/covid/covid_index.do)

learning content is quite traditional and cookbook-like (Appendix A), which means the results of experiments are expected to fit relevant theories. After taking the introductory laboratory, students in STEM departments take major-course labs in their second year and/or later. The laboratory at Hankuk University deals with about 10 topics in a semester.

Table 1. Number of students who finished introductory laboratory courses in 2020

Physics lab	Chemistry lab	Biology lab	Earth science lab [a]
1,095	642	508	134

[a] The researcher counted the number of students in the spring and fall semesters for the earth science lab, while others only in the spring semester. Unlike other introductory labs, most earth science labs are offered in the fall semester.

1.4. Study Design

This dissertation consists of three studies. The researcher intended to scrutinize the remote labs implemented at Hankuk University in 2020 in Study 1 and 2, which are conducted simultaneously. And the researcher planned to provide a systematic guide to design and implement a remote lab in Study 3. The overall scheme of the study process is presented in Figure 1.

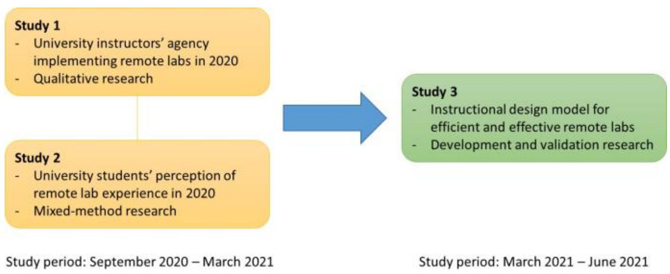

Figure 1. The overall scheme of the study process

1.4.1 Study 1

The researcher investigated what happened in the spring semester of 2020 while the remote labs were implemented, on the instructors' side (Study 1) and the students' side (Study 2), respectively. The two studies were conducted simultaneously, making each function as an interpretive aid for another.

In Study 1, the researcher examined how university instructors responded to the COVID-19 by implementing their remote labs. The researcher adopted the theoretical lens of instructor agency upon the given structure. Qualitative interviews were conducted with 10 instructors at Hankuk University, who taught general physics, chemistry, biology, and earth science labs and other major-level labs in remote settings in 2020. The difficulties they encountered while implementing remote labs and how they tried to overcome those were identified.

1.4.2 Study 2

In Study 2, the researcher investigated Hankuk University students' perception of remote labs they took in 2020 to examine their consequences. A mixed-method approach was used in Study 2. A quantitative survey was conducted with 338 students' perceptions of their remote lab experiences. Among the survey respondents, 18 participants were qualitatively interviewed to elaborate on their experiences and ideas on various aspects of remote labs, including pros and cons and suggestions for the future remote lab.

1.4.3 Study 3

Study 3 was planned to suggest a better way to implement future remote labs beyond the COVID-19, rather than just depicting what happened in the crisis.

In study 3, the researcher utilized the design and development research approach. The product was an ID model for the university remote labs. While developing the initial model, the result of the literature review and lessons from Study 1 and 2 were incorporated. The iterative validation process included internal validation from 13 experts and six users and external validation from seven students who took the Analytical Chemistry Experiment course at the Department of Chemistry Education at Hankuk University in the first semester of 2021. The ID model was revised twice to become the final one.

Chapter 2. Theoretical Framework

The researcher suggests a framework to view URLs as the locus where the components of laboratory sessions and e-learning intersect (Figure 2; Lee & Hong, 2021b). The reasons for implementing laboratory or e-learning courses lie in the purpose of laboratory or the promises requirements of e-learning. As kinds of instructional programs, laboratory and e-learning should consider how the content is delivered, interactions between learners promoted, and assessment and feedback are given - those three factors naturally correspond to each other (see Q1–Q3 in 1.2 Purpose of Research; cf. Jang et al., 2020). The COVID-19 situation in 2020 made the two strands of educational tradition meet, interplay, and blended in the various URL courses that emerged in 2020. The characteristics of the URL course in 2020 were shaped according to the teaching and learning context. And the lessons from URLs in 2020 (Study 1 and 2) led the researcher to an extended understanding of blended learning for laboratory education (see 2.3.4) and the need for an ID model for URLs (see 2.5 and Study 3).

The following sections will review previous literature on the laboratory in science education, e-learning and effective teaching strategies, and remote laboratory. Additionally, some theoretical components will be reviewed, such as sociocultural perspective and instructor agency relevant to Study 1, and model development and validation research frequently used in the educational technology field relevant to Study 3.

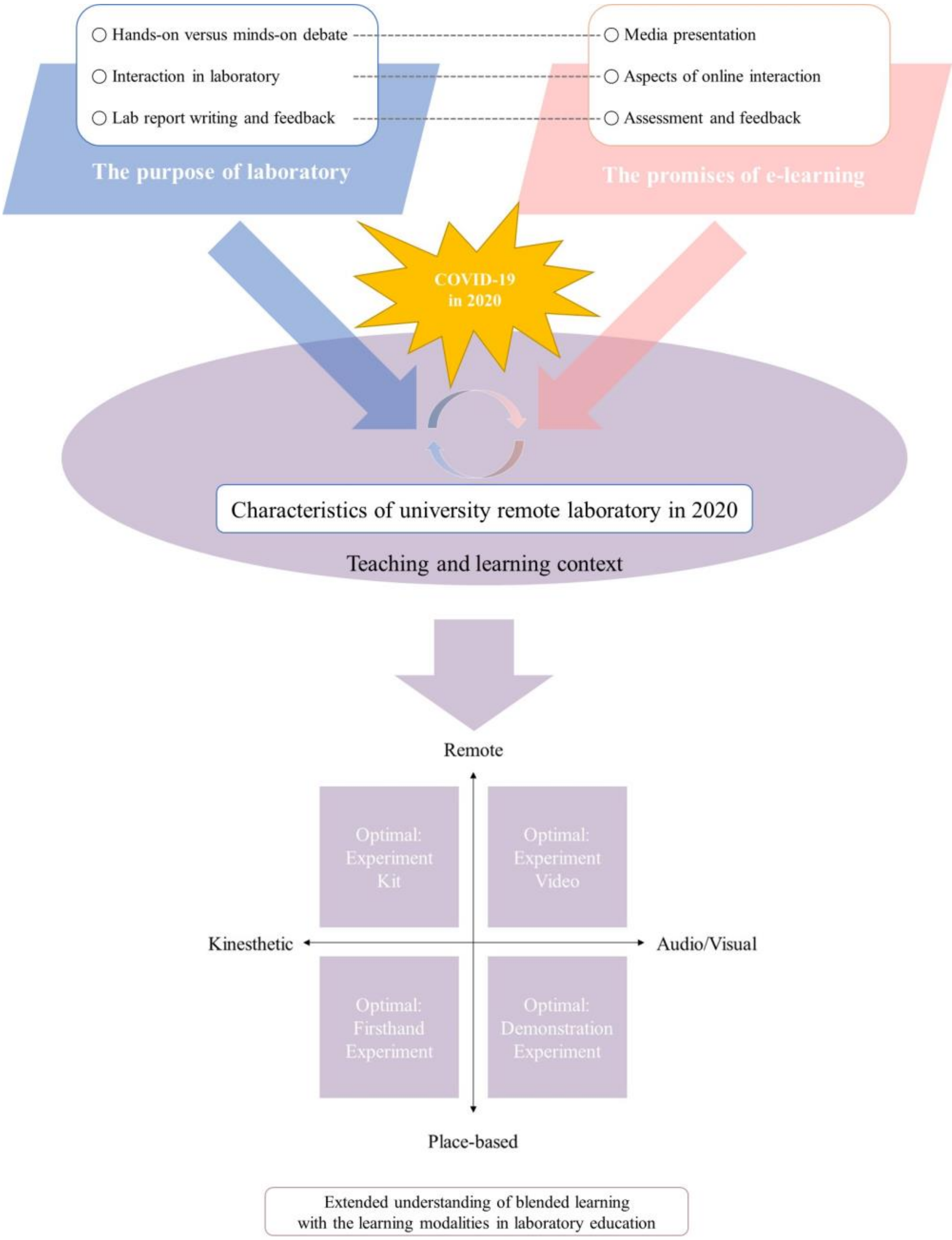

Figure 2. The interplay of laboratory and e-learning that shapes the characteristics of a remote laboratory course in a given teaching and learning context leading to the extended understanding of blended learning with the learning modalities in laboratory education

2.1 Laboratory in Science Education

2.1.1 The purpose of laboratory

Like any other teaching and learning method, the implementation of the laboratory is shaped by its supposed purpose. Many scholars have set or summarized the purpose of laboratory, which are diverse and needs contemplation. Some of the notable literature are as follows.

Some literature focused on the K–12 context. Hofstein & Lunetta (1982) reviewed the studies of their time related to the goals of the laboratory and reframed the goals as creative thinking and problem-solving, scientific thinking, intellectual development, practical skills and abilities, and the affective domain, which they called for further research.

Hart et al. (2000) showed that the laboratory session could be implemented with the purpose of letting students understand the NOS (the way scientific facts are established) rather than getting science content related to the experiment, which was successful in fostering students' cognitive and affective domain.

Hofstein & Lunetta (2004) listed the updated goals of the laboratory after decades of their previous review. Those were understanding of scientific concepts, interest and motivation, scientific practical skills and problem solving abilities, scientific habits of mind, understanding of the NOS, methods of scientific inquiry and reasoning, and application of scientific knowledge to everyday life.

Meanwhile, others focused on the higher education context, specifically concerning chemistry labs. Domin (1999) suggested the learning outcomes of a laboratory can be set as conceptual understanding, retention of content knowledge, scientific reasoning skills, higher-order cognition, laboratory manipulative skills, better attitude towards science, and a better understanding of the NOS.

Reid & Shah (2007) comprehensively reviewed the historical perspective of chemistry laboratory work and the aims and objectives of it suggested by the previous literature. And they rearranged those as four headings: skills relating to learning chemistry, practical skills, scientific skills, and general skills. Note that here ‘scientific skills’ refer to the skills of observation, deduction, and interpretation, and ‘general skills’ refer to the skills such as team working, reporting, presenting and discussing, time management, and developing ways to solve problems.

Meanwhile, the researcher investigated how 10 Korean science education experts (two from physics, three from chemistry, three from biology, and two from earth science education) perceived the purpose of the laboratory (Lee & Hong, 2021b). From a qualitative interview of 10 science education experts, it was revealed that they reconsidered the purpose of the laboratory during the COVID-19 as (1) replicating what is learned in theoretical classes, (2–4) gaining tacit knowledge/NOS/practical skills through the experimental process, and (5) preparation of pre-service teachers for the laboratory in the school. However, they also replied that these were not new but deepened their understanding of what previous literature had suggested (cf. Flick, 1993; Domin, 1999; Hofstein & Lunetta, 2004).

It is manifest that scholars understand the purpose of the laboratory diversely, with some commonalities and differences. The various purposes of the laboratory may be simplified following the traditional categories of desired learning outcomes - knowledge, skills, and attitudes. Although each can be interpreted broadly, the simplified framework would make the discussion commensurable. Also, it should be noted that the laboratory is considered a crucial means of accomplishing inquiry teaching in the previous literature (cf. Lee & Lee, 2016). Here, 'inquiry' denotes both "inquiry as means" to understand science content and "inquiry as ends" (learn how to do inquiry, develop epistemological understanding about NOS and the development of scientific knowledge, and relevant inquiry skills) (Abd-El-Khalick et al., 2004).

2.1.2 Hands-on versus minds-on debate

Conceptually, the types of the laboratory can be distinguished by the emphasized activities: firsthand manipulation of laboratory equipment and apparatuses, which is analogized as 'hands-on,' or higher-order thinking of using or applying scientific ideas, which is analogized as 'minds-on' (Lumpe & Oliver, 1991; Flick, 1993; Hofstein & Lunetta, 2004). Note that, for ease of discussion, 'hands-on' and 'minds-on' are used as distinctive terms throughout this study (see NRC, 1996; Abrahams, 2012; Osborne, 2019).

Essentially, all universities with liberal education and STEM departments have managed hands-on laboratories to provide students with embodied experiences. Students usually take the relevant laboratory class after or with the theoretical class, e.g., an analytical chemistry experiment class after or with an analytical chemistry class. A hands-on laboratory class presupposes students' physical attendance and proper experimental environments (Fraser et al., 1995). Laboratory invites students to engage firsthand with equipment, apparatuses, and reagents to conduct science experiments following prescribed procedures (Reid &

Shah 2007). Students usually attend laboratory classrooms once a week and spend a couple of hours following an experimental procedure and producing data. Then, they write a lab report for the experiment. Through hands-on laboratory classes, university students are expected to gain the knowledge (conceptual/theoretical), skills (hands-on manipulation, data processing, and lab report writing), and attitudes toward science or science classes that they need to perform advanced scientific research and begin a professional science career (Domin, 1999; Reid & Shah, 2007).

However, the hands-on approach was sometimes criticized by the proponents of the so-called minds-on approach. They argued that although students might participate physically in an experiment firsthand, they would not mentally participate in the inquiry that socially constructs scientific knowledge, and thus hands-on laboratory classes were an inefficient use of resources (e.g., Schamel & Ayres, 1992; Abrahams, 2012; cf. Abrahams & Millar, 2008). They argued that the essential component of a laboratory class was a collaborative process among students interpreting experimental data - in this view, instructors may provide students with demonstrations or simulations representing experiments using appropriate media such as video or animation rather than firsthand experiences (O'Brien, 1991; Ma & Nickerson, 2006). After that, instructors can trigger students' inquiry, meaning their interpretation of experimental phenomena and/or data in light of scientific theories (Rice et al. 2009).

Although the hands-on versus minds-on debate has been over for decades, it is still the concern of science educators. For example, Furtak & Penuel (2019) summarized the hands-on versus minds-on debate since the 1990s and contended for the term 'practice' rather than those two in the upcoming era of the National

Research Council *Framework* and the *Next Generation Science Standards*. However, responding to Furtak & Penuel (2019), Osborne (2019) re-ignited the debate and supported the minds-on inquiry, rebutting the hands-on or ‘practice.’ Parsons (2019), in turn, again refuted Osborn (2019), suggesting “an integrative and inclusive approach” to hands-on and minds-on science learning. This consecutive discussion shows that there is still a need to contemplate how 21st-century laboratory education should be.

If someone understands the hands-on and minds-on laboratories as an opposite set, a laboratory course might be implemented according to the position where he/she stands. The emphasis of the individual instructor can be put on either side, according to the purpose he/she has for the course (Domin, 1999; Reid & Shah, 2007; cf. Hart et al., 2000). For example, if an instructor aims to teach students lab techniques, he/she might highlight the hands-on component of the laboratory even though it consumes many resources. In contrast, if he/she aims to encourage student inquiry rather than manipulative hands-on skills, the minds-on approach may be more efficient and use fewer resources such as time, reagents, and apparatuses.

Meanwhile, Song & Cho (2004) suggested the hearts-on science education as another paradigm shift after the minds-on perspective. They understood the 21st century to be a period perceiving science as a culture based on scientific humanism. And they emphasized context-rich approaches and scientific field trips in science teaching. They said all the cognitive, emotional, and behavioral ways of science learning should be integrated. Although these suggestions not only pertain to the laboratory sessions, their holistic viewpoint on science education is worth noting.

Therefore, the hands-on and minds-on approaches to laboratory classes do not necessarily become contradictory; they could be used in a complementary way focusing on inquiry (Lumpe & Oliver, 1991; Flick, 1993; Abd-El-Khalick et al., 2004; Q1 in 1.2 Purpose of Research). In this respect, students' collaborative inquiry process in the laboratory is considered pivotal (Hart, 2000; Hofstein & Lunetta, 2004). In other words, laboratory classes can incorporate hands-on and minds-on learning processes because students should be engaged in bodily experiences and mental operations. However, there seems to be little research that presents practical guidelines to integrate the hands-on and minds-on notion of laboratory courses. It will be discussed later in 2.3.4.

2.1.3 Interaction in laboratory

Science education researchers have emphasized that an experimental class following an inquiry procedure needs to involve learner-centered and constructive activities (whether cognitive or sociocultural). In other words, inquiry classes should be conducted through interaction and cooperation among multiple learners. In an experiment class followed by the inquiry process, collaboration among peers and instructors leads them to construct scientific knowledge based on experimental results. This student-centered class configuration also increases lab participation (French & Russell, 2006). It has been shown that students participate more actively in lab activities by explaining their opinions to each other in argumentation through hypotheses and evidence (Okada & Simon, 1997). Also, note that the interaction between students has been naturally supposed to be synchronous in a laboratory classroom before the COVID-19 (Q2 in 1.2 Purpose of Research).

2.1.4 Laboratory report writing and feedback

It is common for science lab classes to include lab report writing as part of the inquiry procedure, which is crucial as it enables students to train or practice scientific writing. Lab reports generally consist of the following sections: introduction, principle (theoretical background), procedure, results, discussion, and reference. This style of writing has a typical structure; however, students often struggle with writing lab reports. For instance, since the content of the lab report is domain-specific, students find it difficult to interpret their findings from experiments (Kalaskas, 2013). Therefore, it is very important to promote student inquiry while writing lab reports - i.e., the interpretation of data in light of their prior understanding of scientific theories, through accommodating or assimilating (see O’Brien, 1991; Q3 in 1.2 Purpose of Research). Students also find it difficult to follow the scientific writing style required for laboratory reports. For example, when describing experiment results, students may find it difficult to construct an appropriate sentence format (e.g., using passive voice; Abulazain, 2019) or use visual representations (table, figure, graph, etc.) suitable for the data. However, these difficulties can be resolved by interaction with professors and peers and continuous feedback (Ahmad et al., 2019; Cho & MacArthur, 2011).

2.2 E-learning and Effective Teaching Strategies

2.2.1 The promises and requirements of e-learning

E-learning has become a learning system widely used in corporate education, lifelong education, and school (particularly higher) education since the late 1990s with the development of the internet (Park et al., 2012). The reason why the stakeholders (particularly organizations) utilize e-learning includes their desire to (1) provide consistent, worldwide training; (2) reduce delivery cycle time; (3) increase learner convenience; (4) reduce information overload; (5) improve tracking; and (6) lower expenses (Welsh et al., 2003; cf. Rosenberg, 2001). Meanwhile, Clark & Mayer (2016) suggest the promises of e-learning as (1) customized training, (2) engagement in learning, (3) multimedia, (4) acceleration of expertise through scenarios, and (5) learning through digital games.

Then, being what e-learning makes those promises? However, the definition of e-learning is not easy as anticipated. Table 2 shows the definitions of e-learning according to scholars, which are various but have many commonalities that make terms such as e-learning, online learning, internet-based instruction, and distance learning interchangeably (Dempsey & Van Eck, 2017). Viz., e-learning (1) utilizes the electronic material based on the internet, (2) emphasizes flexible learning environments that overcome constraints of time and space, (3) is oriented toward interaction activity (using the internet), and (4) emphasizes various learning experiences, self-directed learning activities, and thus a learning system (Park et al., 2012; p. 340).

Notably, Clark & Mayer (2016) defined e-learning as "instruction delivered on a digital device [which can range from desktop or laptop computers to tablets or smart phones] that is intended to support learning." (p. 7) Here, "intended" implies that carefully designed e-learning components are crucial for accomplishing its learning objectives. Therefore, scholars stress that e-learning should be designed according to well-established models to ensure those characteristics are exploited in a learning system (Horton, 2006; Dempsey & Van Eck, 2017; Clark & Mayer, 2016; Park et al., 2012). Unsurprisingly, teaching strategies used in e-learning courses yield different consequences (Clark & Mayer, 2016). E-learning can be as effective at least equivalently as traditional learning and even can yield better learning outcomes when the quality of the instructional system is secured by careful design and implementation (Tallent-Runnels et al., 2006). However, when e-learning courses are not appropriately designed, problems such as low participation and high dropout rates are expected (Lee et al., 2019). Among the components of e-learning, teaching strategies for conveying the learning content with multimedia, synchronous or asynchronous interaction, and assignments will be emphasized in this study.

Table 2. The definition of e-learning in previous literature

Source	The definition of e-learning
Rosenberg (2001)	"The use of Internet technologies to deliver a broad array of solutions that enhance knowledge and performance."
Khan (2004)	"An innovative approach for delivering well-designed, learner-centered, interactive, and facilitated learning environment to anyone, anyplace, anytime by utilizing the attributes and resources of various digital technologies along with other forms of learning materials suited for open, flexible, and distributed learning environment."
Welsh et al. (2004)	"The use of computer network technology, primarily over an intranet or through the Internet, to deliver information and instruction to individuals."
Horton (2006)	"The use of electronic technologies to create learning experiences."
Park et al. (2012)	"A learning system where learners overcome the time and space to have various learning experiences through interaction and self-directed learning activities in a flexible learning environment implemented Internet-based electronic media."
Clark & Mayer (2016)	"Instruction delivered on a digital device [which can range from desktop or laptop computers to tablets or smart phones] that is intended to support learning."

2.2.2 Media presentation

E-learning in science education has been considered plausible, partly because science involves a considerable amount of conceptual/theoretical learning, which appropriate technologies can support while overcoming the limitation of time and space in content delivery (Clark & Mayer, 2016).

In the educational technology field, media and methods that convey content are inseparable from the effectiveness of e-learning. In the 1980s, Clark (1983) posited that media were economic conveying methods rather than influential factors for learning effectiveness, but Kozma (1991) stated that both media and methods affect learning.

Recently, a prominent feature of e-learning has been affording the provision of learning materials through multimedia such as photos, animation, and videos. For example, the motion and reactions of microscopic particles (e.g., atoms, molecules) that cause macroscopic natural phenomena can be better represented in a dynamic animation or simulation using a computer program rather than in a fixed, printed figure (Ardac & Akaygun, 2004). Essentially, multimedia theory, echoing dual-coding theory and cognitive load theory, suggests that visual and auditory channels should be utilized complementarily in multimedia material to enhance students' science learning (So et al., 2019; Clark & Mayer, 2016). Therefore, many studies have focused on media design principles to present learning content effectively. Research about instructional video materials for STEM courses has shown what factors make the video more effective (e.g., students learn better from videos filmed from a first-person perspective rather than a third-hand perspective; Mayer et al., 2020). When video instruction material is provided in a science course, students can repeat it to understand complicated scientific terms or concepts (Lee et al., 2021; Loveys & Riggs, 2019). Videos of experiments can allow students to grasp the experimental procedure, imitate/simulate it, interpret data, and write a lab report (Cicciarelli, 2013; Q1 in 1.2 Purpose of Research).

2.2.3 Aspects of online interaction

The importance of promoting interactions between participants of e-learning has been well documented in the computer-supported collaborative learning (CSCL) field (Clark & Mayer, 2016). In terms of time, interactions can be divided into synchronous and asynchronous interactions. Synchronous methods can promote more interaction than asynchronous (Clark & Mayer, 2016; Q2 in 1.2 Purpose of Research). Regarding participants, interactions can be classified into instructor-learner and learner-learner interactions, and promoting both is desirable (Wut & Xu, 2021). Common web-based tools that support interaction by providing learning materials and having Q&As are learning management systems (LMSs). Interactions of e-learning participants promoted via LMSs help reduce dropout rates and result in effective e-learning courses (Lee et al., 2019).

2.2.4 Assessment and feedback

Since e-learning does not happen FTF in a classroom, learning cannot avoid relying on students’ self-paced assignments, typically homework. However, there seems to be little literature that comprehensively theorized the effect of various assignments in e-learning, although some empirical research considered the provision of those while designing their e-learning course (Bidarra & Rusman, 2017; Bulić et al., 2017; Leung, 2003). There is a couple of notable exceptions. Clark & Mayer (2016) mentioned that properly regulated assignment structure and difficulty and working in collaborative groups maximize the learning effect. It has further been suggested that challenging tasks solved collaboratively (whether synchronous or asynchronous) are constructive for student learning (Q3 in 1.2 Purpose of Research). Also, Koohang et al. (2009) presented that the variously designed e-learning assignments from the constructivist viewpoint can lead to different student responses.

2.3 (Re-)emergence of Remote Laboratory

There has been a tremendous number of studies regarding remote laboratories. However, its notion has been changed since its first appearance in the late 1990s, similar to that of e-learning. The technological progress including high-speed internet and the inclusion of researchers from various STEM fields probably have impacted the varying denotation of ‘remote’ lab or equivalent terms such as ‘online,’ ‘virtual,’ ‘simulated,’ ‘distance’ labs. Further, the COVID-19 situation in 2020 manifestly changed the notion and practice of remote labs. Therefore, in the following sections, studies on remote labs before and after the COVID-19 would be reviewed, followed by exploring its appropriate meaning. After that, the researcher’s view - remote laboratory as blended learning - would be explicated.

2.3.1 Studies on remote laboratories before the COVID-19

Research about remote labs began long before the COVID-19, particularly in higher education sites (Brinson, 2015; Bidarra & Rusman, 2017). Some literature is worth noting:

The first suggestion of the “remote laboratory” “paradigm” is attributed to Aktan et al. (1996). They attempted to apply “distance learning” to “control engineering laboratories” and elicited crucial agenda for implementing remote laboratory courses, including preparation of audio and video material, detailed evaluation of software, safety features, open architecture, student collaboration, communication tools, and working with a multidisciplinary team.

Winer et al. (2000) suggested that a 'Distributed Collaborative Science Learning Laboratory' (DCSLL) became possible on the internet. The theorized concept of DCSLL "emerged from work in distance education and new technologies, cooperative/collaborative learning, and science education." They derived some instructional principles from these backgrounds and reported the results of a pilot study in a module on electricity content in an introductory university course.

Gustavsson et al. (2009) urged that setting objectives and employing individual assessment is crucial to the engineering laboratory courses. Further, they suggested that a collaborative remote laboratory is possible based on remote control technology on an electrical circuit and showed that university students in Sweden and South Australia could work together practically.

Meanwhile, Lowe et al. (2013) raised the possibility of remote laboratories in secondary schools also has been suggested. They devised and applied a couple of remote physics lab sessions for high school students. They evaluated that remote labs for high school students can be beneficial, but considerable care should be taken to deliver issues such as student reaction to remote labs, student gender and learning styles, and students' interactions with experimental apparatus.

Interestingly, Childers & Jones (2017) investigated high school students' perceptions of virtual presence, science learning motivation, and science identity during a remote microscopy investigation experience. Based on quantitative and qualitative data, they concluded that science learning drive, environmental presence, and inner realism presence are the factors contributing to a remote learning investigation.

A literature review of remote labs suggested that they might be better than hands-on labs in terms of achievement according to the interest of individual research, such as knowledge and understanding (Brinson, 2015). However, there had been no clear standards to compare the effects of remote labs with hands-on labs (Ma & Nickerson, 2006; Tho et al., 2017; Lowe et al., 2013; Faulconer & Gruss, 2018). Also, those studies were conducted within cautiously designed environments with cutting-edge technologies that required many resources and the labor of innovative researchers (e.g., Lowe et al., 2013), which might explain why the literature related to URL has been led by engineering or technology educators with expertise in remotely controlled machines (Prada et al., 2015; cf. Brinson, 2017). Consequently, the research field was also mostly limited to engineering and physics subjects rather than other STEM subjects, while the number of studies in natural science was increasing (Brinson, 2017). Therefore, it can be said that the dissemination of such research in general university science laboratory classes has been limited until 2020.

2.3.2 Studies on remote laboratories after the COVID-19

The COVID-19 situation in 2020 caused remote labs to reemerge as unanticipated and unavoidable teaching and learning method used worldwide.

In 2020, many science instructors perceived remote teaching as inefficient (Salta et al., 2021). Many university STEM instructors endeavored to adaptively implement their own remote labs regardless of disciplines (West et al., 2021; Lee & Hong, 2021b), including shooting and editing videos of experiments to offer students some laboratory experiences (e.g., Jang et al., 2020), rather than establishing a remote control environment. University chemistry educators in particular have reported case studies about URL during the pandemic, and in them, students reported primarily negative perceptions of the motivation, study pacing, interaction, and learning outcomes of URL due to the lack of hands-on experiences (Blizak et al., 2020; Petillion & McNeil, 2020; Youssef et al., 2020; Jang et al., 2020). Although those works were prompt and responsive to the COVID-19, most did not provide comprehensive insights or total instructional guidelines into the remote lab phenomena to offer more generalizable pedagogical knowledge.

One notable exception is Jang et al. (2020), who conducted a mixed-method case study on their URL implementation experience in the spring semester of 2020. In the research field of an inorganic chemistry experiment course for pre-service chemistry teachers, the instructors reported that they provided learners with multimedia videos of experiments, communicated with learners via online communication tools, and complemented the indirect guidance through feedback on the student lab report.

Since 2021, research has explored and reported the possibilities of remote labs as an innovative teaching and learning method (West et al., 2021). For example, Sung et al. (2021) developed and implemented “remote labs 2.0,” which shows instructors conducting an experiment while receiving students’ real-time responses. They reported that their URL system helped students’ engagement and provided them a sense of telepresence. Hu-Au & Okita (2021) explored the differences in student learning and behavior between real and virtual reality chemistry laboratories, finding that learning general content knowledge, laboratory skills, and procedure-related safety behaviors were comparable. Lee & Hong (2021b) interviewed 10 science education experts about their perceptions of remote labs. They thought the decrease in hands-on experience and FTF interaction and increase in instructor's burden were the main weaknesses of remote labs, contemplated the nature of lab sessions without hands-on experience (in other words, minds-on), and attempted to improve their remote labs in various ways.

However, there have still been very few studies that have investigated more than three URL cases implemented in 2020 to elicit generalizable and practical implications for future science education.

2.3.3 The meaning of remote laboratory revisited

Table 3 shows the varying definition of remote lab or equivalents in the previous literature. As shown, the remote lab can be defined in various ways, and sometimes the similar terms ('online,' 'virtual,' 'distance,' 'simulated' labs) are used simultaneously or interchangeably. Therefore, it is not easy to derive the only exact meaning of the remote lab. However, some important issues should be pointed out:

(1) A remote lab can be defined as a laboratory class that is 'non-traditional,' in the sense that it is implemented in NFTF e-learning settings using media such as videos, simulations, and remote controls to present experimental processes or acquire experimental data (based on Tho et al., 2017; Brinson, 2015; Zacharias et al., 2015; Lee & Hong, 2021b).

(2) The remote lab can be understood as an attempt to replace or complement hands-on processes with e-learning materials while retaining minds-on collaborative inquiry processes (Brinson, 2015; Zacharias et al., 2015). Therefore, remote labs have been thought to suggest possibilities for overcoming limitations of time, space, and resources spent in the physical hands-on labs while securing

more resources for interpreting data (Tho et al., 2017; Youssef et al., 2020; Lee & Hong, 2021b).

(3) The notion of the remote lab should be broadened to embrace the global instructional practices during the COVID-19. The pandemic forced nearly all university STEM instructors worldwide to implement remote labs immediately. Therefore, the significance of remote labs has risen dramatically since 2020. Also, the details in remote lab practices have become various after the COVID-19 (e.g., Blizak et al., 2020; Petillion & McNeil, 2020; Youssef et al., 2020; Jang et al., 2020; Lee et al., 2021b; Sung et al., 2021). For example, instructors heavily relied on the video material, which is sometimes shot and edited by themselves, rather than remote controls that are not convenient to everyone. Also, the use of the Zoom or similar webinar programs was also a worldwide educational change during the pandemic, enabling synchronous online sessions with a real-time conversation between instructors and students that were previously understated in remote labs.

Therefore, the researcher has suggested that the remote lab should be understood broadly as "laboratory teaching and learning implemented in e-learning" (Lee & Hong, 2021b) to interpret the remote lab phenomena re-emerged by the COVID-19. Then, the definition and design principles of e-learning (see 2.2) can be directly related to the meaning of a remote laboratory. Also, the essence of the science laboratory experience becomes the content to be delivered (see 2.1). The theoretical and practical elaboration of this understanding will follow in the next section.

Table 3. The definition of remote laboratory or equivalents in previous literature

Source	Concept	The definition of remote laboratory or equivalent
Aktan et al. (1996)	Remote lab	"is to make the equipment that we already have available to more students without taking away the experience of being physically present in the laboratory."
Ma & Nickerson (2006)	Simulated lab	"Simulated labs are the imitations of real experiments. All the infrastructure required for laboratories is not real, but simulated on computers."
	Remote lab	"Remote labs are characterized by mediated reality. … they require space and devices. … in remote labs experimenters obtain data by controlling geographically detached equipment."
Gustavsson et al. (2009)	Remote lab	"A variety of web-based experimentation environments"
Crippen et al. (2013)	Virtual experiment	"Students are required to setup virtual (not real) equipment. Students manipulate virtual equipment to complete a laboratory experiment that requires them to collect and analyze data."
	Simulated experiment	"Students do not setup equipment. Students manipulate virtual equipment to complete a laboratory experiment that requires them to collect and analyze data."
	Remote experiment	"Students do not setup equipment. Students manipulate real equipment virtually (the equipment exists somewhere, but the students do not touch it) to complete a laboratory experiment that requires them to collect and analyze data."
Zacharias et al. (2015)	Online lab	"Virtual and remote labs offered through computer technology"
	Virtual lab	"Computer simulations, which allow the manipulation of virtual material and equipment on a computer screen via the computer equipment"
	Remote lab	"Physical labs whose material and equipment are manipulated at a distance via the use of computer technology."
Tho et al. (2017)	Remote lab	"Real-time science experiments using the Internet"
Faulconer & Gruss (2018)	Online lab	"A laboratory experience where the learner accessed simulated experiments, instruments, or equipment through a computer."
	Remote lab	"A laboratory experience where the learner accessed real experiments, instruments, or equipment virtually through a computer."
	Distance lab	"A laboratory experience where the learner performed hands-on labs outside of a traditional laboratory space through portable laboratory kits, often delivered through the mail"
Lee & Hong (2021b)	Remote lab	"A laboratory teaching and learning implemented in e-learning"

2.3.4 Remote laboratory as blended learning

Blended learning has become a prominent teaching method since the early 2000s (Graham, 2006). However, like many other educational concepts, it is difficult to simply define blended learning (Graham, 2006; Oliver & Trigwell, 2005). The issue of defining blended learning converges into what are being 'blended.' Graham, Allen & Ure (2003) abstracted from the literature the three definitions of blended learning as (1) combining instructional modalities, (2) combining instructional methods, and (3) combining online and FTF instruction (cited in Graham, 2006) while supporting the last one as the most appropriate.

Meanwhile, Oliver & Trigwell (2005) provide richer implications on the meaning of blended learning. They summarized the meaning of 'blended' as mixing e-learning with traditional learning, mixing online learning with FTF, mixing media, mixed contexts, mixing theories of learning, mixed learning objectives, and mixed pedagogics. According to variation theory, the most important blending in blended learning should be learning experiences with each learning mode. Also, they focused on the blending of learning spaces. Here, Oliver & Trigwell (2005) refers to the case of Alexander & Cosgrove (1995), who provided various learning experiences in an electric circuit lab through software, kitset, and workbook.

Some literature has suggested a blended (flipped) learning format for laboratory classes (Bergmann & Sams, 2012; Loveys & Riggs, 2019; Gregory & Di Trapani, 2012; Stockwell et al., 2015). The prominent flipped learning approach has also been suggested to improve laboratory classes by placing conceptual/theoretical knowledge online before class and hands-on activities offline in-class time (Bergmann & Sams, 2012). Particularly, the researcher has suggested understanding remote lab after the COVID-19 as “blended learning that complements an online–minds-on–whole class session with an offline–hands-on–small group session” to enable realistic response in the ID perspective (Lee & Hong, 2021b; Q1 in 1.2 Purpose of Research). Note that the combinations of online/offline–minds-on/hands-on–whole class/small group can be various, not limited to the abovementioned. The matter is finding the optimal combination for a specific teaching and learning situation.

To conceptualize remote lab as blended learning that incorporates hands-on and minds-on experiences via an e-learning system, our understanding of blended learning should be extended (cf. Oliver & Trigwell, 2005). The researcher suggests that remote lab as blended learning connotes the two kinds of blending, with reference to the multimodal understanding of blended learning (Picciano, 2009).

First, it is the blending within laboratory experiences - the hands-on and minds-on experiences. If blended learning should be designed to combine “the best of both worlds” (Graham, 2006), the composition of blended laboratory learning should consider the learning objectives and their respective learning modes. The most distinctive learning mode in the hands-on laboratory is the kinesthetic one that allows students to foster manipulative skills, while that in the minds-on laboratory is audio/visual ones (see Flick, 1993). If those two approaches meet in a blended learning format, a long but unresolved dichotomy between the hands-on and minds-on (or virtual, remote, etc.) experiences (Flick, 1993; Parsons, 2019; Lee & Hong, 2021b; cf. Nickerson et al., 2006; Lowe et al., 2013;) could be mitigated.

Second, it is the blending between laboratory experiences and learning spaces. If the previous understanding of blended learning supposed the integration of learning spaces (place-based and remote), the extended understanding that this researcher suggests also considers the integration of learning modes for laboratory sessions (kinesthetic in hands-on and audio/visual in minds-on).

Figure 3 presents the arrangement of four possible laboratory experiences according to learning modes and learning space, based on the extended understanding of blended learning. The first quadrant in Figure 3 suggests 'experiment video' to be optimal with an audio/visual learning mode in a remote setting, the second 'experiment kit' with a kinesthetic mode in a remote setting, the third 'firsthand experiment' with a kinesthetic in a place-based setting (which is conventional), and the fourth 'demonstration experiment' with an audio/visual mode in a place-based setting. Note that Figure 3 supposes there are no essential impossibilities to combining any learning sites and modes. Differently speaking, the arrows in the figure that divide the plane into quadrants signify the supposed optimal settings for each laboratory experience but do not implicate contradictions of directions (there is no origin at the plane).

According to Oliver & Trigwell (2005), the learning experiences and learning space should be as varied as possible in the components of a blended learning system. Then, remote laboratory as blended learning has two possible combinations of laboratory experiences: (1) An experiment kit optimized for the remote kinesthetic mode with a demonstration experiment optimized for the place-based audio/visual mode. Or (2) A firsthand experiment optimized for the place-based kinesthetic mode with experiment video optimized for the remote audio/visual mode.

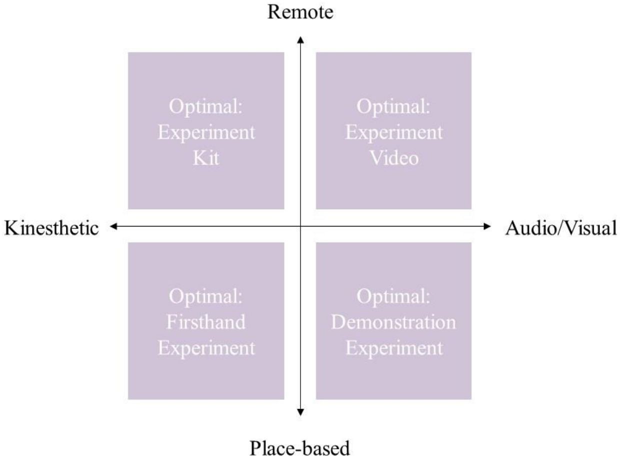

Figure 3. Arrangement of optimal laboratory experiences in each quadrant according to the extended understanding of blended learning with the learning modalities in laboratory education

A couple of additional considerations would be practically helpful while designing a remote laboratory as blended learning. First, the pre-lab or pre-class activities in a blended laboratory class can give students prerequisite learning experiences before the usual class time and allow students to spend their in-person time (Lee et al., 2021; Loveys & Riggs, 2019; Gregory & Di Trapani, 2012). Activities such as preliminary experimentation and pre-lab report writing (including information searching and theory recap) might be beneficial.

Second, student interactions can be promoted by some computer platforms for science teaching and learning (e.g., Sinex & Chambers, 2013). For example, technology can allow students to collaborate in constructing their own scientific knowledge by articulating their scientific arguments concurrently in a program that visualizes the overall discussion (Kirschner et al., 2012). The visualization of such a collaborative process can be a component of the portfolios that students produce during the science course (Huang et al., 2009).

2.4 Instructor Agency and Sociocultural Perspective

2.4.1 Instructor agency in science education

The notion of agency has been considered helpful in sociology in describing the behavior of human agents in a given structure. Although the agency can be defined in a variety of ways (e.g., Giddens, 1976; 1981; 1984; Archer, 2000; Sewell, 1992; 1999), its essence of it denotes “the capacity to act according to one’s choice” rather than “merely following a predetermined path according to their already determined fate or the surrounding environment.” (Ha, 2019, pp. 32-33). Meanwhile, the structure is defined as “a process in which the social practices of agents continue to spread in time and space” that consists of rules (scheme) and resources, which reproduce each other (Ha, 2019, p. 35, based on Giddens, 1981; 1984).

Scholars have noted that the agency | structure framework can be applied to educational agents such as instructors and/or students, including science education situations (Ha & Kim, 2019; So & Choi, 2018; OECD, 2019). Particularly, the dynamic nature of agency | structure dualism has been emphasized in science education research (Ha & Kim, 2019). Although Giddens (1976; 1981; 1984) had an impetus for their dialectical reproduction, it was Sewell (1992) that understood the structure as more changeable by the agents. In this viewpoint, the structure affords and constrains the agency, and the agent contributes to the reproduction or transformation of the structure. Therefore, the relationship between structure and agency is dialectical (Sewell, 1992; 1999), which justifies the use of the framework in the time of change in the teaching and learning context experienced by science instructors (Lee & Kim, 2021a; 2021b).

Bell & Gilbert (1996) contemplated science instructors' agency amid the educational change in classroom activities, values, and thinking. However, they pointed out that as the notion of agency presupposes individualism, science instructors' agency may overemphasize their responsibility. Therefore, it is important to understand that science instructors have and should have limited agency embedded in the teaching and learning situation surrounded by social, cultural, and organizational factors - i.e., structure (Bell & Gilbert, 1996).

The COVID-19 situation in 2020 became the imminent structure that science instructors had to develop and demonstrate their agency to respond to the abrupt educational change from FTF settings to NFTF ones (Fu & Clarke, 2022). Particularly, science teachers' limited agency while implementing lab courses during the COVID-19 has been noted, which requires many material resources such as experimental equipment in a given structure (Lee & Kim, 2021a; 2021b; Fu & Clarke, 2022). However, it seems that there has been almost no research that investigated university STEM instructors' agencies regarding URLs during the pandemic.

2.4.2 Sociocultural perspective on Korean science instructors' agency

It is manifest that instructors' beliefs, the distribution of resources, and the scheme for using them cannot be the same worldwide but different according to the sociocultural background where the teaching and learning occur. Therefore, sociocultural factors affect instructors' design and implementation of science classes, including URL (Q4 in 1.2 Purpose of Research). Then, the way to consider the sociocultural factors in Korea becomes significant.

Several studies have interpreted a particular Korean science education field from a sociocultural perspective. For example, Park et al. (2015) examined how structure shaped teacher and student agency while implementing science classes in an “innovative” middle school. Their seminal work suggested a multi-level (i.e., macro-, meso-, and micro- levels) understanding of a science classroom in Korea, drawn from Bourdieu’s (1986; 1992) suggestion of a nested field. From the sociocultural perspective, the components and interplay of each level were delineated. Curriculum reforms, exam systems, and private education can be components of macro-level structures; family, school, private institute, and peers components of meso-level structures; and schema, students, resources, and teachers components of micro-level structures around science classrooms. Through qualitative analysis, they suggested that although teachers and administrators play essential roles in structuring learning opportunities at the meso- and micro- levels, they had a limited agency to address structural constraints from the macro-level.

Based on Park et al. (2015), Lim et al. (2021) explored the challenges a Korean elementary teacher faced while implementing social action-oriented socio-scientific issues (SAO-SSI) using the dialectical relationship of multi-level structures and agency. Lack of educational resources and a negative perception of society members were difficulties in macro-level structures; Teachers’ tendency to avoid teaching SAO-SSI, administrator’s passive support, and curriculum implementation culture were difficulties in meso-level structures; difficulty in education about the meaning and value of social action, and differences in teacher-student perception were difficulties in micro-level structure.

Also, it is notable that in Lim et al. (2021), with a multi-level sociocultural understanding of the Korean science classroom, Priestley et al.’s (2015) teacher-agency model enabled describing teacher agency in a diachronic sense, with teacher agency being understood in the iterational, practical-evaluative, and projective dimensions. Teacher agency is shaped by teachers' past professional/personal experience; present cultural, material, and structural aspects; and their long- and short-term aspirations for future practice. The teacher agency model of Priestley et al. (2015) was also employed to investigate science teachers' agency during the COVID-19 situation (Lee & Kim, 2021a; 2021b).

However, there seems to be no research that interpreted university STEM instructors' instructional behaviors in the agency framework with a sociocultural perspective, needless to say, concerning the remote labs during the COVID-19. In Chapter 3 (Study 1), the university instructors' agency at Hankuk University utilized in implementing their remote lab courses during the COVID-19 will be explored.

2.5 Design and Development Research

2.5.1 Utility of instructional design model

ID refers to "a system of procedures for developing education and training materials in a consistent and reliable fashion." (Branch, 2017, p. 23) On the other hand, ID can have two meanings: in a broad sense, it refers to describing the overall process of ID and development; in a narrow sense, it refers to the 'design' stage in the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) process (Park et al., 2012; pp. 96-97). Throughout this dissertation, the 'ID' was used with its broad meaning.

ID models describe how to conduct the various steps that comprise the ID process by enabling visualization of the overall process, establishing guidelines for its management, and communicating among team members and with clients. (Branch, 2017, p. 27). Therefore, ID models help instructors understand and conceptualize the authentic teaching and learning field by simplifying the complex procedure and process (Park et al., 2012, p. 99). Traditional and typical ID models are based on a *systematic* approach - i.e., ID is a system consisting of its components, which interact and exchange feedback with each other. Here, the previous stage's output becomes the latter stage's input, and this sequential system defines an ID system that also has its primary input and final output, which can be revised based on the feedback to yield efficient and effective instruction (Park et al., 2012, pp. 100-101). In educational technology, 'efficient' focuses on the instructor's side while implementing the course, and 'effective' focuses on the students' side as learning outcomes. Therefore, if an appropriate ID model is developed and validated, an instructor may utilize it to efficiently design and implement his/her course that ensures desirable learning outcomes.

Particularly, if we understand remote lab as a blending of laboratory courses and e-learning, the necessity of an ID model for it increases. Only an integrative model of the components of each can elicit a synergistic effect over the complex characteristics of a remote lab. It has been reviewed above that a design is considered crucial in e-learning. However, in the case of laboratory courses, the convention of cookbook-style hands-on labs has been strong, and there seems to be almost no research that adopted the ID perspective to improve its existing practice. Consequently, although some researchers have suggested several design principles for a remote lab (Winer et al., 2000; Lowe et al., 2013), the more comprehensive, contemporary, or even the post-COVID-19 ID model for remote labs is still called (Lee & Hong, 2021b; Q5 in 1.2 Purpose of Research).

2.5.2 The need for a flexible model

When the so-called traditional (or classical) approach to ID is *systematic*, which supposes a linear, systematic, deterministic process — evaluation of the instructional system may be fed back only after a demanding analysis, design, and implementation of it to learners (Crawford, 2004; Nixon & Lee, 2001). However, ID must consider the situations in which teaching and learning occur (Reigeluth, 2013). When the linearity of the conventional development approach becomes rigid, it might not provide the "flexibility required to accommodate feedback and revisions during the development process." (Dowding, 1991, p. 26)

Therefore, when a special need for flexibility arises from environmental turbulence or complex educational systems, ID can instead follow a non-traditional - flexible, adaptive, iterative, … - process that starts from the need for a product and uses constant feedback to make improvements (Crawford, 2004; Willis, 1995; You, 1993). The chaotic COVID-19 pandemic, which affected educational practices around the globe beginning in 2020, is undoubtedly a situation that warrants a non-traditional approach (cf. You, 1993; Dowding, 1991). Notably, the classical ADDIE framework can be used to develop a flexible ID model because of its generic characteristics (Crawford, 2004; Branch, 2017).

2.5.3 Model development and validation research

Design and developmental research is defined as "the systematic study of design, development and evaluation processes with the aim of establishing an empirical basis for the creation of instructional and non-instructional products and tools and new or enhanced models that govern their development" (Richey & Klein, 2007). Notably, this approach has rarely been used in science education.

The design and development research can be categorized into product & tool research and model research (Richey & Klein, 2007). Richey & Klein (2007) again categorize the types of ID model research into (1) model development, (2) model validation, and (3) model use. Study 3 corresponds to the first two: the researcher developed an ID model for URL and validated it to guide the ID process for URL.

The model development process can include a literature review, field observations, and data from the experiences of previous designers/developers.

Meanwhile, the model validation process can utilize data from expert review, usability test, and field evaluation. Particularly, the model validation process includes internal validation and external validation. The former focuses on the components and processes in the ID model, while the latter investigates the consequence of the instructional program derived from it (Richey & Klein, 2007; Tracey, 2009). Among the empirical examination, the usability test and expert review are conducted for internal validation and students' responses or test results for external validation (Richey & Klein, 2007; e.g., Tracey, 2009; Lee et al., 2017).

2.5.4 Rapid prototyping approach

To derive an instructional program from the ID model during the external validation, the rapid prototyping (RP) approach was used. As signified in its name, the strengths of the RP approach lie in iterative instructional program building and revision (Nixon & Lee, 2001). Through its iterative process, the RP approach offers high-fidelity problem-finding and problem-solving in the authentic instructional situation, enabling the instructional program's efficient revision (Nixon & Lee, 2001; Tripp & Bichelmeyer, 1990; Lim & Yeon, 2015, pp. 18-26). Therefore, the RP approach requires modularity of the instructional unit and plasticity of the media (Tripp & Bichelmeyer, 1990). The research field of Study 3 — a semester-long remote lab with computer-based instruction — satisfies those requirements.

Chapter 3. Study 1: University Instructors' Agency During the Implementation of Remote Laboratory

Study 1 aims to delineate how the university instructors' agency was utilized while implementing their URLs during the pandemic. Note that the COVID-19 pandemic and related prevention and control responses of governments were an imminent structure imposed on institutions and people's living world, including science education, that shaped science instructors' agencies. Therefore, investigating science instructors' agency during the implementation of remote labs during the period would reveal unforeseen aspects of laboratory course design and implementation process (Lee & Kim, 2021a; 2021b; Fu & Clarke, 2022).

The multi-level sociocultural perspective was supposed to be appropriate for framing the URL phenomena at Hankuk University in the spring semester of 2020. Considering the unavoidable influence of the pandemic and limited power of individuals in the situation, it was construed that structure | agency dialectics had not worked during this period. Instead, only the unidirectional influence from the former to the latter has been dominant, particularly for the first half of 2020. Thus the research plot could be narrowed down from the Korean situation during the global COVID-19 pandemic as a macro-level context, a university as a meso-level context, and each implemented remote lab as a micro-level context. Further, university instructors' perceptions of the implemented remote labs and their suggestions for future remote labs were also investigated. These would be delineated as the practical-evaluative and projective dimensions of university instructors' agency (Priestley et al., 2015).

3.1 Research Questions

Based on the above considerations, Study 1 aimed to (1) interpret the URL phenomena from a sociocultural and teacher agency perspective, and (2) while descriptively report the URL cases, both at a university in the Korean context. A total of three research questions (RQs) were set:

RQ 1. What structures at the macro- (Korea), meso- (Hankuk University), and micro- (each course) levels afforded or limited instructors' agency while implementing remote labs?

RQ 2. How did instructors at Hankuk University implement remote labs in 2020 during the COVID-19 emergency? (Were there any differences in implementations of remote labs?)

RQ 3. How did instructors at Hankuk University perceive the implemented remote labs, and what suggestions did they make for future remote labs?

3.2 Method

3.2.1 Participants

The researcher interviewed 10 instructors at Hankuk University who took charge of URL implementation in 2020. The participants were recruited via e-mail and snowball sampling Participants included one TA in Chief (TAC) in the physics lab, two TAs in the chemistry lab, two lecture professors (LPs), one TAC in the biology lab, two TAs in the earth science lab, and two TAs in major course labs. Here, TAC refers to the lead TA who manages the LS course's overall implementation and directs other TAs. The detailed information of the participants is presented in Table 4.

Table 4. Participants who engaged in the URL in 2020

Code	Semester	Department	Status	Gender	Notes
TAC_PhysLab1	1st and 2nd	Physics	Ph.D. student	M	
TA_ChemLab1	1st	Chemistry	M.S. student	M	
TA_ChemLab2	2nd	Chemistry	Ph.D. student	F	
LP_BioLab1	1st and 2nd	Life science	Lecture professor	M	Has engaged in biology lab since 2013
LP_BioLab2	1st and 2nd	Life science	Lecture professor	F	Has engaged in biology lab since 2013
TAC_BioLab1	2nd	Life science	Ph.D. student	M	
TA_EarthLab1	1st and 2nd	Earth science Education	MA student	F	Had been a secondary teacher
TA_EarthLab2	2nd	Earth science education	MA student	F	Had been a secondary teacher
TA_MajorLab1	1st	Chemistry education	MA student	M	Course: Analytical chemistry experiment; Had been a chemistry lab TA/Had written a case-study article about URL
TA_MajorLab2	1st	Biology education	Ph.D. student	M	Course: Life science experiment and teaching method

3.2.2 Qualitative interviews

Qualitative interviews were conducted from November 2020 to March 2021. The researcher interviewed most participants individually (except LP_BioLab1–2), with semi-structured questions. Interview questions included information about the URL instructional system, decision-making processes, endeavors, and perceptions of URL implementation in 2020 (Figure 4). The interviews took about 50 minutes each. Considering the pandemic situation, six of the ten participants were interviewed via the Zoom webinar program, and the other four were interviewed FTF abiding by the Korean government's public health and safety rules. All the interviews were recorded and transcribed.

○ **Participant information**
- Please explain your affiliation and status.
- What RLS were you engaged in implementing in 2020?

○ **Characteristics of the course**
- What do you think of the characteristics of the RLS you engaged in? (As a science discipline and/or LS)
- Please describe the details of the RLS instructional system you engaged in.

○ **Emergence and implementation of LS**
- What was the decision-making process for the implementation of the RLS in the non-face-to-face format in 2020?
- Through what process were the course details, such as shooting the video, course content, and lab report evaluation decided?
- What were the resources, such as human resources, that were available while implementing the RLS?

○ **Perception on the RLS**
- Do you think students fostered the appropriate knowledge, skills, and attitudes in the RLS course?
- What were the pros and cons of the non-face-to-face RLS that you implemented in 2020?

○ **Thoughts on future RLSs**
- Have you planned or did you realize possible improvements for the future while implementing the RLS in 2020?
- What do you suggest for future RLSs should the emergency situation continue?

Figure 4. Examples of the questions in the semi-structured interviews

3.2.3 Data analysis

The constant comparative method (Glaser, 1965) was used to analyze the interview data. The researcher initially coded the transcription and constantly compared the codes with the data to revise the codes several times. Here, the framework of the macro-, meso-, and micro- level structures (Bourdieu, 1986, 1992) that afforded and limited university instructors while implementing URL (see Park et al., 2015) was used. As each level needed different emphasis in the Korean context, broader social contexts and literature were referred to for the macro-level structure. The previous practices of laboratory courses in the university and the interview data were referred to for the meso-level structure. Finally, mainly the interview data was referred to for the micro-level structure. Meanwhile, the practical-evaluative aspect of the teacher-agency model (Priestley et al., 2015) during the first (spring) semester was focused on because most of the instructors had no significant past professional experience in the laboratory courses. However, the projective aspects of instructors' agency toward the future remote labs they might implement were considered, including the information from the second (fall) semester.

The interview participants were requested to provide documents related to their remote labs, such as syllabuses and/or course plans. In addition, Study 1 was conducted in step with Study 2, which examined university students' perception of the remote labs implemented at Hankuk University in 2020 via an online survey and follow-up interview. This information was used to triangulate the analysis of the interview data. In addition, the research process was continuously shared and discussed via an online international joint symposium and internally in the research team in Korea.

3.3 Results

The structural elements that shaped remote labs at Hankuk University in 2020 according to macro-, meso-, and micro- levels are visualized in Figure 5.

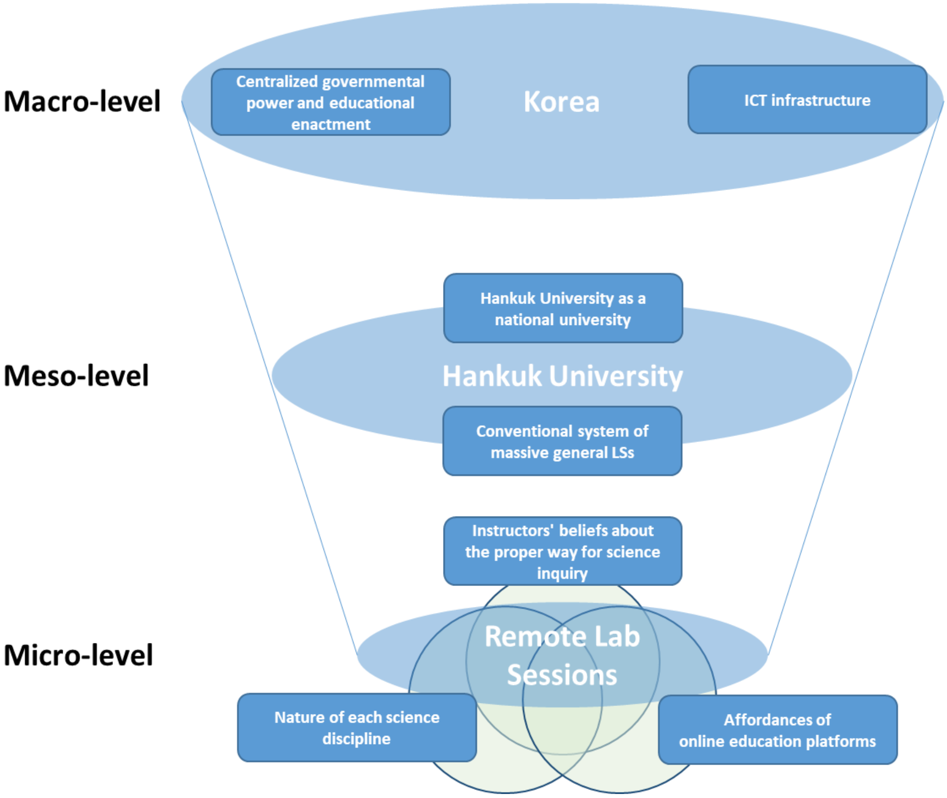

Figure 5. Structural elements that shaped remote labs at Hankuk University in 2020

3.3.1 Macro-level context: South Korea

Centralized governmental power and educational enactment

As universities in Korea cannot avoid being dependent on the KMOE, they had to wait for and follow the decision of the Ministry concerning education during the pandemic situation. However, the response from KMOE to the COVID-19 pandemic can hardly be said to have been expeditious (although they cannot be blamed because of this). K-12 schools and universities in Korea usually start their first semester of the year in the first week of March. However, this was not the case in 2020. The first confirmed case of COVID-19 in Korea was reported on January 20th, 2020, and as the disease spread in Korea, on February 5th, the KMOE recommended that universities postpone the start of the first semester up to 4 weeks which was unprecedented. Moreover, the KMOE specified that all university courses should be implemented using an NFTF format. As a result, most universities in Korea had to make not easy decisions and consequently started the semester in the third week of March, and all courses started in an NFTF format. Although the KMOE allowed some FTF classes in practical work courses in May, the KMOE inspected whether the universities abided by preventive guidelines, and most universities retained the NFTF format until the end of the semester.[3]

These preventive and regulative responses of the government and education authority were a macro-level structure connected to the meso-level structure of Hankuk University. The administrators and instructors had to wait until

[3] For the timeline described here, the researcher referred to the news articles from University News Network (2020a, 2020b).

they got the information, which indirectly but significantly limited the agency of laboratory instructors.

The ICT infrastructure

Korea is well known for its high-quality ICT infrastructure: More than 95% of the population (approximately 45 million people) have access to high-speed internet. This helped the country respond more successfully to the COVID-19 pandemic than some other countries could (see Park et al., 2020). In education, in particular, many high school students in Korea are accustomed to attending internet online lectures as a form of private shadow education in addition to formal education in school (see Shin & Jang, 2011). Therefore, when the whole education system in the country had to shift to NFTF education via the internet, instructors and students could make an easy transition. No instructor who participated in this study said that anybody had any problem with internet access while implementing URL - instead, the ICT structure of Korea was appreciated for enabling smooth NFTF courses.

> I just thought it ran well compared to what I've expected. ... anyway, observing various responding methods, I felt 'Oh, our country is an IT powerhouse.' (TA_EarthLab2)

And as described later, this ICT infrastructure was closely related to the use of various online education platforms in the micro-level context that afforded and/or limited instructors' design and implementation of URLs.

3.3.2 Meso-level context: Hankuk University and previous practices in laboratory courses

Hankuk University as a national university

As Hankuk University is a national university, governmental requirements must be followed more than private universities - for instance, public safety rules concerning the COVID-19. Hankuk University has a somewhat rigid administrative atmosphere: Once the university administration decides something, departments and instructors must follow. This meso-level structure limited the implementation of remote labs. As the university administration decided that laboratory courses also should be NFTF, instructors needed to prepare for these unprecedented remote labs:

> Consequently, the guidelines of our [physics] department were determined according to the direction of the superior office. (TAC_PhysLab1)

> There was only a unidirectional notification last year [2020]. (TA_MajorLab2)

Therefore, only after the announcement from the administration the instructors started to utilize their agency to implement remote labs:

> We just follow … the direction of the university and department. [After that] we can handle the details under our authority. (LP_BioLab1)

> The announcement was delivered from the university that laboratory courses are determined to be non-face-to-face … As I fully do [take charge of] experiments, I decided… (TA_EarthLab1)

The conventional system of massive general laboratory courses

As mentioned above, about 1,500 first-year students at Hankuk University take general laboratory courses annually. Therefore, relevant departments have developed a conventional system to implement massive courses in the university that have been used for decades. Many aspects of this system were retained and worked as a structure that affected general LS instructors' decisions in 2020:

> The teacher [officer in the department] has the accumulated know-how in the case of the chemistry lab. (TA_ChemLab2)

> What existed previously [i.e., curricula] has been around for more than 20 years. We have been changing that gradually, not abruptly. (LP_BioLab2)

Consequently, instructors rarely pointed to the lack of resources in implementing remote labs. This was because Hankuk University already had many resources to run massive laboratory courses in the conventional system, including the TA labor force and apparatus. Therefore, instructors at Hankuk University utilized any resources they needed to implement URLs, from the conventional course syllabus to materials, except for the laboratory classroom they did not need.

Meanwhile, major course lab instructors barely mentioned the conventions but revealed they had much flexibility because a relatively small number of students take those in each autonomous department.

3.3.3 Micro-level context: Remote laboratories according to science discipline

The micro-level structural elements can be delineated in more detail, as in Figure 6. The micro-level structural elements were closely intersected; from there, specific issues in the teaching and learning of remote labs were raised during implementation. Therefore, the researcher would explicate the micro-level structural elements, describe the implemented remote labs, and reveal the related problems.

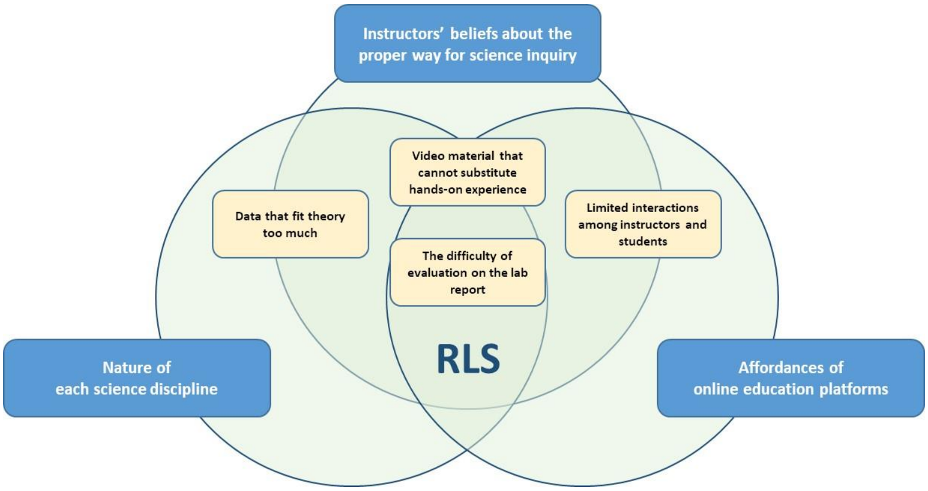

Figure 6. Micro-level structural elements in detail and issues raised in intersections

Instructors' beliefs about the proper way for science inquiry

Due to the imminent influence of the COVID-19, instructors have realized their own beliefs about the desirable laboratory teaching and learning methods, which is understood as a schema that shaped their agency. Although the instructors did not use the exact term “inquiry” (as most of them were not educational scholars), they believe that scientific inquiry should base on hands-on experiences - students should follow the experimental procedures and yield their own data firsthand, followed by the interpretation of it. Therefore, when instructors at Hankuk University had to implement URL, they felt embarrassed between their beliefs and preventive requirements:

> [The physics laboratory is] a process that students embody .. the scientific knowledge they had learn in the theory classes coming to laboratory and using apparatuses ... [Even after the decision from the university headquarter], most [TAs] thought that ‘isn’t at least the laboratory course should go face-to-face?’ (TAC_PhysLab1)

Probably, chemistry instructors seem to have felt much confusion (e.g., Youssef et al., 2020; Jones et al., 2021; Jang et al., 2020), which may have caused a somewhat inflexible response to the mandated non-face-to-face course format:

> If we look inside weekly chemistry experiment topics such as the molecular weight of carbon dioxide, separation of components using HPLC, … these things are impossible to do in the non-face-to-face format without experiment. … Eventually, chemistry involves mixing reagents, increasing temperature, and boiling. It is nonsense to run an experiment course without experiments. (TA_ChemLab1)

Nature of each science discipline

The implementation of remote labs was related to the perceived nature of each science discipline; in other words, not only administrative rationale but also the structure of knowledge limited the agency of each university instructor.

This was most apparent in the earth science lab. Unlike the other three general laboratory courses, TAs instructed students via a real-time lecture on the Zoom webinar program. TAs in the earth science lab said it was natural as they usually did so even before the pandemic:

> There is almost no experiment that puts models or reagents [in front of the student] as is done in chemistry or biology. … As I said before, it is data interpretation. … In that aspect, if each [student] should do it themselves, I think there would be no significant difference between face-to-face and non-face-to-face. (TA_EarthLab1)

> Our earth science lab curriculum has been run by setting assignments and students doing them. Physics and chemistry [labs] do actual operating [hands-on] experiments. So [I] thought physics, chemistry, biology [URL] would be very burdensome, but earth science would not be affected much [in the non-face-to-face format].… For example, earth science lab experiments mostly involve running simulations or animations, which are available at home alone. (TA_EarthLab2)

Meanwhile, in biology, both the introductory biology and a major course lab had modularized laboratory curricula even though the departments were different, which is unique compared to the other disciplines. This provided instructors flexibility in implementing remote labs responding to the COVID-19 situation:

> Previously there were four modules; they were reduced to three, and the lab reports were also reduced from per experiment to per module. (LP_BioLab1)

> In the last year [2020], Part 1 was entirely online. Part 2 was half-online and half-offline. Part 3 was offline but was shortened. (TA_MajorLab2)

Affordances of online education platforms

Instructors could utilize various online education platforms in the first semester of 2020, besides the usual e-mail. The conventional LMS of Hankuk University named an “ETL (E- Teaching and Learning),” provided online blackboards for announcements, course material sharing, homework (mainly lab report) submission and scoring, and Q&A. Therefore, almost all instructors and students at the university relied much on the LMS during the pandemic situation. Meanwhile, some courses such as physics lab used other LMS such as “Turn it in,” which checks plagiarism for the homework and enables online feedback on it and/or their own intranet.

The most prominent online platform was the Zoom webinar program. The Zoom enabled instructors to manage real-time classes and students to access those via computer or mobile smart devices, which might overcome time and space constraints of teaching and learning. Also, it was possible to open several small-group sessions in the Zoom webinar program to facilitate small-group activities. Hankuk University provided all the instructors and students a Zoom account for holding unlimited online sessions to support non-face-to-face online education.

3.3.4 The remote laboratories implemented at Hankuk University in the spring semester of 2020

Instructors at Hankuk University designed and implemented their own remote labs utilizing their own agency shaped under the influence of the above structural elements. Figure 7 shows the shift of the four general laboratory courses from their original formats - kinesthetic learning mode for the physics, chemistry, and biology labs, and audio/visual learning mode for the earth science lab (blue dots), all in a place-based learning space - toward an audio-visual learning mode in remote learning space (purple dots). Also, the general remote labs implemented at Hankuk University in the first semester of 2020 were compared in Figure 8, which shows their commonalities and apparent differences.

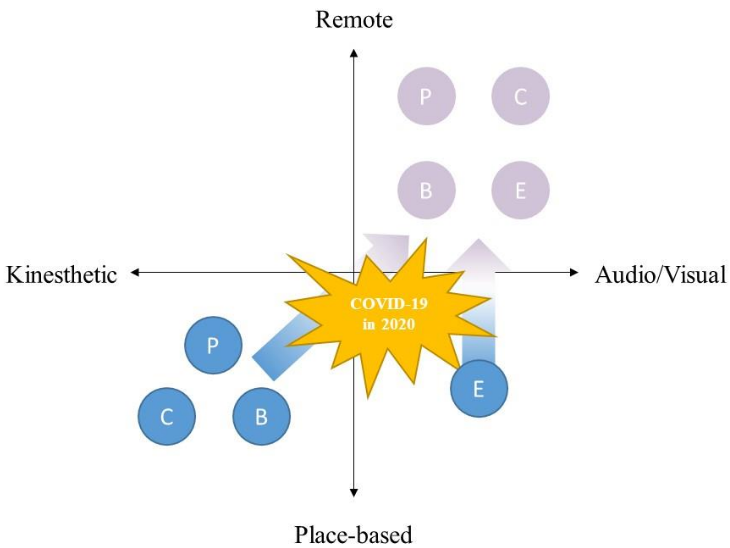

Figure 7. The shift of the four introductory laboratory courses during the COVID-19 according to the extended understanding of blended learning with the learning modalities in laboratory education

Commonalities

As laboratory courses had had similar formats before the COVID-19, the remote labs had several commonalities in 2020. All of them had one session per week. Instructors also reduced the total number of sessions. They followed the sequence of introducing particular scientific theories to students, showing experimental procedures, and requiring students to write lab reports periodically. They provided students with videos as learning material (except the earth science lab), and none of them used quizzes for preview to enhance students' learning (because of the cheating issue as in the physics lab). All the remote labs required lab reports in an electronic format, which was the first time for physics and chemistry labs. If students had any questions, they could contact the TA via e-mail or LMS.

Differences

However, many differences occurred in the remote labs in 2020. Only physics and biology labs newly recorded and edited experiment videos for students. TAs in these two courses conducted a preliminary experiment to record and produce experimental raw data, which is essential for writing a lab report. Strikingly, the chemistry lab utilized experimental videos which were only introductory and had been recorded more than 10 years previously and did not provide students with any experimental raw data. Meanwhile, the earth science lab did not record any new video material, but TAs instructed students via real-time Zoom classes with lecture slides and accessible data in online repositories, which was unique.

The synchronicity also differed. The physics and earth science labs were the only two remote labs that required real-time attendance of students at a particular time on weekdays. However, in the physics lab, TAs played experimental videos while the students were online in Zoom class and they all watched them together. After watching, TAs and students had Q&A sessions. However, the chemistry and biology labs uploaded video material online, and students watched it themselves.

Except for the biology lab, the other three remote labs required students to write one lab report for each experimental topic. However, the biology lab reduced the number of required lab reports to three, corresponding to the three modules of nine experiments based on their themes. The requirements for the lab reports were also different. The physics lab did not mandate students to follow a specific content system but provided some guidelines, and references were not considered important. As the chemistry lab did not provide students with experimental raw data, it also did not require a results section; instead, they were required to do assignments on theoretical problem-solving. In the biology lab, references were the most crucial part of the lab report, which contrasts with the physics lab. In the earth science lab, discussion was sometimes required, and occasionally there was an assignment for advanced problems.

		Physics lab	Chemistry lab	Biology lab	Earth science lab
Video	Repeatable	Y	Y	Y	N
	Newly recorded and edited	Y	N	Y	N
	Type	(1) theoretical: background theory (2) experimental: process and result	Only introductory content	(1) theoretical: background theory (2) experimental: process and result	Zoom instruction
	How watched	Students access Zoom session and watch the video with TA simultaneously	Student self-directed	Student self-directed	Students access Zoom session and watch TA's instruction
	Length	〈 20 min.	〈 10 min.	〈 30 min.	〈 30 min. (TA lecture)
Attendance required		Y (Zoom)	N	N	Y (Zoom)
Quiz		N (abolished after initial two weeks due to a cheating issue)	N	N	N
Given experimental raw data (produced by TA)		Y	N	Y	△ (Sometimes students downloaded data from relevant institutional websites or gathered their own data)
Requirements in the report		- Specific system of content not required. - Guidelines are given via intranet : 'introduction'-'body'-'conclusion' - References: relatively less important	- Abstract - Introduction - Discussion - Assignment (homework): most important part. Theoretical problem-solving. - References	- Introduction - Method - Result - Discussion - References: most important part	- Introduction - Method - Result - Discussion (sometimes) - Assignment (advanced problems) - References
Report submission		1 / week	1 / week	1 / 3 weeks (1 module)	1 / 1 (sometimes 2) weeks
Number of experiments		8	12	9	10
Characteristic features		- Provided supplementary materials via intranet - Submitted lab reports via "Turn it in" to check plagiarism - Cancelled every third class	- The assignment was most important	- 3 weeks of RLS session constituted 1 module. There were a total of 3 modules in the semester. - Students (2 in 1 group) had to present their topic of interest in 5 minutes.	- There were almost no experiments that required reagents - No requirement for exact calculation of specific value. - Cancelled a class for mid-term and final exams.

Figure 8. Types of remote labs by science discipline at Hankuk University in the first semester of 2020

3.3.5 Issues raised during the implementation of remote laboratories

Video material that cannot substitute hands-on experience

TAs responded that students could not have actual hands-on experiments in the remote labs implemented in the first semester of 2020. In this situation, instructors shot and edited video materials that presented experimental procedures (except in the chemistry and earth science labs):

> In the department meeting, … there was an opinion that if we cannot avoid going online, that way is only possible, and all consented on that thus determined to shoot video and distribute it. (TAC_PhysLab1)

> Then we could not think of other ways. (TA_MajorLab1)

Remarkably, no experience in manipulating apparatus and equipment was problematic. Although the video cannot fully replace the hands-on experience, instructors endeavored to incorporate some sensory experiences into the video:

> Actually, we shot videos before the non-face-to-face [situation]. … [We encouraged each other that] for now [2020], let's put captions and music to make better videos for each module. (LP_BioLab2)

> To facilitate students' observation, we zoomed in as much as possible using a microscope. While shooting using a microscope, for example, we shot from various angles such as left, right, front to make it similar to students actually looking inside a microscope. (TA_MajorLab2)

Data that fit theory too much

Interestingly, instructors were concerned about the characteristics of the experimental data. They fit the related theory too much without significant error, as TAs conducted preliminary experiments and collected the data rather than students. Students would then have nothing to discuss in the lab report in-depth, and instructors worried that this would decrease the inquiry-like process in laboratory:

> While writing reports, … comparing and analyzing the experimental data whether it matches theory - I think this is most important. … [However, in 2020], it just became writing a report with the data TAs collected. It became that kind of class. (TAC_PhysLab1)

> In the discussion of the report, while preparing experimental data, students had [their own] data regardless of how well they had conducted the experiment. [For now] the data is not theirs and we prepare those virtual data [in some cases], as what is important is data analysis after students finish the experiment, and we instruct how to analyze. (LP_BioLab1)

> I think contemplating why [the result is] spoiled is most important in the undergrad laboratory courses. … [As I experimented, students] could only get theoretical, right experimental results that do not deviate from theory. This is far from the purpose of the undergrad laboratory courses. (TA_MajorLab1)

Limited interactions among instructors and students

Most of the instructors responded that there was much difficulty in interacting with students. This was significant in chemistry and biology labs, where there were no synchronous encounters of TAs and students online in the first semester of 2020.

Instructors particularly mentioned the non-verbal interaction that allowed them to grasp whether students were following up on the teaching, which was not perceivable in the URL.

> I felt last time [first semester] that friendliness is very important in trust-building. … I thought the non-face-to-face [format] has limitations in that respect. (LP_BioLab2)

> There was no interaction between teacher and students at all. Even if I make the same explanation, in face-to-face I can see [students'] eyes and gestures, and [students] see where I point in the slide, and it facilitates interaction and understanding. However, as we did it in non-face-to-face, that was not possible. (TA_EarthLab1)

Instructors also said that the use of an LMS was limited only to the announcements, course material sharing, and lab report submission, which consequently did not support much interaction among instructors and students. In addition, they felt that interaction between students also decreased.

The difficulty of evaluating the lab report

During the URL, all the students in a class had the same data that fit theory too much (or had no data at all in the case of the chemistry lab) because TAs produced it not by students firsthand. Therefore, evaluation of lab reports was difficult for instructors:

> The differences in scores certainly decreased a great deal. There was nobody who had spoiled the experiment, so [students] wrote reports that had one experimental result. (TA_MajorLab1)

So they devised their own ways to get around this problem, for instance, a quiz in a lab report or presentation:

> Then the experiment is done, students submit a report, but it's like just writing an introduction. I also gave [them] quizzes. I gave quizzes because I was concerned that there's nothing to evaluate. Because writing procedures, data, discussion, and contemplation after experiments are all gone. (TA_ChemLab1)

> We thought it would be good to foster [oral] presentation skills. … they make a talk of up to 5–10 minutes. … these accounted for a large part of their grades … (LP_BioLab2)

Not irrelevant to this, universities in Korea, including Hankuk University, are known to have given higher overall grades to students in 2020 in order to take into account students' constrained learning experiences and difficulties in evaluation.

3.3.6 University instructors' perceptions of the learning outcomes of remote laboratories

Instructors had different expectations for the learning outcomes of remote labs than they had for the usual laboratory courses (Figure 9). For the knowledge aspect, most replied that students could gain some or even a sufficient amount of knowledge. For the skills aspect, some said that students may have gained data processing or lab report writing skills to some extent, but naturally, none of them were optimistic about hands-on skills. Instructors' responses to the attitudes aspect varied the most, possibly because observing students' attitudes via NFTF remote labs was challenging.

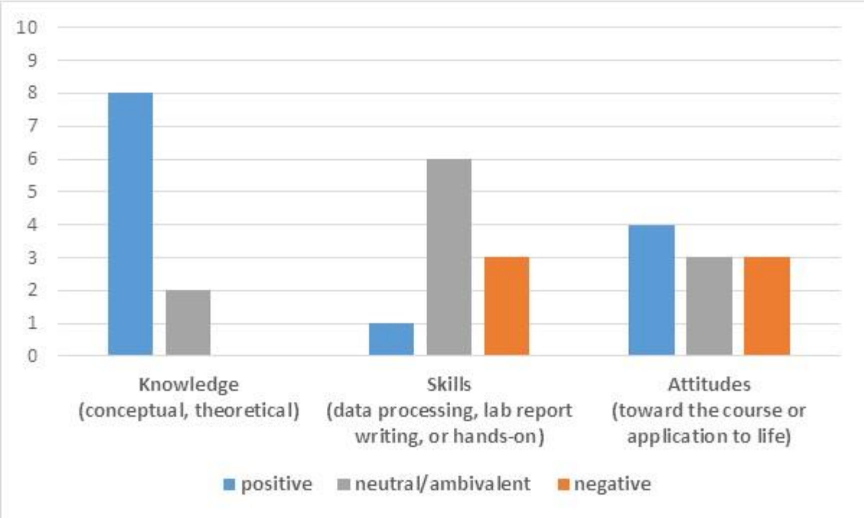

Figure 9. Instructors' expectations for students' gaining in consequence of remote labs in 2020 (N = 10)

Instructors were concerned about the quality of teaching and learning in remote labs, in other words, whether students could "gain" much from the courses because they "did not actually do" the experiments (see Reid & Shah, 2007). They worried about the lack of authentic observation and hands-on-experience learning processes that normally occur in laboratory courses:

> I still doubt that students can gain much in non-face-to-face laboratory. … Although they watch videos showing how the experimental results are

> collected, there will be a gap or differences from actually doing. (TAC_PhysLab1)

> I agonized about how students could feel this even indirectly. However, when we see this from the third-person viewpoint, what the student gains … will not be an advantage. (TA_ChemLab1)

3.3.7 University instructors' adaptations and suggestions for future remote laboratories

After the first semester of 2020, university instructors adapted to online courses and revised their classes, revealing their projective teacher agency. It was acknowledged that physics, chemistry, and biology labs became similar to some extent in the second semester of 2020 (however, the instructors said they did not know how the other departments were implementing remote labs nor communicated between the first and second semesters.) The physics lab only made trivial changes (e.g., due dates for assignments changed by one day), but chemistry and biology labs became similar to the physics lab. In the chemistry lab, TAs conducted preliminary experiments to get raw data, shot experiment videos, and provided these to students. They opened a Zoom session every week, watched the experimental video with students, and had a Q&A. Biology lab also changed the video watching from an asynchronous student-directed way to a synchronous Zoom session with the TA. Notably, the earth science lab did not make essential changes and retained the instructional system they had used during the first semester.

Remarkably, some changed their views on URL from unfavorable to promising to some extent because of its convenience and efficiency, and speculated further strengths of it:

> For the pros, students can take the course conveniently. … What was good for me during the non-face-to-face course was that the feedback would be good to be online, even might be better, I think. … if we run a non-face-to-face course, a student can access a small meeting room with a TA [in Zoom to get individual feedback], and others can do other work … in a more flexible environment. (TA_BioLab1)

Also, some highly valued their innovative URL instructional system implemented in 2020, with their utilization of agency:

> … examining how students take it, and we revised [the course] inch by inch. … the system for now is constructed in the best imaginable way. (TAC_PhysLab1)

> Thus, we prepared all the things we could do in the non-face-to-face situation. … Although students did not know, many people endeavored behind [the scenes]. … such as TAs' hidden endeavor … (LP_BioLab1)

> Personally, I would do it like this if I come back. Even if it were not due to CORONA, I think these ways were very successful [in fostering lab report writing skills]. (TA_MajorLab1)

Further, university instructors werer asked to imagine a future situation (after the COVID-19) that would necessitate remote labs rather than traditional laboratory courses. Some proposed the development of experimental kits that can be delivered to students' homes:

As a kind of project, selecting themes with simple apparatuses that students can experiment with at home … (TAC_PhysLab1)

… the most realizable is an experimental kit, … So a small pack with a few pincettes, spatulas, bottled reagents with beaker … It would be possible in major course labs. I don't think it would cost much. (TA_MajorLab1)

Still, others suggested the URL could also be an effective teaching and learning format, adopting appropriate educational technologies:

We should split them [videos] into short steps. If a student presses a button, it would play … we should make [bi]directional [web]pages. (TA_ChemLab1)

It would be good to try to make virtual things [learning materials]. (LP_BioLab2)

If I want to set formative evaluations in the class and give a quiz, [there could be a] function that enables me to see how students are controlling the screen. (TA_EarthLab2)

3.4 Discussion

This study investigated and described how various online remote labs emerged at Hankuk University in Korea in 2020, as necessitated by the COVID-19. Four general laboratory courses that had previously been similar and two major course laboratory courses were compared. The URL phenomena were interpreted from a sociocultural perspective, focusing on the structure posed by the COVID-19 pandemic and the educational authorities and agency of university instructors. The macro-level context of Korea, the meso-level context of Hankuk University, and the micro-level context of each URL were closely interconnected with each other and the university instructors' agency (Figure 5). In the first semester of 2020, the multi-level structures strongly shaped instructors' agency. However, each remote lab implemented in each discipline became quite diverse due to the instructors' endeavors. University instructors' concerns were about video materials, data characteristics, limited interactions between them and students, the difficulty of evaluation, and what students could "gain" from the URL without hands-on experience. Since the second semester of 2020, instructors have adapted to the situation to revise their remote labs and have suggested further improvements.

The results of this study reveal that university instructors' agency can lead to the emergence of divergent course implementations even under similar structures given during an emergency. The researcher did not evaluate or judge the remote labs implemented in 2020 nor consider differences in superiority or inferiority because the criteria of accountability should not assess instructors' endeavors during the crisis. Therefore, the agency the instructors revealed in each

URL should be appraised as a unique “achievement rather than an (individual) capacity” (Priestley et al., 2015, p. 35) which even reached extensive revision of their URL instructional systems in the second semester of 2020.

We must contemplate how we would go beyond the chaotic situation caused by the pandemic. There are several points to review in the internal aspects of remote labs.

First, it should be mentioned that adopting cutting-edge educational technology was suggested to be a breakthrough for future remote labs. Many education researchers also raised the possibility of appropriate technology that provides more affordances to the instructors. For example, technology such as simulation, augmented reality (AR), and virtual reality (VR) that deliver observations in an experiment without physical experiments would be helpful (Lee & Hong, 2017; Hu-Au & Okita, 2021). However, it should be noted that individual instructors had difficulty producing satisfactory experiment videos. Therefore, rather than adopting cutting-edge technologies with a high threshold, shared versions of or producing guidelines for video materials would support instructors. Regarding the provision of experimental videos, contemplating the nature of laboratory courses from a constructivist view (Abd-El-Khalick et al., 2004), synchronous video watching and discussion sessions are recommended. A collaborative/cooperative learning model could be adopted together to promote instructor and student interactions (Hofestein & Lunetta, 2004).

Interpreting the URL in the light of minds-on science teaching and learning was also possible. Students’ theoretical knowledge and data processing, and scientific writing skills could be fostered through remote labs. However, hands-on operational skills and attitudes cannot (Reid & Shah, 2007). It was pointed out that that the characteristics of data—(re)producing via preliminary experiments, provision to students, and the extent of matching with theoretical prediction—strongly affected the method of instruction and lab report writing. They can essentially define the nature of inquiry in (remote) laboratory courses (see Hofstein & Lunetta, 2004). Therefore, if we are to improve future remote labs, the data characteristics should be designed carefully.

Chapter 4. Study 2: University Students' Perception of Remote Laboratory

In Study 2, Hankuk University students' perception of their learning experiences in URLs was investigated. Study 2 focused on the difference in student perception according to their URL course in 2020 to provide generalizable information about the effects of teaching strategies than single-case. Possible differences in student perception were contemplated according to emergent teaching strategies related to media preparation, aspects of interaction, and assessment and feedback. Based on the results, theoretical and practical suggestions for university STEM instructors who may implement URLs in the future will be made.

Note that no quasi-experimental method could be used during the pandemic in 2020 because the experimental and control groups could not be differentiated then. Also, a large-scale standardized test was not applicable in an imminent emergency. Therefore, the consequences of implementing URLs could only be examined *ex post facto*, investigating the perceptions of students who experienced those (Pertillion & McNeil, 2020; Blizak et al., 2020; Lee & Hong, 2021b).

4.1 Research Questions

1. How did university students perceive the various remote labs necessitated by the COVID-19 in 2020?

2. Were the university students' perceptions of the various remote labs different in each course? If so, how did the emergent teaching strategies influence the differences?

4.2 Teaching Strategies Used in Remote Laboratories in 2020

This research was conducted in step with another study about how the instructors at Hankuk University implemented remote labs in 2020 (Study 1). The researcher interviewed 10 instructors in introductory physics, chemistry, biology, earth science, and major-level remote labs. Therefore, It was able to determine the teaching strategies they used in the crisis situation of the COVID-19 pandemic in the spring semester of 2020 and access documents such as syllabuses. The remote labs were similar in that they (1) changed the content of the experiments every week, (2) provided no hands-on experience to students, and (3) required lab report writing for assignments.

However, instructors used different remote teaching strategies in presenting media, promoting interaction, and assessing and guiding assignments (lab report). The types of remote labs presented above (Figure 8) are reorganized around the emergent teaching strategies (Figure 10). Their differences are explicated around general laboratory courses. Also, rather than focusing on why these remote labs differed (which was explicated in Study 1), Study 2 focuses on the consequences of different teaching strategies.

Emergent Teaching Strategies			Physics lab	Chemistry lab	Biology lab	Earth science lab
Media preparation	Video	Repeatable	Y	Y	Y	N
		Newly recorded and edited	Y	N	Y	N
		Type	Theoretical and experimental	Only introductory content	Theoretical and experimental	Zoom instruction
		Length	〈 20 min.	〈 10 min.	〈 30 min.	〈 30 min. (TA lecture)
Aspects of interaction	Real-time attendance required		Y (Zoom)	N	N	Y (Zoom)
	Content delivery		Students access Zoom session and watch the video with TA simultaneously	Student self-directed video watching	Student self-directed video watching	Students access Zoom session and watch TA's instruction
Assessment and feedback	Requirements in the report		- Specific system not required. - Guidelines are given via intranet: "introduction"-"body"-"conclusion" - References: relatively less important	- Abstract - Introduction - Discussion - Assignment (homework): most important part. Theoretical problem-solving. - References	- Introduction - Method - Results - Discussion - References: most important part	- Introduction - Method - Results - Discussion (sometimes) - Assignment (advanced problems) - References
	Report submission		1/week	1/week	1/3 weeks (1 module)	1/1 (sometimes 2) weeks
	Regular instruction and feedback		N	N	N	Y
Other features			- Provided supplementary materials via intranet - Submitted lab reports via "Turn it in" to check plagiarism - Cancelled every third class	- Did not provided experimental raw data	- 3 weeks of RLS session constituted 1 module. There were a total of 3 modules in the semester. - Students (2 in 1 group) had to present their topic of interest in 5 minutes.	- No requirement for exact calculation of specific value. - Cancelled a class for mid-term and final exams.

Figure 10. Emergent teaching strategies in URLs at Hankuk University in the spring semester of 2020

4.2.1 Media preparation

Most remote labs provided repeatable videos of experiments. However, only the physics and biology labs featured newly recorded and edited videos of TAs conducting experiments. In the chemistry lab, instructors only provided short introductory videos that were shot more than 10 years ago. The earth science lab instructors did not record nor provide students with videos of experiments; instead, they directly instructed students via Zoom.

4.2.2 Aspects of interaction

Only the physics and earth science labs required real-time attendance via Zoom. In the physics lab, TAs and students watched the videos simultaneously and had Q&A sessions. In the earth science lab, TAs opened Zoom sessions to directly instruct students about content and tasks related to weekly topics. Meanwhile, in the chemistry and biology labs, students did not attend any synchronous sessions but accessed the LMS system to download videos and course materials.

4.2.3 Assessment and feedback

No remote labs utilized quizzes, relying on lab report writing for assessment. Although the physics and biology labs provided students with experimental raw data collected by TAs, the chemistry lab did not; instead, the latter required students to search for additional information and/or solve theoretical problem sets.

The earth science lab required students to download relevant data from repositories and process them. Only the earth science lab instructed students on lab report writing and provided feedback weekly. Meanwhile, the biology lab greatly reduced the number of lab report submissions and required students to give 5-minutes presentations on a biology topic of interest to them.

4.3 Method

An explanatory mixed-method design (Fetters et al., 2013) was used to investigate university students' perceptions of various remote labs at Hankuk University in 2020. By incorporating quantitative and qualitative data, the mixed-methods design enables the examination of complex processes and systems, helping us understand the studied phenomena (Creswell, 2012). In this study, a quantitative online survey preceded qualitative interviews. Although the qualitative data were used to complement the information from quantitative data, they are closely integrated to delineate university students' perception of remote labs.

Recruited participants were students who took the remote physics lab, chemistry lab, biology lab, earth science lab, and major course labs in the spring semester of 2020, when the COVID-19 pandemic started to spread and emergent remote labs were implemented. However, students who took the earth science lab in the fall semester were allowed to respond to the online survey to secure an appropriate number of participants (Table 1). Note that the earth science lab is offered mainly in the fall semester and its implementation method did not change between the spring and fall semesters in 2020; therefore, including students who took an earth science lab in the fall semester would not bias the results seriously.

4.3.1 Phase 1: Quantitative online survey

The online survey was conducted from September to December 2020, which is during the fall semester. Participants were recruited through a bulk e-mail system and two online communities at Hankuk University. Repeated responses for different subjects were allowed: For instance, if a student took a physics lab and a chemistry lab, they could respond to the survey up to twice. Three hundred and thirty-eight responses were collected (Tables 5 and 6).

Table 5. Number of responses to the online survey and follow-up interview

	Physics lab	Chemistry lab	Biology lab	Earth science lab	Major course labs	Total
Online survey*	73	53	25	34	153	338
Follow-up interview*	8	5	4	4	6	27

* Repeated responses for different URL subjects were allowed
- Gender: M = 180, F = 157, NA = 1
- Year in school: first year = 123, second year or higher = 215

Table 6. Number of responses to the online survey and follow-up interview by college

College	Participants in the online survey (%)*	Participants in the interview (M/F)*
Nursing	14 (4.14)	
Engineering	141 (41.72)	11 (9/2)
Agriculture & Life Science	47 (13.91)	4 (1/3)
Fine Arts	2 (0.59)	
Education	38 (11.24)	9 (4/5)
Social Sciences	2 (0.59)	
Human Ecology	10 (2.96)	
Veterinary Medicine	13 (3.85)	
Pharmacy	9 (2.66)	1 (1/-)
Medicine	11 (3.25)	
Humanities	1 (0.30)	
Natural Sciences	40 (11.83)	2 (2/-)
Liberal Studies	10 (2.96)	
Total	338 (100)	27 (17/10)

* Repeated responses for the different URL subjects were allowed. Number of interview participants = 18

The survey items were designed to explore students' perceptions of remote labs that had been implemented at Hankuk University in 2020. It comprehensively considered various aspects of the remote lab to serve theoretical viewpoints of science education and/or e-learning. They were constructed via repeated discussion among one expert, two doctoral students, and one master's student in science education. I named the survey as Remote Laboratory Perception Survey (RLPS) (Appendix B).

The survey started with items about demographic/course information. Participants were allowed not to respond to the video-related items if the remote lab they took had no videos. Fifty-eight among the 338 responses did not include these questions: 34 from the earth science lab, 15 from major course labs, three from the physics lab, and six from the chemistry lab. Students and instructors in physics and chemistry labs reported that they had provided videos, so it was concluded that those nine responses were mistakes. Those observations were deleted list-wisely while analyzing video-related items. There were no missing values in other items.

The survey included 30 items on a 4-point Likert scale that fell into 10 categories with 3 items each (Table 7) and were reorganized from literature relevant to laboratory and/or e-learning courses. If a remote lab student took provided video of experiments, items in the *video satisfaction* category asked about the audio-visual sensory quality and editing (Clark & Mayer, 2016). After that, *learning outcome expectation* items asked how much appropriate knowledge, skills, and attitudes students expected to gain through each remote lab (Domin, 1999; LaBay & Comm, 2004), and *learning outcome satisfaction* items whether they actually gained these things (Lee, 2014). *Class participation* items asked about student engagement and remaining in the course (Russel & French, 2001; Lee et al., 2019), and *class preparation* items asked how much students prepared for each weekly session before class time (Glynn & Koballa, 2006). *Experience during class* items asked whether students felt they could have enough experience with the tangible laboratory components (e.g., apparatuses), content and process of the experiment, and interpretations of and discussions about data (Rice et al., 2009). *Use of LMS* items asked how much the online system helped them manage their course materials and have interactive discussions (McBrien, Cheng & Jones, 2009; Rahman & Sahibuddin, 2010). *Interaction with instructors and colleagues* items asked how much instructor-student and student-student cooperation were encouraged and smooth (Ni, 2013). *Lab report writing* items asked whether students could get the necessary information, help for scientific writing, and appropriate feedback (Nguyen et al., 2020; Rice et al., 2009). Finally, *evaluation* items asked whether students perceived assessments as reasonable, with clear criteria that allowed objection (Figure 11; see Appendix B for all items of RLPS). The reliability (Cronbach's α) of items in each category spanned .73–.86, and for the overall survey items .92 (Table 7).

Some open questions for a few categories were included to allow students to describe their URL experiences, comparing them to the hands-on laboratory experience they had anticipated. The survey also asked them to discuss the pros and cons of the URL they took and what they would suggest for revising remote labs in the future.

Table 7. Number of items in the online survey (RLPS)

Category	Number of items		
	Categorical	4-point Likert scale (Cronbach's α)	Open question
Demographic/course information	4		1
Video satisfaction		3 (.85)	1
Learning outcome expectation		3 (.81)	
Learning outcome satisfaction		3 (.79)	1
Class participation		3 (.79)	
Class preparation		3 (.81)	
Experience during class		3 (.80)	1
Use of the LMS		3 (.77)	
Interaction with instructors and colleagues		3 (.86)	1
Lab report writing		3 (.74)	1
Evaluation		3 (.73)	
Pros and cons of and suggestions for future remote labs			3
Total	4	30 (.92)	9

Video satisfaction	The videos provided in the RLS course were…	SD	D	A	SA
	satisfactory in image quality and composition.				
	satisfactory in sound quality and background.				
	satisfactory in editing and captions.				
	Open Question 2: Do you have any additional ideas for videos used in RLSs in the future?				
Learning expectation	Before taking the RLS class, I …	SD	D	A	SA
	expected to acquire appropriate knowledge.				
	expected to acquire appropriate skills.				
	expected to acquire appropriate attitudes.				
Learning outcome satisfaction	After taking the RLS class, I …	SD	D	A	SA
	have acquired satisfactory knowledge.				
	have acquired satisfactory skills.				
	have acquired satisfactory attitudes.				
Class participation	While taking the RLS class, I …	SD	D	A	SA
	studied at the same pace as the class.				
	studied all the content for each class.				
	participated until the end of the semester.				
	Open Question 3: What do you think your expectation, satisfaction, and participation in the face-to-face laboratory class would have been if there had been no COVID-19?				

Figure 11. Examples of online survey items (RLPS) (see Appendix B for all items)

4.3.2 Phase 2: Qualitative interview

Eighteen students were interviewed who gave their consent to the online survey. The interviews were conducted from November 2020 to January 2021. As some students took multiple remote labs in 2020, a total of 27 cases from 18 students were investigated (Tables 5 and 6).

The interview was semi-structured, while the questions corresponded to the topics in the online survey because the purpose of the interview was to complement it. For example, the interviewees were asked questions such as “What did you expect to learn from the course?” “How did you perceive the videos you were provided?” “How much were you satisfied with the learning outcomes?” and “How were the interactions and/or collaborations with peers?” Students were asked to elaborate on why they had the perceptions, the pros and cons of remote labs, and their recommendations for revising future remote labs. All participants were interviewed individually, and the interviews lasted about 40 minutes each. Some were interviewed FTF, and others NFTF via the Zoom webinar program. All the interviews were audio-recorded and transcribed.

4.3.3 Data analysis

Three items in each perception category in the online survey were averaged to yield descriptive statistics. The mean perception scores of remote labs in each science discipline were compared via analysis of variance (ANOVA) to test any significant differences, followed by a Bonferroni post hoc test. The null hypothesis of equal variance in every dependent variable was accepted in Bartlett’s test (*p*

> .05). I used the STATA 16 statistical program throughout the quantitative analysis.

The transcribed interview data was analyzed qualitatively. Two experts and two doctoral and one master's students in science education participated in the analysis. Coders initially read the transcripts. As these data were to elaborate on findings from the quantitative data, they decided to refer to the overall scheme of the online survey. However, they extracted meaningful head-level codes while reading the qualitative data. The number of codes was reduced by repeatedly comparing the content and combining related categories. In the process, disagreements among researchers were resolved through constant discussion. Also, information from URL instructors at Hankuk University in 2020 and students' responses to open questions on the online survey were used to triangulate the analysis.

4.4 Results

4.4.1 Statistics of the online survey

Descriptive statistics of university students' perceptions of remote labs and ANOVA *F*-test results for each science discipline are presented in Table 8. Note that there were no gender differences found in these perceptions except for two categories: *learning outcome expectation* and *class participation*.

The overall perception score was highest in earth science lab (M = 2.82; SD = .52), followed by major course labs (M = 2.74; SD = .50), biology lab (M = 2.73; SD = .47), physics lab (M = 2.71; SD = .47), and chemistry lab (M = 2.45; SD = .48). Remarkably, there were significant differences in overall perception scores in each remote lab (F (4, 333) = 4.31, $p < .01$). The results of the Bonferroni post hoc test show that the chemistry lab had significantly lower overall perception score than physics lab, earth science lab, and major course labs ($p < .05$).

Among the perception categories, *class participation* showed the highest score (M = 3.53; SD = .6), followed by *learning outcome expectation* (M = 3.02; SD = .68); these were the only two categories that had mean scores larger than 3. In contrast, *interaction with instructor and colleagues* (M = 2.31; SD = .89) and *use of the LMS* (M = 2.46; SD = .81) showed the lowest scores. Also, every perception category showed significant differences in scores in each remote lab (F = 2.53–11.58, $p < .05$ or less) except for *learning outcome expectation* (F (4, 333) = 2.12, $p > .05$) and *class participation* (F (4, 333) = 1.29, $p > .05$). The results of Bonferroni post hoc tests show between which remote lab the significant differences occurred in each category.

Table 8. University students' perceptions of remote labs (mean [SD]) (N = 338)

Category	Physics Lab (PL) (n = 73)	Chemistry lab (CL) (n = 53)	Biology lab (BL) (n = 25)	Earth science lab (ESL) (n = 34)	Major course labs (MCLs) (n = 153)	**Average (N = 338)**	ANOVA F-statistic	R^2	Bonferroni post hoc test
Video satisfaction[a]	2.89 (.72)	2.21 (.84)	3.23 (.55)	-	2.76 (.80)	**2.74 (.81)**	11.58***	.1118	PL↔CL; BL↔CL; CL↔MCLs; BL↔MCLs
Learning outcome expectation	2.92 (.67)	2.84 (.69)	3.04 (.8)	3.07 (.66)	3.11 (.65)	**3.02 (.68)**	2.12	.0249	-
Learning outcome satisfaction	2.45 (.75)	2.24 (.69)	2.61 (.77)	2.78 (.71)	2.64 (.73)	**2.55 (.74)**	4.34**	.0496	CL↔ESL; CL↔MCLs
Class participation	3.54 (.57)	3.53 (.58)	3.73 (.47)	3.64 (.48)	3.48 (.65)	**3.53 (.6)**	1.29	.0153	-
Class preparation	2.85 (.76)	2.36 (.98)	2.05 (.88)	2.11 (.8)	2.47 (.85)	**2.47 (.88)**	6.97***	.0772	PL↔CL; PL↔BL; PL↔ESL; PL↔MCLs
Experience during class	2.42 (.70)	2.31 (.79)	2.44 (.78)	2.71 (.74)	2.61 (.76)	**2.51 (.76)**	2.53*	.0295	-
Use of the LMS	2.50 (.80)	2.13 (.76)	2.31 (.78)	2.64 (.78)	2.55 (.81)	**2.46 (.81)**	3.48**	.0401	CL↔ESL; CL↔MCLs
Interaction with instructor and colleagues	2.3 (.82)	1.84 (.83)	1.93 (.85)	2.58 (.82)	2.48 (.89)	**2.31 (.89)**	7.52***	.0829	PL↔CL; CL↔ESL; CL↔MCLs; BL↔ESL; BL↔MCLs
Lab report writing	2.5 (.81)	2.25 (.79)	2.76 (.78)	2.89 (.66)	2.51 (.77)	**2.52 (.79)**	4.18**	.0478	CL↔ESL
Evaluation	2.69 (.73)	2.72 (.57)	3.21 (.56)	2.97 (.71)	2.80 (.77)	**2.81 (.72)**	3.129*	.0362	PL↔BL; CL↔BL
Overall	2.71 (.47)	2.45 (.48)	2.73 (.47)	2.82 (.52)	2.74 (.50)	**2.69 (.50)**	4.31**	.0493	PL↔CL; CL↔ESL; CL↔MCLs

* p < .05, ** p < .01, *** p < .001; ↔: significant difference in Bonferroni post hoc test (p < .05)

[a] Only video satisfaction had 280 observations, while all the others had 338.

Pearson's correlations of perception scores are presented in Table 9. All categories showed a very highly significant correlation with the overall perception score (p < .001), while *learning outcome satisfaction* showed the highest (r = .8092) and *class participation* the lowest (r = .346). Although most of the categories showed a very highly significant correlation with each other (p < .001), *class participation* had the lowest correlation with other categories (r = .2407 – .1055), which was even non-significant with the *interaction with instructor and colleagues* (r = .1055, p > .05).

The reason why these patterns appeared in the quantitative analysis will be explicated below with qualitative data.

Table 9. Pearson's correlation of university students' perceptions of remote labs (N = 338)

Category	Video	Expectation	Satisfaction	Participation	Preparation	Experience	LMS	Interaction	Report	Evaluation	Overall
Video satisfaction	1										
Learning outcome expectation	.2436***	1									
Learning outcome satisfaction	.5443***	.4401***	1								
Class participation	.2228***	.2313***	.1401**	1							
Class preparation	.2094***	.19***	.2327***	.162**	1						
Experience during class	.419***	.3569***	.6787***	.147**	.302***	1					
Use of the LMS	.4061***	.2703***	.5868***	.1344*	.3172***	.5151***	1				
Interaction with instructor and colleagues	.3817***	.3284***	.5742***	.1055	.3604***	.5667***	.6255***	1			
Lab report writing	.4459***	.3381***	.6113***	.1228*	.2426***	.559***	.5151***	.5654***	1		
Evaluation	.3553***	.2745***	.4604***	.2407***	.1465**	.3019***	.3636***	.3412***	.5432***	1	
Overall	.6525***	.552***	.8092***	.346***	.5056***	.7516***	.7426***	.7669***	.7628***	.6074***	1

* $p < .05$, ** $p < .01$, *** $p < .001$

4.4.2 Students' high expectations for laboratory contrasted with low satisfaction due to lack of hands-on experiences

A common feature of remote labs in 2020 can be summarized as high expectancy and low satisfaction. *Learning outcome expectation* (M = 3.02; SD = .68) was relatively high compared to other perception categories. This was due to few opportunities for Korean students to engage in labs during K-12 school, thus causing students to anticipate opportunities in university education:

> In high school, … there are many unseen things and much precise measurement is impossible. After coming to university, controlling certain conditions and more precise measuring, and running [processing] them through a program to analyze graphs practically—I expected these detailed procedures for experiments. (Student_1 on chemistry lab)

Students naturally anticipated that university laboratory courses would be hands-on-oriented. However, the unprecedented COVID-19 situation forced introductory laboratory courses to be implemented remotely, causing them to be minds-on. Therefore, *learning outcome satisfaction* (M = 2.55; SD = .55) was significantly lower than *learning outcome expectation* in a paired t-test (t (337) = 11.40, p < .001). Students were concerned about what they had "gained" from remote labs, as they did not do practical, hands-on experiments:

> First, it was disappointing. … When we say "experiment-based course" we expect to come to a [laboratory] classroom and learn something or do experiments … (Student_17 on physics lab and earth science lab)

> After I concluded that I had nothing to gain even after I finished this course … I almost neglected it … I had expected very much, and I liked experimenting … my satisfaction decreased as the expectation was high. (Student_8 on chemistry lab)

> But we did not conduct experiments firsthand, so I thought I could not gain anything besides what the video presented. (Student_14 on a major course lab [Analytical Chemistry Lab])

4.4.3 Video material determined the quality of the learning experience

Different teaching strategies, however, yielded different student perceptions. As described above, students could only indirectly engage with experiment procedures via videos in most remote labs. In consequence, the dependence on the video constrained student learning into video characteristics and qualities.

For example, videos in the chemistry lab (*M* = 2.21; *SD* = .84) were recognized as "inconvenient" and "not so meaningful," as the content of the videos was outdated and already in the documented materials (Student_7 on chemistry lab). In some major course labs (*M* = 2.76; *SD* = .80), instructors also did not adequately edit the videos but live-streamed or just uploaded the whole procedure. These were not considered to be much help because of the crudity of the experiment videos:

> They showed us real-time video while experimenting. When the camera runs fast, the definition suddenly worsens. … if an important scene passes at that moment, … I may have a question [but cannot ask] … My concentration decreased greatly. (Student_2 on a major course lab [Animal Science Lab])

> Sometimes, the waiting time of 3 hours for separation is just presented … I feel they are unrefined and thus have low quality. … Not edited, too long or too short … (Student_11 on a major course lab [Pharmaceutical Lab])

Consequently, most students responded that their lack of "firsthand" *experience during class* limited their learning experience during class (M = 2.51; SD = .76). They also specified that there was a lack of trial and error during the class (Student_5 on physics lab and biology lab).

In contrast, in a few remote labs, students responded that the repeatability of video helped their learning. Students responded particularly positively to cases where TAs conducted experiments and shot and edited videos, such as physics lab (M = 2.89; SD = .72) and biology lab (M = 3.23; SD = .55):

> The overall content of the experiment could be figured out perfectly via video: What was seen and what results come when we control something. The process and results of the experiment could be figured out in an overall sense. (Student_4 on physics lab)

> So I repeated the video five or six times in a short time and discussed [scientific terms] with friends … The quality of sound and definition was quite good. (Student_17 on biology lab)

4.4.4 Synchronous sessions allowed opportunities for interaction among instructors and students

As students took the remote labs individually, their perception of *interaction* with peers and instructors was the lowest (M = 2.31; SD = .89) among the categories. Students responded that they could not interact with instructors and colleagues. They also responded that *the use of the LMSs* had not been promoted much in the remote labs (M = 2.46; SD = .81).

However, it was found that the synchronicity of online sessions affected student perception of *interaction* in URL. Students who took remote labs with no synchronous session, such as chemistry lab (M = 1.84; SD = .82) or biology lab (M = 1.93; SD = .85), showed lower perception of interaction:

> Anyway, … first, the fact that there was no Zoom. I mean, there was no connection at all. (Student_8 on chemistry lab)

> We did not make groups but just did [work] individually … There were almost no [interactions]. (Student_3 on biology lab)

In contrast, students who took the remote labs with synchronous learning sessions among instructors and students showed relatively higher scores on *interaction* (physics lab: M = 2.3; SD = .82; earth science lab: M = 2.58; SD = .82), which is supported by the post hoc test. Note that the physics lab showed a significantly higher perception score (M = 2.85; SD = .76) in *class preparation* than all others, which is also attributed to the unique synchronous session in the physics lab:

> The sharpest contrast was whether there was Zoom or not. If there is a Zoom … I and TA reveal faces and hear voices (Student_8 on physics lab and chemistry lab)

> Wait, I don't think there has been little interaction. Because we could send a 1:1 message [in a Zoom] if we wanted. (Student_17 on physics lab and earth science lab)

Meanwhile, students who took major course labs responded they were better able to *interact* with TA and peers (M = 2.48; SD = .89) than in the above chemistry lab and biology lab. This could be attributed to group assignments in a department, which obliged synchronous peer interaction to some extent:

> I think the collaboration was quite good. … Friends went together to a mountain and caught them [insects]. During this, sharing information and knowledge was smooth … (Student_12 on a major course lab [Insect Diagnostics Lab])

> The LS has been group work … In my case, there were six members for three modules; [we] allotted two members for each module … to process data and make a presentation, and others shared what they made. (Student_13 on a major course lab [Materials Lab])

4.4.5 Regular feedback on lab reports and supportive assessment guided student learning

As mentioned above, many lab courses depend on lab reports in evaluation. Most students responded that it was possible to get help from a TA in principle via course material, telephone, e-mail, and the LMS in *lab report writing* (*M* = 2.52; *SD* = .79).

Here, regular instruction and feedback from TAs seems to have made differences between earth science lab (*M* = 2.89; *SD* = .66) and chemistry lab (*M* = 2.25; *SD* = .79) in *lab report writing*:

> In the earth science lab, it was like [the TA] gave the basic report format and we filled it in. (Student_17 on earth science lab)

> I totally did not know I could ask my questions to my TA. (Student_10 on physics lab and chemistry lab)

Students responded that, through lab report writing, they had cultivated theoretical knowledge and data processing and lab report writing skills to some extent, rather than hands-on skills and appropriate attitudes. Again, the earth science lab showed the highest *learning outcome satisfaction* (*M* = 2.78; *SD* = .71), implying that there was little difficulty in NFTF settings compared to others.

> For the case of the earth science lab, I think I would not feel much [difference] between FTF and NFTF. (Student_15 on earth science lab)

> For the biology lab … lab report writing ability was increased to some extent. … For the earth science lab, I learned graph-drawing ability using Excel. (Student_16 on biology lab and earth science lab)

Meanwhile, an attempt for supportive assessments other than lab reports in the biology lab is notable. Short talks about biology topics students were interested in seem to have made differences in *evaluation* between biology lab (*M* = 3.21; *SD* = .56) and physics (*M* = 2.69; *SD* = .73) and chemistry (*M* = 2.72; *SD* = .57) labs. Students responded that they could take another route to receive additional feedback from TAs in remote teaching situations:

> I think that [remote labs] were certainly synergistic … there was a presentation in the biology lab. … Students picked a topic and recorded a video about that and uploaded it. Then TAs watched and evaluated it. (Student_3 on biology lab)

> It was a 5-minutes presentation. … Once each [student] uploaded their topic, [the TA] gave feedback on whether the topic was good and how to develop it, based on which student made [presentation] video. (Student_7 on biology lab)

4.4.6 Student participation remained high even during the pandemic

Finally, unexpected student perceptions of remote labs in the spring semester of 2020 should be reported. *Class participation*'s high mean score (*M* = 3.53; *SD* = .6) and low correlations with other categories (Tables 8 and 9) suggest that most Hankuk University students diligently participated in remote labs even during the pandemic. This contrasts with the concerns such as low participation and high class-dropping rates in introductory laboratory courses (Seymour & Hewitt, 1997), e-learning (Lee et al., 2019), and remote teaching situations during the COVID-19 pandemic (Lee & Hong, 2021b; Petillion & McNeil, 2020). This was due to the students' strategy to complete the mandatory courses when their requirements were reduced during the COVID-19:

> Chemistry lab is one of the courses that we need to clear up. … It's a notorious course when it goes on FTF. It had been changed to NFTF, … it was all convenient. (Student_6 on chemistry lab)

4.5 Discussion

Based on the above findings, it will be discussed how remote labs can be understood based on the hands-on versus minds-on framework and improved with specific teaching strategies to guide university STEM instructors.

4.5.1 Remote labs in light of the hands-on versus minds-on debate

Although participants in this study worried about what they could "gain" through the remote lab without hands-on experience (Reid & Shah, 2007), they responded that they were able to acquire some knowledge and skills while writing lab reports. This indicates that remote labs should be designed and evaluated in light of learning objectives for each specific course (Ma & Nickerson, 2006). For example, if instructors aim to foster students' practical skills and attitudes in performing experiments, hands-on experience is necessary (Reid & Shah, 2007). However, if instructors aim to foster students' other "scientific skills" (observation, deduction, interpretation, etc.) or general skills (teamwork, reporting, presenting, discussing, etc.; Reid & Shah, 2007), instructors may implement remote labs as a type of minds-on class (Lee & Hong, 2021b).

4.5.2 Teaching strategies for future remote labs

This study has shown differences in university students' perceptions of each remote lab—mainly in the four introductory laboratory courses. As the departments manage each massive laboratory course equivalently and the same students usually take a few introductory laboratory courses, the class/teacher effect and student group effect diminish. Therefore, the differences in perception scores can be attributed to the different teaching strategies used, providing lessons for future remote labs.

Strategy 1: Record and edit new video material

First, the importance of videos was verified, as videos essentially determined students' learning experiences in remote labs. Although some cutting-edge technologies such as AR/VR can be used for remote labs (Hu-Au & Okita, 2021), these can be burdensome for usual instructors. Therefore, recording and editing effective videos of experiments would be practically helpful in implementing remote labs (Jang et al., 2020; Mayer et al., 2020). While preparing fresh video material, an instructor can also be prepared for the Q&A. Because the psychology of "presence" should be considered significant (Ma & Nickerson, 2006; Brinson, 2015), videos of experiments should not merely show experimental procedures but also focus on specific apparatuses and equipment to provide students with indirect but authentic experiences of laboratory activities. However, live-streaming the whole experimental process without editing should be avoided.

Strategy 2: Promote synchronous interaction and assign group work

As the collapse of instructor-student and student-student feedback was very problematic in remote labs, there need to be remedies for it. Synchronous video watching and Q&A sessions are strongly recommended, as were done in the physics lab. Tools to support collaborative learning other than just video watching could be introduced to real-time online sessions, for example, systems for real-time visualization of student discussion, an e-portfolio constitution, or an LMS to store collaborative processes and products (Luchoomun et al., 2010; Clark & Mayer, 2016; Youssef et al., 2020). Also, some major course labs reaffirmed that collaborative group work could also promote student-student interaction in remote labs (see Clark & Mayer, 2016). If possible, even during the pandemic, allowing small groups of students to visit the laboratory and have the necessary hands-on experience while the overall course is taught online would provide another chance for interaction between instructors and students (Lee & Hong, 2021b).

Strategy 3: Promote lab report writing with regular feedback and adopt supportive assessment

Although lab reports reflect the consequence of student inquiry and heavily influence evaluation, the results show that physics, chemistry, and biology labs did not provide timely assessment and feedback, while the earth science lab did. The earth science lab was an exemplary case in promoting lab report writing: (1) providing students regular feedback on their lab reports is strongly recommended, and (2) direct instructions on the structure and writing style of the lab report are also helpful particularly for first-year students. Visualization, portfolio, and LMS systems could also function as repositories that support lab report writing and evaluation. Also, planning for other evaluation criteria such as searching and presenting each student's topics of interest, as was done in the biology lab, is also an option to consider in remote labs. As interviewees in this study suggested, allowing several students to physically attend laboratory classrooms or developing and sending experiment kits to students' homes seems a plausible choice to secure and evaluate minimal hands-on skills even during the pandemic (Jang et al., 2020).

4.5.3 High participation in remote labs: A possibility for innovation?

Finally, we should contemplate the reason why students' participation was high in remote labs they had not expected to have. Although most students expressed many negative views on remote labs in 2020, some positive views were also reported. Most significantly, remote labs were "convenient" and time-saving. Students did not have to attend the laboratory physically and could just watch a video (a)synchronously and write lab reports in their homes. Some students did not even need to reside near the university. Also, lab reports could be submitted online, while conventional laboratory courses required printed-out copies. This may have lowered the physical and/or psychological threshold of laboratory courses for first-year university students, helping them remain in the course.

Here, it should be noted that many Korean university students must have been accustomed to e-learning in some sense. As some interviewees said, many Korean high school students take so-called internet lectures as private shadow education (Kim & Jung, 2022). That experience probably helped students taking remote labs. However, it is significant that the context of e-learning shifted to institutional education at the university level from shadow education. Students were able to experience how technologies could be used in formal learning contexts, and possibilities for better implementation of remote labs in the future were acknowledged. Therefore, the URL experiences in 2020 somewhat ironically accelerated changes in university science teaching and learning:

> Rather, I think those courses, including NFTF ones, were not that bad, but they revealed what we didn't know. … Without the COVID-19, NFTF courses like those using Zoom … were thought to be stories in the far future [but were realized already]. (Student_18 on earth science lab and a major course lab [Architectural Design Studio])

4.5.4 Limitations

As students at Hankuk University are high achieving and highly engaged, they may not represent university students in general. Students who finished their remote labs may have been more comfortable responding to the survey. Also, university first-year students' perceptions of remote labs compared with hands-on laboratory courses are unavoidably speculative, as they had not experienced the latter. Therefore, the perceptions of second-year students and higher, some of which have been included in this study, would be more informative. As the data of this study were hurriedly collected amid the fluctuating COVID-19 situation in 2020, more thorough future research would shed more light on remote labs at the university level.

4.5.5 Conclusion

Study 2 investigated university students' perception of remote labs necessitated by the COVID-19. It has its strength in comparing students' perceptions of remote labs at a university between different courses. Discussions revealed that remote labs may be planned in light of the theoretical backgrounds of laboratory courses and e-learning, with specific future suggestions for teaching strategies.

Also, is is notable that implications for the teaching and learning from Study 1 and 2 overlap. The issues raised during the implementation of URL in Study 1 and the promising teaching strategies were related to (1) the effectiveness of video material, (2) limited interaction between instructors and students, and (3) difficulty of lab reporting writing that is crucial in evaluation. In this regard, developing and validating an instructional design model for remote labs systematically incorporating the effective teaching strategies discussed above would be fruitful (Lee & Hong, 2021b; cf. Winer et al., 2000).

Chapter 5. Study 3: The BLEND Model for University Remote Laboratory

5.1 Introduction

Study 1 and 2 were conducted in 2020. In 2020, individual instructors struggled to adapt to the rapidly changing teaching and learning context due to the COVID-19 pandemic (West et al., 2021; Lee & Hong, 2021b). In 2021, the pandemic remained a threat shaping the teaching and learning context, so planning and preparation for the post-COVID-19 science education had to be conducted immediately.

One solution for this educational cataclysm could be developing and suggesting ID models for URL (Lee & Hong, 2021b; Winer et al., 2000; cf. Lowe et al., 2013; Reimers & Schleicher, 2020). To design a procedural ID model that helps individual practitioners, both the theoretical and practical aspects should be considered thoroughly (Richey & Klein, 2005). Therefore, Study 3 has to incorporate the result of the literature review and lessons from Study 1 and 2 before developing an ID model.

The lessons from Study 1 and 2 were contemplated while developing the ID model for URL. Most participants in the preliminary study responded negatively to the URL that emerged in 2020 in response to the COVID-19. The lack of hands-on experience and diminished interaction between students and the instructor were consistently deemed problematic. Problems also arose with the experimental data. Because the TAs conducted the experiments instead of students, they provided a dataset that fit the theory too well, limiting student inquiry in interpreting the data and lab report writing for evaluation. However, participants also responded that students could gain theoretical knowledge and data processing and lab report writing skills, finding URLs “convenient” and time-saving. Participants’ suggestions for the future URL included minimal hands-on experiences, more opportunities for interactions between instructors and students, appropriate technology to support online sessions, and reasonable guidance for lab report writing and thus evaluation.

A synthesis of the literature review and lessons from Study 1 and 2 about effective remote labs is presented in Table 10. To briefly summarize, a URL should be based on both grounds of (1) laboratory sessions that provide students with hands-on and minds-on experience and (2) e-learning that broaden the learning time and space with multimedia learning materials and tools to support students’ collaborative work.

Table 10. Synthesis of the literature review and lessons from Study 1 and 2 for efficient and effective remote lab design and implementation

Aspect		Considerations	Selected references
Laboratory session	Hands-on	- Provide as many hands-on experiences as possible to students (e.g., a small group attends the laboratory classroom physically). - Data should be produced by students firsthand (without inhibiting student inquiry). - Prepare necessary equipment, apparatuses, reagents, etc.	Hofstein & Lunetta (2003); Reid & Shah (2007); Jang et al. (2020); Lee & Hong (2021); Domin (1999); Fraser et al. (1995); Flick (1993)
	Minds-on	- Provide representations of a science experiment (e.g., demonstrations, videos of experiments, simulations, animations, remote controlled–tools). - Invite students to use a collaborative inquiry process to understand the experimental data.	Ma & Nickerson (2006); Tho et al. (2017); Abrahams & Millar (2008); Flick (1993); O'Brien (1991); Cicciarelli (2013); Schamel & Ayres (1992); Zacharia et al. (2015)
	General	- Set clear learning objectives for the laboratory. - Pre-lab and class time can be separated to offer students learning experiences that differ from regular class time (blended learning). - Student inquiry and lab report writing should be guided by instant feedback.	Hart et al. (2000); Lee & Hong (2021); Lee et al. (2021); Bergmann & Sams (2012); Loveys & Riggs (2019); Reid & Shah (2007); Stockwell et al. (2015); Gregory & Di Trapani (2012); Zacharia et al. (2015)
E-learning		- Provide well-designed video learning materials. - Synchronous learning sessions are highly recommended (e.g., video watching). - Use online platforms to enhance interactions among students. - Provide tools for visualizing and sharing student argumentation.	Mayer et al. (2020); Lee et al. (2021); Lee & Hong (2021); Loveys & Riggs (2019); Tsai (2018); Jang et al. (2020); Lowe et al. (2013); Huang et al. (2009); Kirschner et al. (2012)

The researcher suggests that only a blended learning format can satisfy the various considerations, utilizing several learning modes across time and space (Lee & Hong, 2021b; cf. Oliver & Trigwell, 2005). Therefore, the name of the ID model for URL was suggested as the BLEND (Blended Laboratory and E-learning iNstructional Design) model to reveal its essence. The BLEND model aims to help instructors design and implement an efficient and effective URL instructional program, incorporating the components of laboratory sessions and e-learning as blended learning that combines offline and online learning.

The BLEND model is based on the extended understanding of blended learning for laboratory education (Figure 3). The BLEND model ideates that combining two of those laboratory experiences in a URL course would utilize both hands-on and minds-on processes in both place-based and remote settings, leading to better student learning. Therefore, the BLEND model integrates two laboratory experiences into one URL instructional system.

Then, the matter of which laboratory experiences should be incorporated becomes crucial. In Study 1 and 2, university instructors and students stressed that there should be "minimum" hands-on experience even during the emergency, i.e., allowing a small number of students to come to the laboratory classroom to conduct firsthand experiments (the third quadrant in Figure 3) or sending experiment kits to students' home (the second quadrant in Figure 3). However, as the latter might have some safety issues or the impossibility of sending machines, the former might be the better choice (Lee & Hong, 2021b). Then, combining the experiment video watching in a remote setting for a minds-on process (the first quadrant in Figure 3) would maximize the variation of learning modes and experiences (Oliver & Trigwell, 2005). Note that the course modules in the external validation process of the BLEND model were elicited by incorporating those two (cf. Lee & Hong, 2021b).

5.2 Research Questions

This study aimed to develop and validate the BLEND model for URL. Research questions are as follows:

(1) What is the BLEND model for URL?

(2) How effective is the BLEND model for URL?

5.3 Method

5.3.1 Research field

The research field was the Analytical Chemistry Experiment (ACE) course offered by the Department of Chemistry Education at Hankuk University in South Korea. The ACE is a mandatory major course for junior students in the department and usually aims to provide students with hands-on experiences. The course content (Appendix C) includes various experiments related to the content of the theoretical course, e.g., acid-base titration, determination of dissociation constant, and electrochemical analysis. Usually, about 20 students take the ACE course. However, in 2021, only seven students took it, which indicates the difficulty of teaching and learning during the COVID-19 pandemic and the need for a systematic ID model.

5.3.2 Procedure

The procedure for this study is visualized in Figure 12. As explained above, the BLEND model for URL was developed through an iterative process with internal and external validations. The initial BLEND model was developed by synthesizing the literature review and the implications of the preliminary studies on URL at Hankuk University in 2020 (Tripp & Bichelmeyer, 1990). The professor and TA of the ACE course then took a usability test, and based on those results, the initial ACE course module was elicited. While the instructor implemented that first module for five weeks, the researcher conducted participatory observation, experts reviewed the initial ID model, and at the end, the participating students completed an online survey and follow-up interviews. The results of the expert review, participatory observation, online survey, and follow-up interviews were incorporated into the draft of the 2nd BLEND model. Based on the results from another usability test, the 2nd BLEND model was developed, and the second ACE module was elicited from it. That second module was also implemented for five weeks, during which the researcher conducted participatory observation, experts reviewed the 2nd model, and the students completed an online survey and follow-up interviews upon completion of the course. The results of those expert reviews, participatory observations, online surveys, and follow-up interviews are reflected in the finalized BLEND model (Richey & Klein, 2007; cf. Crawford, 2004).

Note that the uncertainty and complexity of the remote labs necessitated by the COVID-19 pandemic require a flexible approach such as RP, which overcomes the limitations of the traditional linear design process for an instructional program (Nixon & Lee 2001). Because the fluctuating pandemic situation is “a new situation, with a unique problem to be discovered and solved,” it is also “a design environment which makes it practical to synthesize and modify instructional artifacts quickly” using the RP approach (Tripp & Bichelmeyer, 1990). Therefore, the ACE course modules here show how design and development research with the RP approach can validate the efficient and effective BLEND model for URL.

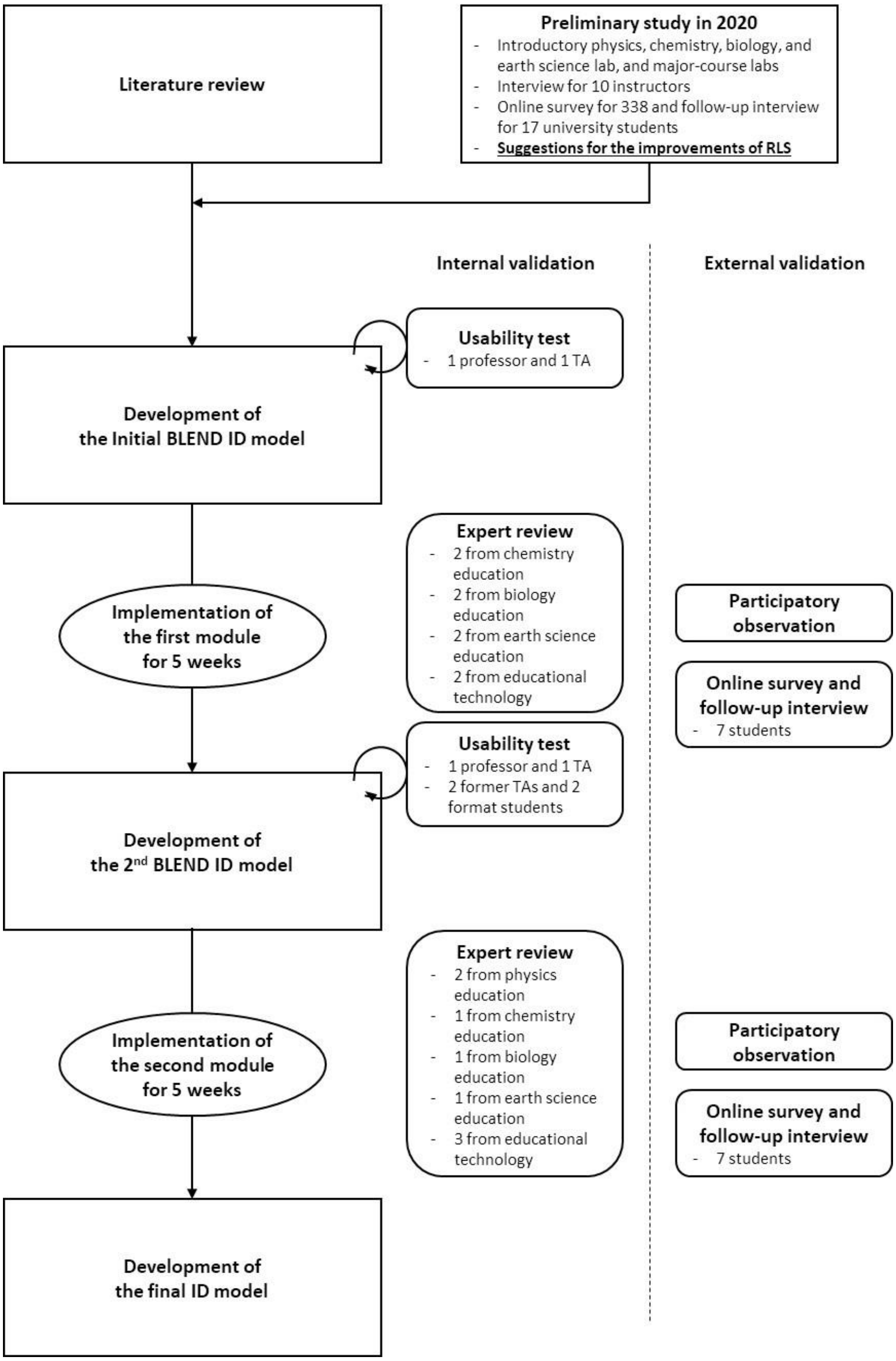

Figure 12. The procedure for developing the BLEND model

5.3.3 Internal validation

Usability test

The usability test was conducted for two purposes during the development of the BLEND model for URL. Two instructors (one professor and one TA) of the ACE course in 2021, two former TAs, and two former students of the ACE course participated in the usability test (Table 11). They were provided with the developing BLEND model at each stage and asked their opinions about its convenience, satisfaction, and likely outcomes, along with suggestions for model revision, which was the primary purpose of the usability test (cf. Lee, 2017; Park, 2019). The usability test was FTF with the professor and TA of the ACE course and written NFTF with the other participants.

At the same time, for the subsidiary purpose, they were asked to evaluate the prototype URL instructional program derived from the developing BLEND model before its implementation, following the RP method (Tripp & Bichelmeyer, 1990; Lim et al., 2020). It was to to examine whether the developing ID model could provide practical help for instructors facing the immediate need to conduct the ACE course. Based on the usability test panel responses, the researcher worked collaboratively with the two instructors of the ACE course to revise the instructional program (Dorsey et al., 1997) and implement it in the form of two course modules.

Expert review

In developing an URL design model, it was necessary to comprehensively consider various perspectives, collected from science education and educational technology researchers. The expert review panel for this study consisted of two experts from physics education, three from chemistry education, three from biology education, two from earth science education, and three from educational technology (Table 11). Because all the expert review panelists had backgrounds in educational studies, they all understood ID model development to some extent. All the experts had taught hands-on/minds-on scientific inquiry classes or managed e-learning classes in their universities. Also, all of them had experienced the remote teaching and learning environment provoked by the COVID-19 pandemic. They were interviewed individually for about 40 minutes, except for two experts who preferred to participate in written form via e-mail. The interviews were sometimes FTF and sometimes NFTF.

At each stage, the experts were asked to validate the BLEND model for URL in terms of its validity, explicability, comprehensibility, usability, and generality. A few numerical indices were needed to objectify the results from the expert review (Rubio et al., 2003). The experts were asked to rate each of the five aspects of the ID model on a 1–4 point scale. The content validity index (CVI) was calculated by dividing the number of experts who gave positive responses (3–4 points) by the total number of experts. Interrater agreement (IRA) is calculated by dividing the number of items with an IRA greater than 0.8 by the total number of items, and it is particularly important when the number of expert review panelists exceeds five (Rubio et al., 2003; cf. Kim, 2014).

Table 11. Participants in the usability test and expert review

Participant	Participation period	Position	Field of expertise	Years of teaching experience
Usability test (n = 6)				
A	1st and 2nd	Professor (Ph.D.)	Chemistry education	28
B	1st and 2nd	TA (MA student)	Chemistry education	-
C	2nd	Former TA (MA)	Chemistry education	-
D	2nd	Former TA (MA)	Chemistry education	-
E	2nd	Former student (BS student)	Chemistry education	-
F	2nd	Former student (BS student)	Chemistry education	-
Expert review (n = 13)				
G	2nd	Professor (Ph.D.)	Physics education	30
H	2nd	Professor (Ph.D.)	Physics education	19
I	1st	Researcher (Ph.D.)	Chemistry education	18
J	1st	Researcher (Ph.D.)	Chemistry education	2
K	2nd	Professor (Ph.D.)	Chemistry education	8
L	1st	Professor (Ph.D.)	Biology education	32
M	1st	Researcher (Ph.D.)	Biology education	6
N	2nd	Professor (Ph.D.)	Biology education	2
O	1st and 2nd	Professor (Ph.D.)	Earth science education	20
P	1st	Professor (Ph.D.)	Earth science education	17
Q	1st and 2nd	Teacher (MA)	Educational technology	7
R	1st and 2nd	Professor (Ph.D.)	Educational technology	24
S	2nd	Professor (Ph.D.)	Educational technology	10

5.3.4 External validation

The ACE course at Hankuk University was the research field, as explained above. The researcher collaborated with two instructors (a professor and a TA, who are participants *A* and *B* in Table 11) of the ACE course as an instructional design team, and provided consultation to them. In that way, the instructors derived and implemented a remote lab from the developing BLEND model. Ten experimental sessions of the ACE course were divided into two modules of five weekly experiments (Appendix C). An URL instructional system derived from the initial BLEND model was implemented and evaluated in the first module. The second instructional module was derived from the second BLEND model.

Observation

While the ACE course was being implemented, the researcher observed the preliminary experiments conducted by the pre-lab groups and the real-time Zoom session every week (Appendix C; D), recording notable features of the class. However, the researcher did not give directions to the TA or students during the class. Instead, the researcher recommended only that the TA follow what had been decided for the module.

Online survey

All seven students responded to the online survey twice, at the end of the first and second modules. The survey contained 30 items developed for the URL context (RLPS), 41 items adopted from the literature, and nine open questions.

The survey included the same RLPS used in Study 2 (Appendix B); it contains questions about students' perceptions of the URL, specifically *laboratory video satisfaction, learning outcome expectation, learning outcome satisfaction, class participation, class preparation, experience during class, use of LMS, interaction with instructors and colleagues, lab report writing, and evaluation*. Each category contained three items, all of which were answered on a 4-point Likert scale.

Other items about university laboratory environments or experiences from the literature were adopted. (1) The Science Laboratory Environment Inventory (SLEI) (Fraser et al., 1995) was used to investigate science laboratory learning environments, which have a strong association with student outcomes, such as chemistry-related attitudes. It has five categories — student cohesiveness, open-endedness, integration, rule clarity, and the material environment — each of which has seven items. After excluding the material environment category (seven items), which strongly presupposes the physical presence of students in a laboratory classroom, and item no.27 (which was added after the statistical validation of the SLEI; Fraser et al., 1995), a total of 27 items were adopted. Among the personal/class actual/preferred forms of the SLEI, the personal actual form was adopted to measure what each student thought of the actual remote lab module derived from the ID model. (2) Further, 13 items about students' laboratory class experiences from the Chemistry Attitudes and Experiences Questionnaire (CAEQ) (Dalgety et al., 2003) were adopted. Those 40 adopted items, which were answered on a 5-point Likert scale, were translated into Korean by the researchers and reviewed by three previous students of the ACE course for readability.

The open questions asked about the pros and cons of the present remote lab and suggestions for future remote lab implementation. Example survey items are presented in Figure 13. Although important, the item reliabilities and inferential statistics could not be provided here because of the small course size during the pandemic. Therefore, the descriptive statistics were presented in the results section.

Follow-up interviews

Five participants consented to be interviewed after the first module, and four consented after the second module. They were interviewed individually for about 20 minutes after completing the online survey, mainly in NFTF interactions. The interviews were semi-structured, and the questions asked for their opinions about the aim and essence of a science laboratory class, their expectations and experiences of URL, and their perceptions of the pros and cons of the remote lab they took, all of which corresponded to the categories in the online survey. All the interviews were audio-recorded and transcribed.

Questionnaire (# of items)	Example					
	Area	Question	Response			
RLPS (30)	Use of learning management system (LMS)	In the RLS class I have taken, …	SD	D	A	SA
		the active use of the LMS was promoted and encouraged.				
		sufficient teaching and learning materials were uploaded to the LMS.				
		instructors and learners actively interchanged ideas.				
		Open Question 4: What do you think the use of the LMS in the face-to-face laboratory class would have been like if there had been no COVID-19?				
	Interaction with instructors and colleagues	In the RLS class I have taken, …	SD	D	A	SA
		cooperation and interaction with instructors and colleagues were encouraged.				
		cooperation and interaction with instructors were smooth in general.				
		cooperation and interaction with colleagues were smooth in general.				
		Open Question 5: What do you think the preparation, experience during class, use of the LMS, and interaction with instructors and colleagues in the face-to-face laboratory class would have been like if there had been no COVID-19?				
	Lab report writing	While writing my lab report after class, I …	SD	D	A	SA
		could easily get the necessary information.				
		was able to get the assistance necessary for scientific writing.				
		was able to get appropriate feedback.				
SLEI (27) (Fraser et al. 1995)	**Student cohesiveness** "I get on well with students in this laboratory class." **Open-endedness** "In this laboratory class, I am required to design my own experiments to solve a given problem." **Integration** "I use the theory from my regular science class sessions during laboratory activities." **Rule clarity** "My laboratory class is run under clearer rules than my other classes"					
CAEQ (13) (Dalgety et al. 2003)	"When writing up experiments in my laboratory book, the relationship between the data and the results was clear." "The experiments were interesting." "The demonstrators explained problems clearly to me."					

Figure 13. Example online survey items

5.4 Results

5.4.1 The initial BLEND model

The initial BLEND model for URL was constructed based on the literature review and the lessons from the preliminary study (Figure 14). The initial BLEND model consisted of four steps — analysis, design, development, implementation and formative evaluation — taken from the ADDIE process.

In the analysis phase, the goal and content of the instructional system and learners, the technology environment for remote teaching and learning, and the experimental environment for pre-lab work and video shooting are analyzed. The design phase begins by defining the objective of the course. After choosing the content features and study schedule, the features of the videos are designed. The data features and lab reports are designed to shape an inquiry-like process. Then the online platform, pre-lab activity, and real-time activity to accommodate the e-learning aspects of URL are designed. In the development phase, the learning materials, videos, activities, lab report requirements, and evaluation rubric are produced. The implementation and formative evaluation are aligned together — when the video clips were uploaded and the class was implemented, student-student interactions and student-instructor interactions are promoted. The comprehensive formative evaluation takes the course material, video clips, activity monitoring, and student reflection in the lab report as sources.

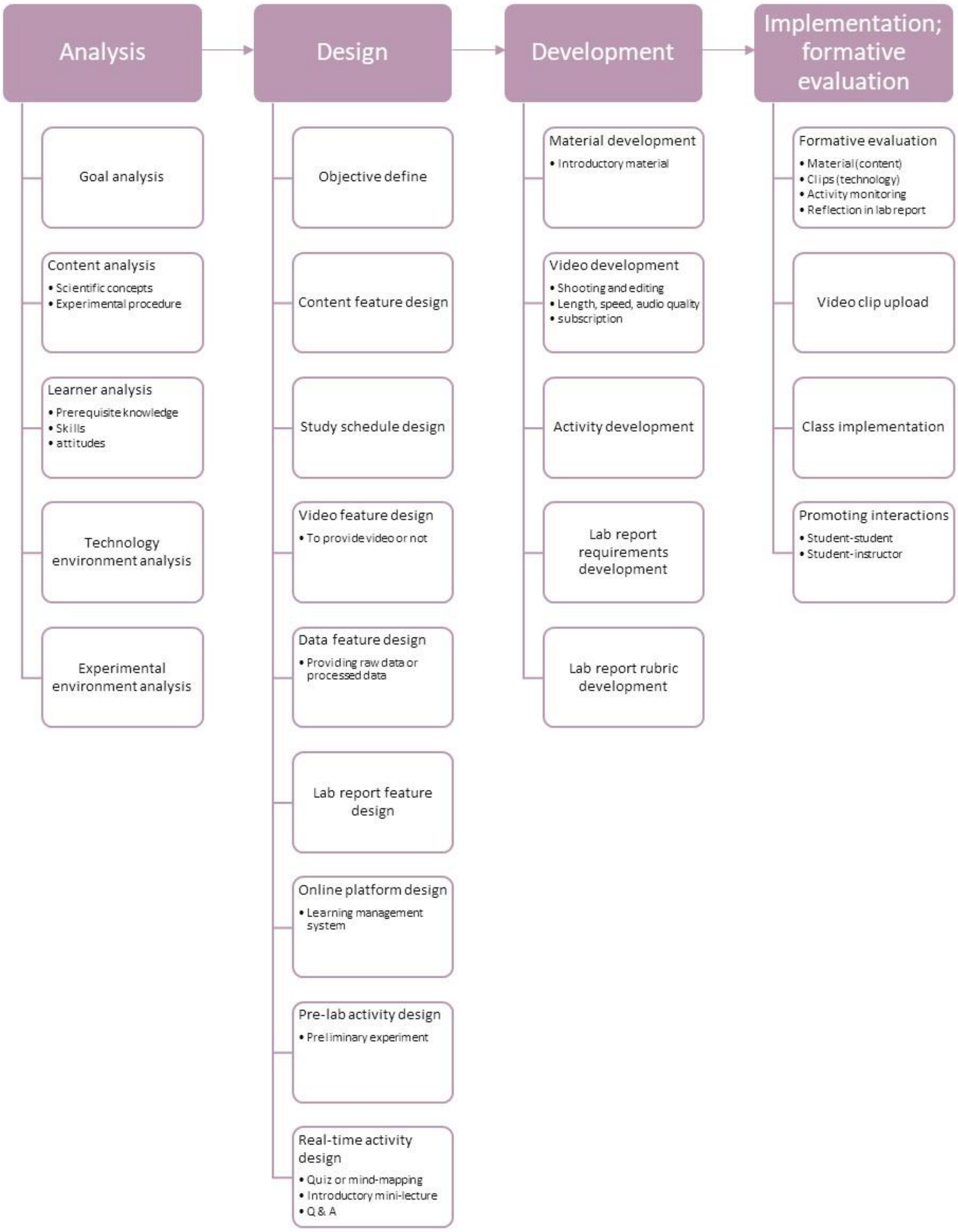

Figure 14. The initial BLEND model

Internal validation

The instructors of the ACE course responded positively to the usability of the initial model in an overall sense and decided to undertake the ID process. Consequently, they designed an URL module for external validation through consultation with the researcher.

The expert panel gave the initial BLEND model a mean score of 3.55 (SD = 0.64), with CVI of 0.925 and IRA of 1. In the interviews, the experts responded that the model included the essential features of URL, which involves both a science laboratory and e-learning. The experts agreed on most components of the initial ID model and strongly suggested providing detailed information about the course implementation experience.

To improve the ID model, the experts suggested (1) emphasizing the circular characteristics of the ADDIE process, (2) simplifying the overall model by integrating or chunking similar components (particularly for the design phase), (3) separating the implementation and evaluation phases, (4) emphasizing the scientific inquiry features, (5) considering the possibility of transitioning between FTF and NFTF settings adaptively based on decision factors (such as the COVID-19), and (6) generalizing the applicability to URL that might not use videos of experiments (e.g., it was reported in the preliminary study that the earth science lab did not provide videos of experiments).

External validation

The 1st ID model was used to design an URL module for the first half of the ACE course. The derivation of the first module is explicated in detail because a large part of it was maintained throughout the external validation process until the development of the second module, and the expert review panel suggested that this information would be helpful to users of the URL design model.

In the analysis phase, instructors and the researcher delineated the goal of the ACE course to be fostering appropriate scientific knowledge, skills, and attitudes among students and connecting theoretical concepts to the experimental content (Appendix C; Domin, 1999; Hofstein & Lunetta, 2004). Six of the seven students were juniors, and the seventh was a master's student. They all had the previous learning experiences required to take the ACE course and personal computers with internet access. Also, the laboratory classroom had enough equipment and reagents to conduct the required preliminary experiments.

In the design phase, they designed the course content (Appendix C) and weekly class structure (Appendix D-1). They planned for seven students and divided them into three groups of 2–3 students. Before class, one group performed a pre-lab activity — preliminary experimentation and video shooting and editing — by rotation. That group also prepared a presentation to introduce the experimental procedure with the video. The video was required to include all the experimental procedures and appropriate subtitles. Students in all the groups wrote pre-lab reports investigating the experimental procedure and relevant scientific theories. All the students and the TA had access to a real-time Zoom session during the class period. At that session, the pre-lab group presented the relevant scientific theories and procedures and played the video they produced (Appendix E). After watching the presentation and video, the students and TA had a Q&A session followed by a simultaneous mind mapping activity using the Mind Meister webpage (Appendix F)[4] for the wrap-up. The students in the pre-lab group and the TA helped the other groups with their mind mapping. The mind maps produced for each week remained available throughout the course and could be referred to while writing lab reports and preparing for the final exam. After the class, the experimental data produced by the pre-lab group were provided to all students, and they all wrote lab reports. During the design phase, the instructors and researcher also designed the online platform to be used for the course. The ETL ('E- teaching and learning,' LMS used at Hankuk University) was used to upload announcements, the template for the lab reports, experimental videos and data, and pre-lab reports. Meanwhile, the Turnitin website[5] was used to submit the lab reports, which the TA evaluated after an automatic plagiarism check. The TA was asked to promote student interaction and provide appropriate scaffolding throughout the process.

During the development phase, learning materials for the experiments (such as procedures and keywords), videos of the experiments made by each pre-lab group using their smartphones, detailed activities, requirements for the lab reports (which were developed with reference to the template in the *Journal of the Korean Chemical Society* to give students experience with scientific writing), and the lab report evaluation rubric were developed.

[4] https://www.mindmeister.com/
[5] https://www.turnitin.com/

During and after implementing the first module for five weeks, the formative evaluation was conducted via participatory observation, online survey, and follow-up interviews, as described above.

In the RLPS, the overall mean score was 3.32 (SD = .32) on a 4-point Likert scale (Table 12; Figure 16). Notably, the overall RLPS score in the preliminary study, which surveyed 338 students about their URL experience in 2020, was 2.70 (SD = .50), which indicates that the first module scored better by more than 1-standard deviation. All ten perception categories from the video to the evaluation scored higher in 2021 (this study) than in the 2020 non-ID remote labs (Study 2). Specifically, *video satisfaction*, *learning outcome satisfaction*, *class participation*, and *interactions with instructors and colleagues* were improved by more than or equal to 1-standard deviation. Surprisingly, the perception score for the *interaction* increased by more than 1 on a 4-point scale (from 2.31 to 3.38). These differences show the strength of the first module derived from the initial BLEND model in this study (Table 12; Figure 15).

Table 12. Descriptive statistics of students' perception scores for the URL (mean [SD]) (N = 338 in 2020 [N = 280 for video satisfaction], and N = 7 in 2021)

Category	Non-ID cases in 2020	The first module of the ACE course	The second module of the ACE course
Video satisfaction	2.74 (.81)	3.62 (.45)	3.43 (.63)
Learning outcome expectation	3.01 (.68)	3.38 (.76)	3.67 (.43)
Learning outcome satisfaction	2.55 (.74)	3.29 (.40)	3.62 (.65)
Class participation	3.54 (.59)	3.67 (.47)	3.76 (.37)
Class preparation	2.47 (.88)	3.33 (.54)	3.28 (.49)
Experience during class	2.52 (.76)	3 (.47)	3.43 (.46)
Use of LMS	2.46 (.81)	3.19 (.79)	3.57 (.42)
Interactions with instructors and colleagues	2.31 (.89)	3.38 (.59)	3.57 (66)
Lab report writing	2.52 (.79)	3.14 (.42)	3.33 (.58)
Evaluation	2.81 (.72)	3.24 (.53)	3.62 (.59)
Overall	2.7 (.50)	3.32 (.32)	3.53 (.38)

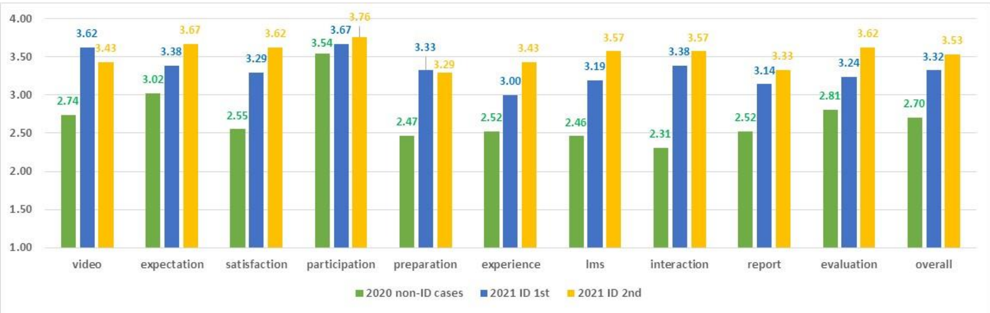

Figure 15. Students' RLPS scores in the 1st (blue) and 2nd (yellow) surveys, along with those from the non-ID URLs surveyed in 2020 (green)

Students also expressed their perceptions of the first URL module in the open questions in the online survey and the follow-up interviews. Most students responded that the first module of the ACE course was satisfactory to some extent, primarily for its convenience in allowing them to gain some knowledge, skills, and attitudes about a science laboratory (Table 12) without requiring their physical presence or labor in a laboratory.

More specifically, *Student 1,* who had taken a remote biology laboratory course in 2020, responded that the first ACE module was better than her previous URL experience because of the enhanced blended learning aspect that incorporated pre-class activity into the real-time session:

> I thought that the most significant objective [of a laboratory class] was to let students apply what they have learned in the [theoretical] class and use the method practically. … I think the writing process of the pre-lab report is very important … Anyway, we conducted experiments firsthand several times [in the pre-lab activity]. … Those two points are the most necessary. … Actually, I took the biology laboratory course [in 2020], and I anticipated that this would be similar to that. However, we did not do it like that before. So I think this course was better [than the biology URL]. - *Student 1*

Meanwhile, *Students 2*, *4,* and *5* indicated their contentment with the online collaborative activities, which helped them understand theoretical components and write lab reports. Notably, *Students 2* and *4* expressed that they had been "alone" in their previous laboratory courses, but they were not during the remote ACE course:

> I cannot think of anything when I write a lab report alone. Anyway, it is very nice to use that — Mind Meister. (researcher: Can you explain this further?) What I'm going to write. What I would write is organized, so I look inside it and check while writing [the lab report]. And the TA comes in when we do that [collaborative mind mapping], so we get constant feedback at that time. It kind of gives me confidence. - *Student 2*

> [In the laboratory course], situations happen that are different from theory. When those situations occur, there should be opportunities to solve them while communicating. I'd say that this laboratory course was better than the usual [ones]. … In this remote class, I used the Mind Meister and actually had more chances to communicate [with peers] than in the usual classes. - *Student 4*

> I'm content in general, but it's split into two. It is very unfortunate not to do experiments firsthand. However, we used Mind Meister and discussed constantly. Previously, it was my fight alone while experimenting and writing lab reports. Even if I'm in a group, if the data were spoiled, we could not ask anyone for help … But now, we have time to discuss the data for all the experiments, which is good. - *Student 5*

Of course, as revealed in the excerpt from *Student 5*, the decreased hands-on experiences compared with previous hands-on laboratory classes were acknowledged as a weakness of the remote lab. Although *Student 5* expressed that loss as "inevitable" to avoid COVID-19 infection and said that she felt safe, *Student 3* responded more acutely to that loss.

> Actually, the laboratory course is now degraded in its differentiated meaning compared with the theoretical course. So I think the differentiated things [hands-on experiences] should be revived. - *Student 3*

Students also responded that they had no skills for shooting and editing videos of their experiments and needed some guidance.

5.4.2 The 2nd BLEND model

The initial BLEND model was significantly revised based on the results of the internal and external validations. The 2nd BLEND model (Figure 16) (1) clearly articulated the circular characteristics of the ID model, (2) structured the design phase by chunking relevant features (grouped by color), (3) separated the implementation and evaluation phases, (4) emphasized the scientific inquiry features in the design phase, (5) specified the decision-making process used prior to designing the URL, and (6) considered “media” rather than just “video.” The most prominent feature in the 2nd model is the design phase, which presents general features (‘2.1 Content design,’ and ‘2.2 Learning schedule design’) (red), inquiry-promoting features (‘2.3 Dataset design,’ ‘2.4 Lab report design,’ and ‘2.5 Evaluation rubric design’) (orange), and e-learning features (‘2.6 Pre-class activity design,’ ‘2.7 Real-time activity design,’ ‘2.8 Media presentation method design,’ ‘2.9 Online platform design,’ and ‘2.10 Manual design’) (green) in parallel. The circular arrows in the inquiry-promoting features indicate the interconnections required when writing lab reports. In the e-learning features, “manual design” was added because the students experienced difficulty in shooting and editing videos in the first URL module. Also, arrows were added to show the (bi)directionality of the ID model.

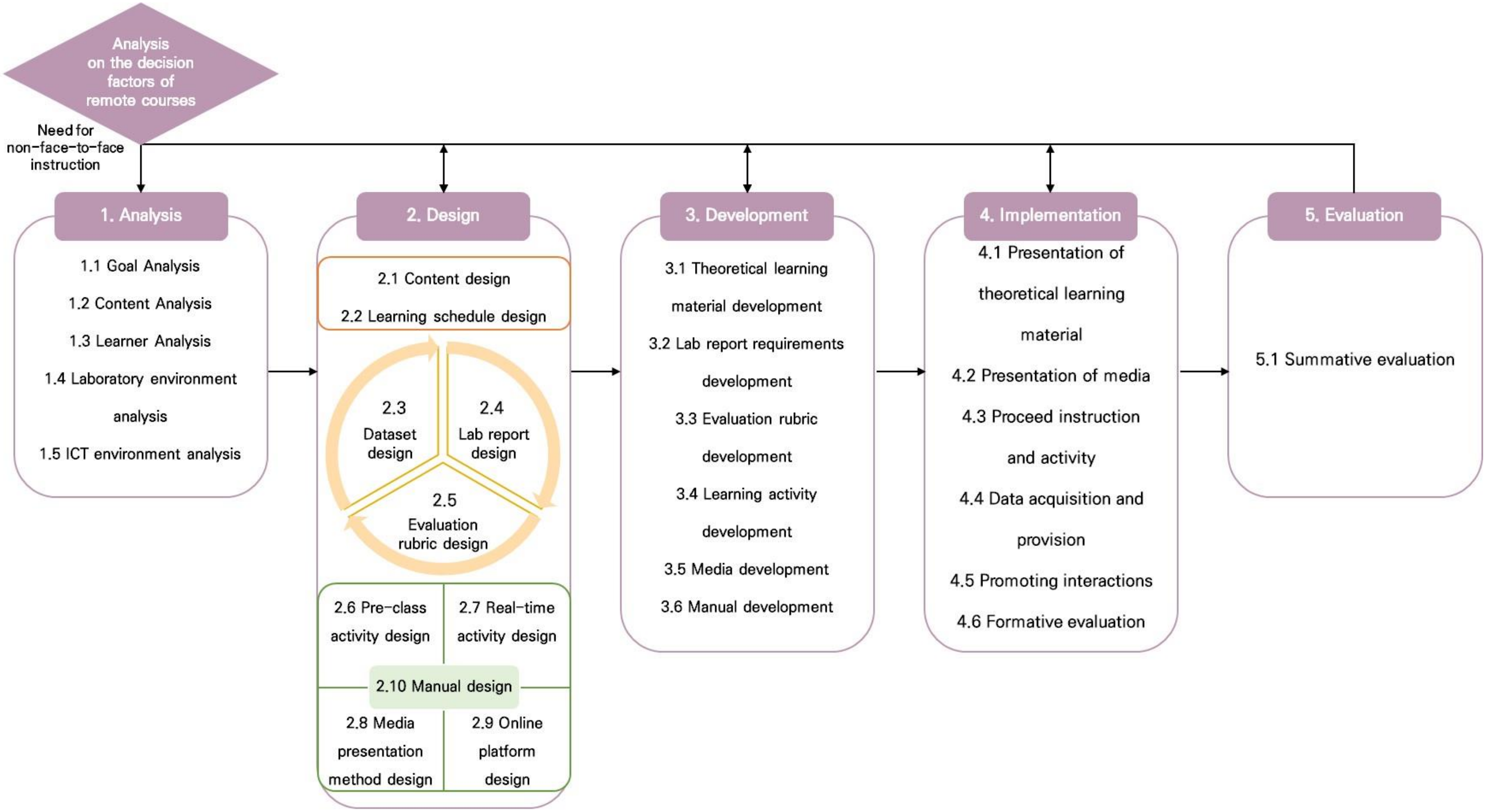

Figure 16. The 2nd BLEND model

Internal validation

In the usability test, the instructors of the ACE course responded that the draft of the 2nd model "is better than the previous one at first glance" because the revised model is succinct, and it is easy to follow the flow through the structure and numbered components. Although the researcher originally intended to include 'inquiry open-endedness' in the design phase, the two former TAs opposed it because the end "is thought to be fixed" in most university-level laboratory courses, and thus the open-endedness became an obstacle when they simulated their URL designs. Therefore component was excluded from the model. Also, the two former students of the ACE course responded that focusing the model on the online collaborative process to facilitate inquiry and lab report writing would be helpful to the students.

The expert panel gave the second BLEND model a mean score of 3.73 (SD = 0.53), with a CVI of 0.943 and an IRA of 1. In the interviews, the experts said that this ID model had a reasonable structure with the essential features of URL, which was similar to their opinion of the initial model. *Experts O*, *Q*, and *R*, who reviewed both the initial and 2nd models (Table 11), said that the 2nd model improved upon the first and gave it a high score of 3.93.

When asked for ways to improve the 2nd ID model, the experts suggested (1) naming the chunked components in the design phase, (2) delineating the behavior of instructors and learners and their interactions in the weekly class time in the implementation phase, and (3) specifying that formative evaluation and feedback should be constant to respond to the changing (pandemic) situation that sometimes allows and sometimes limits FTF instruction. Furthermore, they suggested explaining the decision factors for remote courses as optimized conditions for URL rather than the inevitable constraints of NFTF courses. Providing future readers with specific examples and lessons that arose in the external validation process was also strongly recommended.

External validation

The 2nd model was used to design an URL module for the second half of the ACE course, partly by revising the first module (Appendix D-2). After an internet and communication technology (ICT) environment analysis, the instructors and researcher that the TA should first upload the student-made videos to YouTube and play them, to prevent the interruptions that occurred when students played them on their own computers, which sometimes had inadequate memory. They redesigned the dataset by providing raw experimental data from the previous year's ACE course to promote student inquiry during lab report writing. They designed and provided a summary of the design principles for e-learning videos (Kim, 2015; Mayer, 2009; 2011; Mayer et al., 2020) as a manual. The pre-lab group was asked to write a reflection journal that included what they learned in the process of the pre-lab and preparing the presentation, reflections on that process, and what they wanted to share with their colleagues about their hands-on experiences. Furthermore, after the real-time mind mapping activity within the groups, each group presented its mind maps to the whole class and shared opinions.

During and after the implementation of the second module for five weeks, a formative evaluation was conducted via participatory observation, online survey, and follow-up interviews. The overall RLPS score increased to 3.53 (SD = .38) on a 4-point Likert scale, compared with 3.32 for the first module (Table 12; Figure 15). All except for *video satisfaction* and *class preparation,* eight of the ten perception categories showed higher scores than the first module. Those increases show the improved strength of the second module derived from the 2nd BLEND model. The change in the *class preparation* category can be attributed to a random measurement error because the difference is very slight (0.04, from 3.33 to 3.29); thus, we can say that it was retained equivalently. The decreased score in the *video satisfaction* will be discussed later.

The SLEI and CAEQ scores were compared from the first and second modules (Table 13; Figure 17). For the first module, the overall SLEI score was 3.21 (SD = .38), and the CAEQ score was 4.10 (SD = .35), each on a 5-point Likert scale. In the categories of SLEI, the open-endedness score was lower (2.33, SD = .35) than that of other categories (3.10–3.65). For the second module, the overall SLEI score increased to 3.47 (SD = .42), and the CAEQ increased to 4.33 (SD = .41). The categories of SLEI showed increased scores — by 0.55 for student cohesiveness, 0.31 for integration, and 0.25 for rule clarity — but open-endedness decreased by 0.14. The issue of open-endedness in the SLEI will be discussed later.

Overall, the online survey scores for the RLPS, SLEI, and CAEQ all indicate that the course module derived from the 2nd BLEND model was improved from the one based on the initial model.

Table 13. Descriptive statistics for the SLEI and CAEQ scores from the 1st and 2nd surveys (mean [SD]) (N = 7)

Survey	Category	First module of the ACE course	Second module of the ACE course
SLEI	Student cohesiveness	3.10 (.66)	3.65 (.92)
	Open-endedness	2.33 (.35)	2.19 (.51)
	Integration	3.63 (.51)	3.94 (.43)
	Rule clarity	3.65 (.56)	3.9 (.53)
	Overall	3.21 (.38)	3.47 (.42)
CAEQ		4.1 (.35)	4.33 (.41)

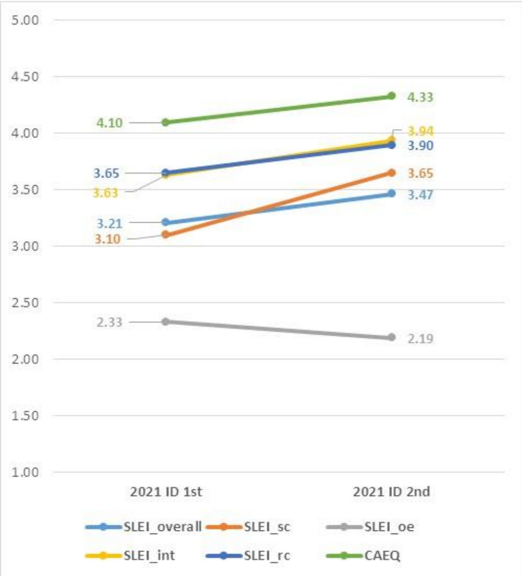

Figure 17. The SLEI and CAEQ scores in the first and second surveys

In the open questions in the online survey and follow-up interviews, *Student 2* responded that she did not feel much had changed between the two ACE course modules, except for the video playing method and the lab report evaluation rubric. The other students responded that the second module was better than the first. Specifically, they reported that the reflection journal helped them indirectly experience the unexpected situations that happened during the preliminary hands-on experiments conducted by other students.

> I think it's been improved. (researcher: in what way?) I thought it was more systemized. We need [systems] such as 'introduction - development - turn - and conclusion' for when I start to study, to talk about the objective, search for it, conduct the experiment, analyze it, and discuss it. There is an order. That order was maintained by putting those things [in the second module]. And communicating feedback with the TA doing those [systemized components of URL] has also been better. - *Student 1*

> I think the ACE was good. I feel it was very successful. (researcher: in what sense?) I think using programs to communicate has facilitated [communication] more than with FTF courses. There was no discussion nor sharing of the results or the experiment itself. … I would say it [the second module] was good. … It was good even when I considered all the laboratory classes I've taken until now. - *Student 4*

Notably, *Student 3*, who had a negative perception of the first module, reacted positively to the second module of the ACE course:

> Generally speaking, … I thought it was better, despite very little time to make changes [from the first module]. … Uploading videos on YouTube and playing them was definitely a technological improvement. … For the reflection journal, … I said previously that the NFTF laboratory decreases the sense of reality, but [colleagues] talked a lot about that in the reflection journal, so it has been improved to a degree. … - *Student 3*

5.4.3 The final BLEND model

The 2nd BLEND model was revised based on the results of its internal and external validations. The final BLEND model is presented in Figure 18. At first, a remote lab could be chosen when the optimized conditions are satisfied. The names of the chunked components in the design phase were specified as “general features,” “inquiry-promoting features,” and “e-learning features.” The implementation phase was also structured, visualizing the components related to the instructor’s side and the learners’ side before, during, and after the weekly classes. Note that the components in the design phase correspond to the components in the development and implementation phase - e.g., ‘2.4 Lab report design’ to ‘3.2 Lab report requirements development’ and ‘2.6 Pre-class activity design’ to ‘4.2 Proceed with pre-class activity.’ Finally, the iterative formative evaluation and feedback were specified below the overall process.

The detailed explanations for the ID model and the specific considerations used during the external validation process are presented in Figure 19.

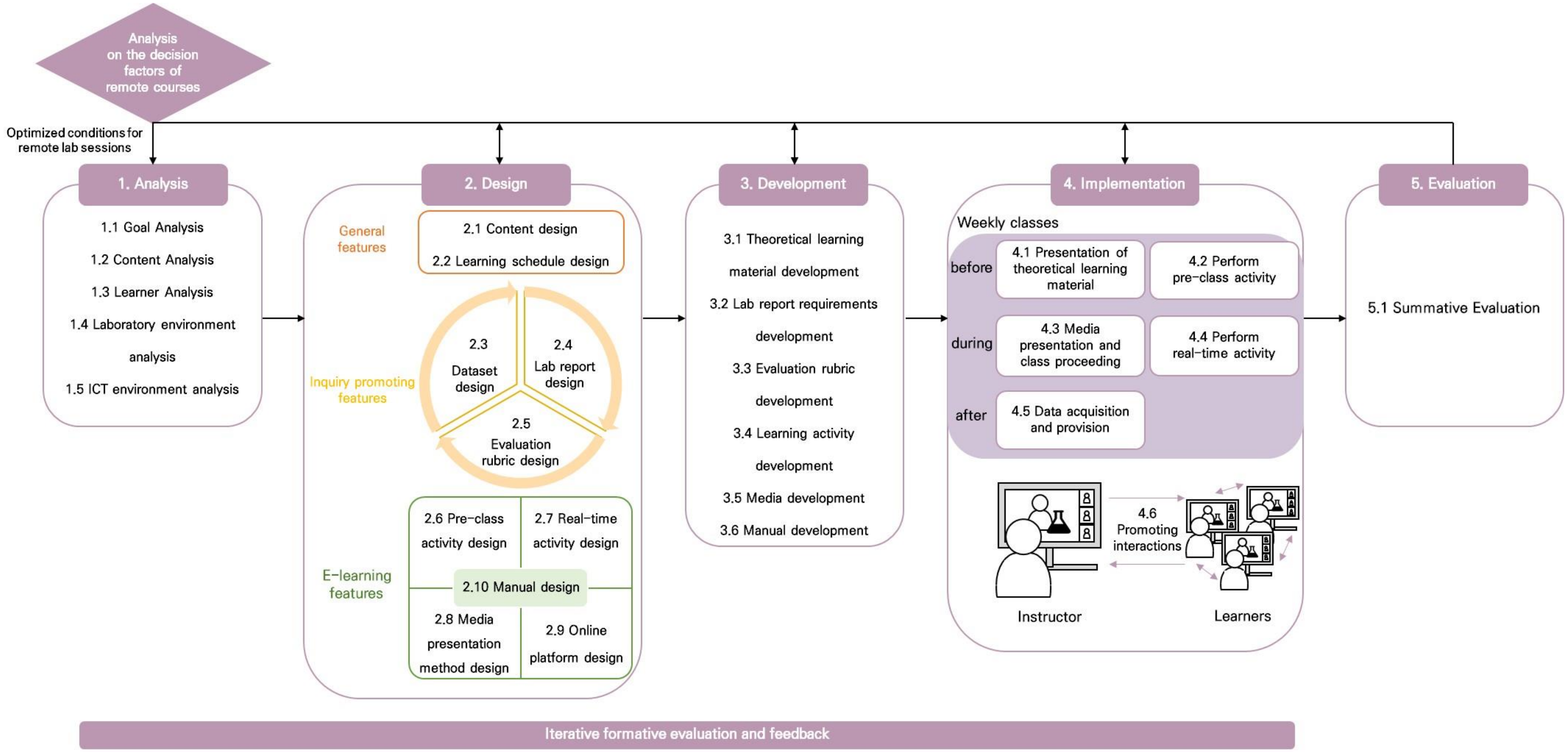

Figure 18. The final BLEND model

Introduction

This BLEND (Blended Laboratory and E-learning iNstructional Design) instructional design (ID) model for university remote laboratory (URL) has its basis on the ADDIE model to present generalizable principles to enhance laboratory education with e-learning. The characteristics of this ID model include structuralized and visualized procedures of designing and implementing an instructional system. Also, this model emphasizes iterative formative evaluation and circularity. Note that the decision factors of remote courses would change how the RLS course is being designed and implemented, even during the process.

Analysis of the decision factors of remote courses

Primarily check the instructional environment. Proceed when there are optimized conditions for the implementation of effective remote courses.

1. Analysis

1.1 Goal analysis

Specify the goal of the RLS course. Is the course going to foster students' scientific knowledge? Hands-on skills or minds-on skills? Or science attitudes? See Hofstein & Lunetta (2004) and Reid (2007) to grasp how the goals of laboratory courses can be differentiated.

1.2 Content analysis

Analyze the course content and connect it to the goal of the course. For example, if you want to shift from the traditional face-to-face laboratory course to a non-face-to-face remote format, select content that matches the online environment well and others that do not.

1.3 Learner analysis

Analyze whether the learners have enough prerequisite knowledge. If learners have taken a theoretical course that corresponds to the RLS course now designed - e.g., *Analytical Chemistry* before *Analytical Chemistry Experiment* -, they are expected to have the prerequisites.

1.4 Laboratory environment analysis

Is there enough equipment, apparatus, and reagent to proceed with minimal hands-on activity such as shooting preliminary experiment videos? Is the space large enough to ensure safety?

1.5 ICT environment analysis

Do the instructors and learners have access to the PC and internet required for the remote course? If they do not, find ways to provide those to the needy.

2. Design

The design part consists of the three juxtaposed features that are internally interweaved - general features, inquiry promoting features, and E-learning features.

General features

2.1 Content design & 2.2 Learning schedule design

Design the course content and learning schedule. Connect the content of the prerequisite theoretical courses to the RLS.
A semester-long RLS course in universities may take 15 weeks. Select the experimental topics and arrange them.

Inquiry promoting features

2.3 dataset design

The data produced by the experiment would match the theoretical prediction with some systematic/random error. Therefore, it is important to decide the number of the dataset students would be provided. If the TA or the pre-lab activity group produces only one dataset, it might be too ideal and thus hinder the inquiry process. Providing a couple of datasets is strongly recommend ed. The dataset may be produced through multiple experimentations or recollected from previous courses.

2.4 Lab report design

The format of the lab report is crucial in laboratory courses. Although being informed of the experimental procedures might be important, reviewing the theoretical background would be essential. The instructor should define how much the discussion section would be emphasized. This is related to the number of datasets and their extent of fit to the theory. Lab report might resemble the format of the scientific journal.

2.5 Evaluation rubric design

The evaluation criteria for the lab report might include the adherence to the format, accuracy of the numerical calculation, adequacy of table and figure, the relevance of discussion with the result and theory, and reference style. Other factors that are not necessarily related to the lab report can also be considered - e.g., learners' attitude during the class.

Figure 19. Detailed explanations and example considerations in the final BLEND model

E-learning features

2.6 Pre-class activity design & 2.7 Real-time activity design

Separate the pre-class activity and real-time activity to utilize the strengths of blended learning. The pre-class activity moves up learners' understanding of the week's experiment - e.g., the preliminary experimentation by a small group of learners. In the real-time activity, learners might be invited to the collaborative discussion. The design of the small group members is also crucial.

2.8 Media presentation method design

To provide learners authentic experiences to some extent, experimental videos or simulations are required. Select the most appropriate one in the situation. Although uploading these media on the online learning environment and letting learners watch them self-directly are possible, it may inhibit the collaborative teaching and learning process. Instructors and learners might watch these media altogether and have a collaborative discussion on them.

2.9 Online platform design

The online platform should be designed to support both asynchronous and synchronous learning processes. It can include (1) a learning management system that allows the upload of materials and submission of homework, (2) synchronous online class platforms such as Zoom and WebEx, and other (3) interactive tools that help learners produce portfolios - e.g., Padlet, MindMeister.

2.10 Manual design

Check the possible difficulties the instructors and learners might face. The structure of the weekly class should be explicated succinctly. Also, the usability of the online environment should also be enhanced through the appropriate manuals.

3. Development

3.1 Theoretical learning material development

Theoretical learning material summarizes the science concepts and theories that are relevant to the weekly experiment. It also presents the essential experimental procedures. It may be a form of sheet or slides.

3.2 Lab report requirements development & 3.3 evaluation rubric development

Specify what is required in the lab report and the collaborative learning processes.

3.4 Learning activity development

Develop the pre-class and real-time activities. Decide where to provide the minimal hands-on experience to the learners - before or during the class. If a small group of students conducts preliminary experimentation, they might write reflection journals to transfer their learning experiences to colleagues.

3.5 Media development

Develop the appropriate media. The media may be developed by instructors or learners (if not introduced from external sources) . If learners are to develop those, it may provide them hands-on experiences shooting experimental videos.

3.6 Manual development

Manuals for the weekly instructional system (pre-class and real-time activities) and guidelines for the online platform are required. If learners are to develop the media such as experimental videos, that should also be guided by the manuals.

4. Implementation

The implementation part suggests the structure of weekly classes. Note that 4.1, 4.3, and 4.5 are on the instructor's side, and 4.2 and 4.4 are on the learner's side.

Before class

4.1 Presentation of theoretical learning material

Provide learners with theoretical learning material. It should be uploaded on the learning management system before the pre-class activity so that learners are informed of that beforehand.

4.2 Proceed pre-class activity

Let learners proceed with the pre-class activity - i.e., a small group would visit the laboratory classroom to conduct the preliminary experimentation and shoot and edit the experimental videos.

During class

4.3 Media presentation and class proceeding

Media should be presented in synchronous situations. Instructor or small group participants would present the media to the other learners while connecting the relevant scientific concepts and theories.

4.4 Proceed real-time activity

After learning with the media, learners should participate the collaborative discussion and problem-solving.

After class

4.5 Data acquisition and provision

The instructor finalizes the experimental datasets and provides those to the learners. Leaners then would write a lab report based on the data.

4.6 Promoting interactions

Throughout the process of 4.1-4.5, interactions between instructors and learners should be promoted.

5. Evaluation

5.1 Summative Evaluation

After the course module ends, repeat the procedure presented in the model from the analysis part based on the summative evaluation results.

Iterative formative evaluation and feedback

Before 5.1, the iterative formative evaluation and feedback allow the revision of the instructional system.

Figure 19 (continued)

5.5 Discussion

This study was situated in the distinctive instructional environment provoked by the COVID-19 pandemic. Therefore, the characteristics of the final BLEND model for URL reflect that environment. The final BLEND model comprehensively considers both laboratory education and e-learning. It emphasizes constant formative evaluation and feedback and structures and visualizes the URL instructional system on both the weekly and whole-course levels (cf. Lee et al., 2017).

Whether an ID model is internally well-validated is a touchstone of its plausibility (Richey & Klein, 2007). In addition to a thorough review of literature from both science education and educational technology, the internal validation process reflected the lessons learned from the preliminary study. Thirteen experts from various fields reviewed each iteration of the ID model. All those internal validation procedures were nonlinear and iterative to be feasible in the unstable instructional environment caused by fluctuations in the number of confirmed COVID-19 cases. The RP approach used to derive an instructional program based on the BLEND model also tested its practical aspects. That entire process allowed the continuous improvement of the BLEND model for URL.

The results of the external validation are as follows. An instructional program derived from the initial BLEND model received higher student perception scores than the non-ID remote labs given at Hankuk University in 2020. Particularly, student perceptions of the interactions between instructors and colleagues were higher by more than 1 point on a 4-point Likert scale. Furthermore, the instructional program derived from the 2nd BLEND model received even higher student perception scores and also scored better on the SLEI (except for open-endedness) and CAEQ items than the initial model. Again, student perceptions of interactions and student cohesiveness increased (Tables 12–13). Therefore, it can be said that the BLEND model has remarkable strength in facilitating interactions and cohesiveness within the instructional system. The BLEND model for URL was finalized by editing the 2nd model.

Next, it is necessary to consider why the open-endedness category of the SLEI scored lower than the other categories and even decreased between the first and second modules (Table 13). Fraser et al. (1995) reported that open-endedness showed the lowest score among the categories of the SLEI instrument. Also, remember that two former TAs in the ACE course suggested that the open-endedness should not be incorporated into the model, during the 2nd usability test. Therefore, the problem does not lie in the ID model. Rather, it does in the general characteristics of laboratory courses at universities (and at other school levels, too), using a close-ended format, replicating and confirming what students have learned in their theoretical classes (i.e., the content of the Analytical Chemistry course defines the content of the ACE course; see Appendix C) (Fraser et al., 1995).

Students' learning experiences in the ACE modules largely depended on the videos of experiments conducted by their fellow students. Even though the students presumably improved in their ability to produce videos of experiments they conducted during the ACE course, their perception of that category decreased between the first and second modules. According to the student interviews, that decrease reflects limitations in the videos produced during the second module, in which many of the experiments used complicated machines, such as electrochemical instruments and UV-VIS spectrometers, that produced graphs on a screen that could not be filmed in high definition. Therefore, more empirical study of video design principles in science experiments is recommended (Jang et al., 2020). For example, Mayer et al. (2020) found that the first-person view is more effective than the third-person view when filming a circuit-building demonstration. Likewise, we may further our understanding of the effects of more authentic science-experiment videos by shooting with a head-mounted action camera while conducting the actual hands-on experiments, and that might be convertible to a VR application.

One critical issue in the research about ID model development is model generalizability (Lee et al., 2017; Richey & Klein, 2005; 2007). This study also has a few issues in that regard. First, the developed BLEND model was validated within the specific context of a remote lab about analytical chemistry. However, the expert review panel in this study included scholars from physics, chemistry, biology, and earth science education. Also, the information from the preliminary studies (Study 1 and 2) that investigated remote labs in various STEM courses was considered. Therefore, the BLEND model developed in this study can be applied to various science and technology subjects. Second, the decisions instructors and the researcher made for the remote lab might be context-dependent and appropriate only in a particular situation, such as the pandemic and Korea. However, the rationale for the BLEND model lies in the synthesis of well-established literature about the hands-on/minds-on aspects of scientific inquiry (Hofstein & Lunetta, 2004; Abrahams & Millar, 2008) and the promise of e-learning (Clark & Mayer, 2016; Mayer, 2009) and lessons from preliminary studies. Therefore, the BLEND model for URL can be generalized beyond the COVID-19 pandemic and used in a blended learning environment (Lee & Hong, 2021b). Third, if the module developed in this study has any generalizability problems, it is the targeted teaching and learning context of a university-level laboratory. The BLEND model presupposes university-level resources and competencies of instructors and students; thus, it might not be appropriate to apply it to other school levels.

Also, the influence of the COVID-19 on this research should not be underestimated — only a few students took the class, which shaped the process of implementing and validating the BLEND model for URL. In fact, so few students took the course that plausible inferential statistics could not be calculated. Those are limitations of this study. Nevertheless, the results of the internal validation — usability test and expert review — and students' favorable perceptions of the URL designed using the BLEND model support its validity. Therefore, this study shows the flexible and adaptive and aspects of the BLEND model even in the fluctuating situations.

Therefore, the BLEND model for URL developed in this study can be efficiently applied to university-level courses, and instructional programs designed using this model will effectively provide meaningful learning experiences for students. This study is a rare case of adopting a design and development research method in science education. Ironically, the COVID-19 situation provided an opportunity to deeply contemplate existing practices in science teaching and learning (cf. Klein, 2014), revealing what should be validated in the field and how. Open-endedness is important, although it is difficult in practice, in teaching scientific inquiry (cf. Hofstein & Lunetta, 2004; Abrahams & Millar, 2008; Zacharia et al., 2015), and the BLEND model does not incorporate much of it (Table 13; Figure 17). Although this study targeted a laboratory course with weekly experimental topics, a long-term open-ended inquiry project could be another situation in which to adopt the ID approach. In that kind of instruction, the inquiry process for hands-on experiences is closely related to iteratively conducted experiments and discussion, i.e., according to the interpretation of experimental data made using scientific theories and procedures, the instructor and students re-design the experiment and repeat the cycle in a flexible manner (Berg et al., 2003). That structure seems to fit well with the ethos of a systematic approach to instruction, including the frequent formative evaluation and instruction redesign (Richey & Klein, 2007; Tripp & Bichelmeyer, 1990). Therefore, an ID model for iterative open-ended inquiry learning in science education is a plausible future research topic for the post-COVID-19 era.

Chapter 6. Summary and Conclusion

This study focused on the remote labs necessitated by the COVID-19 situation since the spring semester of 2020. Situated in the research field of Hankuk University, this study tracked how the various URL courses were designed and implemented according to the given conditions and how their aftermaths were in 2020. The theoretical framework enabled the interpretation of URL phenomena as the locus of intersection of laboratory in science education and effective teaching strategies of e-learning. Particularly, the extended understanding of blended learning for laboratory education was suggested. Based on the lessons from the URL courses in 2020, the way to implement a better URL was sought.

In Study 1, the researcher compared four general remote labs, each for physics, chemistry, biology, and earth science, that were previously similar, and two major course labs at Hankuk University. The emergence of URL phenomena was interpreted from a sociocultural perspective, focusing on the structure posed by the COVID-19 pandemic and the educational authorities and the agency of university instructors. The macro-level context of Korea, the meso-level context of Hankuk University, and the micro-level context of each URL were closely interconnected with each other and the university instructors' agency. In the spring semester of 2020, the multi-level structures strongly shaped instructors' agency. However, the implemented URL in each discipline became quite various due to the endeavor instructors put in. The university instructors' concerns were about video materials, data characteristics, limited interactions between them and students, difficulties in evaluation, and what students could "gain" from the URLs without hands-on experience. Since the fall semester of 2020, instructors have adapted to the situation, revised their URLs, and suggested further improvements. Study 1 reveals that university instructors' agency led to the emergence of various remote laboratory course implementations in the context of an imminent emergency.

In Study 2, in step with Study 1, the researcher investigated how Hankuk University students perceived various remote laboratory course experiences in different content disciplines. Conducted as a mixed-methods study, online survey responses were collected from 338 students, and in-depth interviews were conducted with 18 students. ANOVA and Bonferroni post hoc tests of survey responses found that students' perceptions of their URL experiences were significantly different ($p < .05$) dependent on content discipline (physics, chemistry, biology, earth science, and other majors). In addition, student interviews revealed that these differences in perceptions resulted from the different emergent teaching strategies used in each course. Suggestions were made for clearly setting learning objectives, carefully designing videos of experiments, offering collaborative synchronous online sessions, providing guidance and feedback for lab report writing, and introducing supportive assessments as strategies for future implementation of remote labs.

In Study 3, the BLEND model for URL was developed and validated. To respond to the fluctuating instructional environment of the pandemic, an ID model was promptly constructed and applied in the authentic learning context, iteratively revising the model with participant feedback. The research context was an ACE course for pre-service chemistry teachers. The initial BLEND model was based on a literature review and lessons from Study 1 and 2 in 2020. For internal validation, six stakeholders participated in the usability test, and 10 subject-matter experts from various science disciplines and three educational technology experts provided expert reviews. For external validation, the URL course module was developed and implemented, and seven university students who took the course responded to online surveys and participated in follow-up interviews. After two rounds of validation, the BLEND model was confirmed to be internally efficient and externally effective. The interactions with the instructor and peers, in particular, were highly appreciated. The finalized BLEND model for URL emphasizes constant formative evaluation and feedback and structures and visualizes the URL instructional system at both the weekly and overall course levels. Study 3 is a rare case of applying a design and development research method to science education.

Some issues were not resolved in this study and need follow-up research: (1) The interplay between the requirements of remote lab format and the nature of each science discipline (i.e., physics, chemistry, biology, and earth science) should be scrutinized. In Study 1 and 2, some characteristics of each science discipline were hypothesized - the physics lab is sensitive to data characteristics; the chemistry lab more depends on hands-on experiences than others; the biology lab can modularize their course content; the earth science lab less depends on hands-on experiences than others. However, as the introductory URL courses that Study 1 and 2 had focused on were massively implemented and consistently regulated, the course characteristics situated in Hankuk University must have overlapped with the nature of each science discipline. And these two cannot be regarded as the same. For example, Schwartz & Lederman (2008) once showed that even scientists within each discipline have different views on NOS, which implies that the optimal instructional method can also vary within a discipline. Therefore, although Study 3 sought to develop and validate a generalizable ID model for URLs, future research may seek another route to provide a customized prescription for URLs with specific course content. (2) Not irrelevant to this, a discipline or content may rely more on experiment videos - for example, the second course module of the ACE course in Study 3 showed lower *video satisfaction* for the electrochemistry experiments using the potentiostat connected to the computer and H-point standard addition method using UV-VIS spectrometer (Table 12; Figure 15; Appendix C). Then, how the experiment video should be designed, shot, and edited remains crucial. For example, if a session should deal with exquisite equipment or apparatuses, or data plots on a screen attached to a machine, how should those be captured while presenting the overall experimental process? Empirical research should provide evidence for the experiment video design principles (Jang et al., 2020; e.g., Mayer et al., 2020). (3) An ID model for open-ended inquiry laboratories is a plausible future research topic, as suggested in Study 3. Then, how to evaluate the open-ended inquiry module arises as an essential prerequisite, which is also an important research agenda.

The significance of this study lies in its unique research field - Hankuk University in 2020 and 2021. As mentioned above, this study collected extensive data from various remote lab courses that emerged during the initial situation of the COVID-19. In Study 1, it was possible to collect data from 10 instructors who managed a total of six types of remote labs in 2020, and in Study 2, it was possible to collect data from 338 students who took those. Their contextual commonalities and differences enabled identifying the generalizable teaching strategies in URL. Based on those results, Study 3 could devise, iteratively revise, and finalize the BLEND model for URL, reflecting the ideas of instructors and students who experienced the unexpected shift to remote teaching and learning. Therefore, Study

1 to Study 3 can be said the attempt that reports the URL phenomena during the early stage of COVID-19 comprehensively.

However, ironically, the COVID-19 situation that shaped the strength of this study can also be a double-edged sword. As time passes, the situation of 2022 is quite different from that of 2020 and 2021. In the case of Korea, the number of confirmed cases of COVID-19 infection has dramatically upsurged, which reached its peak around April and began to decrease. As of May 2022, the Korean government allowed people to wear off their facial masks outside, and the K-12 and university education courses are turning back to the FTF settings. Consequently, the status of remote teachings, especially of remote labs in the post-COVID-19 era, is hard to predict.

If we take an optimistic view, as Korean science education experts' perceived that our experience of remote labs had broadened our imagination of university laboratory courses, laboratory education will evolve towards a blended format that incorporates various learning modes across time and space (Lee & Hong, 2021b). First, it was the blending of hands-on and minds-on laboratory experiences within an instructional program. Although there have been debates between the proponents of the two, and some rightly suggested the integration of those (Lumpe & Oliver, 1991; Flick, 1993; Abd-El-Khalick et al., 2004; Parsons, 2019), almost no research seems to have presented a systematic guideline to utilize both in an instructional program. Therefore, the blended understanding of laboratory experiences became one way to accomplish what Comenius once stressed - the complementary use of sense and reason in science education, which pertains to the development of the whole person (Lee & Hong, 2021a). Second, it was the blending of laboratory experiences and learning spaces. If the implementation of remote labs was passively determined in 2020 due to the COVID-19, this study (particularly Study 3) showed a possibility of active decision toward the design and implementation of URL based on a systematic BLEND model. To sum up, the extended understanding of the blended learning for laboratory courses shed some light on the path that overcoming the old dichotomies such as hands-on versus minds-on, synchronous vs. asynchronous, physical versus virtual, and place-based versus remote to proceed towards a better laboratory education (cf. Flick, 1993; Domin, 1999; Reid & Shah, 2007; Gustavsson et al., 2009; Chiu et al., 2015; Parsons, 2019; Lee & Hong, 2021b). If the blended learning format becomes prominent in the post-COVID-19 university education (Harvard Future of Teaching and Learning Task Force, 2022) and the crucial role of the laboratory sessions in higher education remains, the BLEND model for URL developed in this study would have no small impact for university STEM instructors around the globe in future with 'new normal.'

In contrast, if we take a pessimistic view, as Boyd (2008) said in his work on *The History of Western Education*, we can expect that even our serious contemplation on remote labs may also disappear someday, as a tremendous number of teaching methods did. Actually, this critique of Boyd (2008) on specific teaching methods is headed to Comenius, who may be appraised as an originator of laboratory education (Lee & Hong, 2021a). But Boyd (2008) also rightly said that we still remember Comenius as having raised fundamental and enduring educational questions (cf. Lee & Hong, 2021a). Then, it would be safe and meaningful to list some important questions on the essence of laboratory sessions or even science education, which are rediscovered while we experience remote labs due to the COVID-19, as pointed out in the 1.2 Purpose of Research (Q1–Q5).

The easiest way to answer those questions would be by relying on the peculiarity of the learning objectives in each laboratory course (Domin, 1999; Hart et al., 2000; Reid & Shah, 2007) - however, it does not provide practical lessons or open the way to more profound contemplations toward the post-COVID-19 laboratory education. Instead, more certain answers could be derived from participants' voices throughout this study. (A1) The minimum firsthand experience should be secured to foster students’ experimentation skills and provide students chances to engage with unexpected phenomena relevant to tacit knowledge and NOS (Lee & Hong, 2021b). According to the participants, the minimum firsthand experience may be provided with an experiment kit or allowing a small number of students to visit the lab to conduct hands-on experiments, even during an emergency. Note that a blended learning format, like in Study 3, can be an alternative that provides students with both hands-on and minds-on experiences. (A2) Instructors and students must have synchronous interactions in a temporal aspect. However, whether the spatial co-presence is necessary is not so manifest. Instructors may deliver content and provide some laboratory experiences in remote settings via verbal interaction when the learning objectives lay in the cognitive dimension. However, it was shown in this study that non-verbal interaction and the sensing of the affective dimension are difficult in remote settings. If there are some ways to secure the sense of “presence” between instructors and students (Ma & Nickerson, 2006; Brinson, 2015), laboratory courses may not require the physical co-presence of instructors and students. Developing technologies such as AR/VR may suggest its possibility for the future (Lee & Hong, 2017; Ray & Srivastava, 2020; Hu-Au & Okita, 2021). (A3) If possible, a semester-long open-ended laboratory class would be the best chance to invite students to in-depth inquiry thinking, as suggested in Study 3. However, it seems that most university laboratory courses, especially introductory ones, cannot avoid taking a role in replicating and confirming what is learned in the relevant theoretical classes - it also has its educational value. Therefore, the gap between the theoretical prediction and the real experimental data seems to be the only possible locus where an inquiry may arise in a practical sense, as participants of Study 1 and 2 said. To invite students to an authentic inquiry, they should be prepared with some theoretical predictions with pre-lab activities. After that, instructors should provide no data that fits the theory too much but with some realistic errors. Providing multiple datasets would be the simplest way to enhance student inquiry. Then, the instructor should guide student inquiry in their lab report as specifically as possible while promoting peer discussion. (A4) If the culture surrounding the laboratory education site favors the hand or mind as a cognitive channel or shapes the interaction between instructors and students vertically or horizontally, the answer would be yes (see Abd-El-Khalick et al., 2004; Parsons, 2019). Particularly, if Korean university first-year students have been eager to have hands-on experiences because of the lack of those in the K-12 education, students in some other countries may have different orientations. Either generalizable or culture-specific implications might be found in international comparative studies (e.g., Abd-El-Khalick et al., 2004). (A5) Like any other instructional traditions, university laboratory courses have not been changed much within decades. Those stable conventions may only be reformed when a strong driving force comes, which was the COVID-19 situation that enforced the remote instruction in the case of this study. The BLEND model developed in Study 3 shows a way to renew the design and implementation of a university laboratory course with other traditions in the educational technology field - viz. e-learning and ID model research. Particularly, the notion of formative assessment of the instructional system may help make the laboratory courses more adaptive and flexible in various instructional situations.

In the introduction of this dissertation, it was mentioned that the word "crisis" implies a decisive point when a certain thing is judged and sentenced to be changed for better or worse. At this point, however, it would be added that the word "crisis" corresponds to a Korean-Chinese term, "위기" (*wigi*, "危機"), which has a compound meaning of "risk" ("위," *wi*, "危") that comes with "chance"s ("기," *gi*, "機"). As of 2022, the structure given by the COVID-19 pandemic has been changing because of the global vaccination trend and endeavors of public areas. Now we are going to face a new world, which cannot be the same as previous. And the researcher acknowledges that the instructors and students at Hankuk University were genuine agents who are getting through from disruption to recovery. Their struggle at the boundary of past and future enabled the emergence of URLs in 2020, which became the source of the development of the BLEND model. Their legacy let us contemplate the essence and broaden the spatiotemporality of laboratory education through blended format, and bestowed us a chance to serve science education research and practice hereafter with a humble heart. Indeed, they were the voices calling us to make straight the way toward the post-COVID-19 laboratory education getting over the crisis.

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Appendices

A. Content examples of introductory remote laboratory at Hankuk University in 2020

Course	Experiment
Physics lab	Newton's apple
	Big collision
	Measurement of moment of inertia
	Motion of object pendulum
	Ohm's law
Chemistry lab	Atomic weight of barium
	Molecular weight of carbon dioxide
	Element analysis and freezing point depression
	Separation of adenine and caffeine using HPLC
	Various gas laws
Biology lab	Instructions for equipment and cell observation
	Cell division
	Protein extraction and quantity measure
	Genetics (module of three consecutive experiments)
	DNA technology (module of three consecutive experiments)
Earth science lab	Interpretation of geological map
	Interpretation of weather chart
	Observation and classification of clouds
	Interpretation of satellite weather picture
	Vertical structure of seawater

B. Remote Laboratory Perception Survey (RLPS) used in Study 2 and Study 3 (translated from Korean)

Category	Question	Response			
Demographic information	To which college do you belong?				
	What is your year in university?				
	What is your gender?				
	What URL course did you take in the first semester of 2020?				
	Open Question 1: What are the characteristic features of that subject?				
Video satisfaction	The videos provided in the URL course were…	SD	D	A	SA
	satisfactory in image quality and composition.				
	satisfactory in sound quality and background.				
	satisfactory in editing and captions.				
	Open Question 2: Do you have any additional ideas for videos used in URL in the future?				
Learning expectation	Before taking the URL class, I …	SD	D	A	SA
	expected to acquire appropriate knowledge.				
	expected to acquire appropriate skills.				
	expected to acquire appropriate attitudes.				
Learning outcome satisfaction	After taking the URL class, I …	SD	D	A	SA
	have acquired satisfactory knowledge.				
	have acquired satisfactory skills.				
	have acquired satisfactory attitudes.				
Class participation	While taking the URL class, I …	SD	D	A	SA
	studied at the same pace as the class.				
	studied all the content for each class.				
	participated until the end of the semester.				
	Open Question 3: What do you think your expectation, satisfaction, and participation in the face-to-face laboratory class would have been if there had been no COVID-19?				
Class preparation	Before URL class times, I …	SD	D	A	SA
	prepared by investigating the apparatuses, materials, reagents, etc.				
	prepared by investigating the content and processes of the experiments.				
	prepared for the quiz.				

Area	Question	Response			
Experience during class	Taking the URL class, I…	SD	D	A	SA
	was able to have enough experience with the apparatuses, materials, reagents, etc.				
	was able to have enough experience with the content and processes of the experiments.				
	was able to have enough experience in the interpretation of results and discussion.				
Use of learning management system (LMS)	In the URL class I have taken, …	SD	D	A	SA
	active use of the LMS was promoted and encouraged.				
	sufficient teaching and learning materials were uploaded to the LMS.				
	instructors and learners actively interchanged ideas.				
	Open Question 4: What do you think the use of the LMS in the face-to-face laboratory class would have been like if there had been no COVID-19?				
Interaction with instructors and colleagues	In the URL class I have taken, …	SD	D	A	SA
	cooperation and interactions with instructors and colleagues were encouraged.				
	cooperation and interactions with instructors were smooth in general.				
	cooperation and interactions with colleagues were smooth in general.				
	Open Question 5: What do you think the preparation, experience during class, use of the LMS, and interaction with instructors and colleagues in the face-to-face laboratory class would have been like if there had been no COVID-19?				
Lab report writing	While writing my lab report after class, I …	SD	D	A	SA
	could easily get the necessary information.				
	was able to get the assistance necessary for scientific writing.				
	was able to get appropriate feedback.				
Evaluation	On the evaluation, I …	SD	D	A	SA
	was able to receive scores that were reasonable for me.				
	was provided with clear evaluation criteria.				
	was able to raise problems with the results of the evaluation.				
	Open Question 6: What do you think the experience of writing lab reports and evaluations in the face-to-face laboratory class would have been like if there had been no COVID-19?				
Pros and cons of and suggestions for URL	Open Question 7: What were the disadvantages of the URL?				
	Open Question 8: What were the advantages of the URL?				
	Open Question 9: What changes are necessary to improve URL?				

C. Schedule and content of the Analytical Chemistry Experiment course

Module	Week	Pre-lab assignment	Content
1	1	TA	- Orientation - Production and standardization of NaOH solution & determination of the concentration of a weak acid. - Titration of a polyprotic acid
	2	Group 1	- Argentometric titration: Volhard method
	3	Group 2	- EDTA titration
	4	Group 3	- Production and standardization of $KMnO_4$ solution (As_2O_3) - Measuring calcium salt ($CaCO_3$)
	5	Group 1	- Iodimetric titration of vitamin C and H_2O_2
	6		Mid-term break
2	7	Group 2	- Titration in a non-aqueous solvent
	8	Group 3	- Determination of dissociation constant using spectrophotometry
	9	Group 1	- Applied electrochemical experiment 1
	10	Group 2	- Applied electrochemical experiment 2
	11	Group 3	- H-point standard addition method
	12		Final-term break
	13		Final exam

D-1. Weekly class structure in the first module of the Analytical Chemistry Experiment course

<table>
<tr><th>Period</th><th>Students in the pre-lab group</th><th>Students in the other groups</th><th>Instructor (TA)</th></tr>
<tr><td>Before class</td><td>- Conduct preliminary experiment at the laboratory with TA
- Shoot and edit video of the experiment
- Prepare for the presentation (slides)
- Write a pre-lab report</td><td>- Write a pre-lab report</td><td>- Conduct preliminary experiment at the laboratory with the pre-lab group
- Help the pre-lab group shooting the video</td></tr>
<tr><td rowspan="4">During class</td><td colspan="3">- Access to real-time Zoom session</td></tr>
<tr><td>- Play the video of the experiment
- Make a presentation that shows theories and experimental procedures</td><td>- Listen to the presentation
- Watch the video</td><td>- Listen to the presentation
- Watch the video</td></tr>
<tr><td colspan="3">- Have a Q&A session</td></tr>
<tr><td>- Help other groups with mind mapping</td><td>- Perform mind mapping via the Mind Meister webpage</td><td>- Help students with mind mapping</td></tr>
<tr><td>After class</td><td>- Write a lab report</td><td>- Write a lab report</td><td>- Evaluate lab reports
- Provide feedback on the lab reports</td></tr>
</table>

D-2. Weekly class structure in the second module of the Analytical Chemistry Experiment course

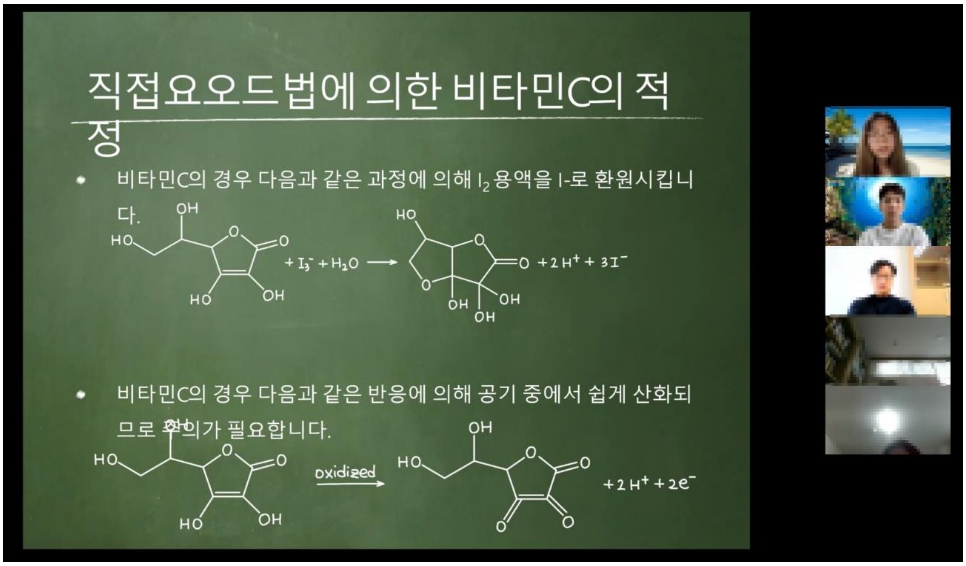
<table>
<tr><th>Period</th><th>Students in the pre-lab group</th><th>Students in the other groups</th><th>Instructor (TA)</th></tr>
<tr><td>Before class</td><td>- Conduct preliminary experiment at the laboratory with the TA
- Shoot and edit video of the experiment
- Send the video to the TA
- Prepare for the presentation (slides)
- Write a reflection journal to share
- Write a pre-lab report</td><td>- Write a pre-lab report</td><td>- Conduct preliminary experiment at the laboratory with the pre-lab group
- Help the pre-lab group shoot the video
- Upload the video to YouTube</td></tr>
<tr><td rowspan="5">During class</td><td colspan="3">- Access to real-time Zoom session</td></tr>
<tr><td>- Make a presentation that shows theories, experimental procedures, and reflection journal</td><td>- Listen to the presentation
- Watch the video</td><td>- Listen to the presentation
- Play the video</td></tr>
<tr><td colspan="3">- Have a Q&A session</td></tr>
<tr><td>- Help other groups with mind mapping</td><td>- Perform mind mapping via the Mind Meister webpage</td><td>- Help students with mind mapping</td></tr>
<tr><td colspan="3">- Present each group’s mind map product</td></tr>
<tr><td>After class</td><td>- Write a lab report</td><td>- Write a lab report</td><td>- Evaluate lab reports
- Provide feedback on the lab reports</td></tr>
</table>

(**bold**: changed from the first module)

E. Student presentation of the preliminary video and slides made while conducting an experiment

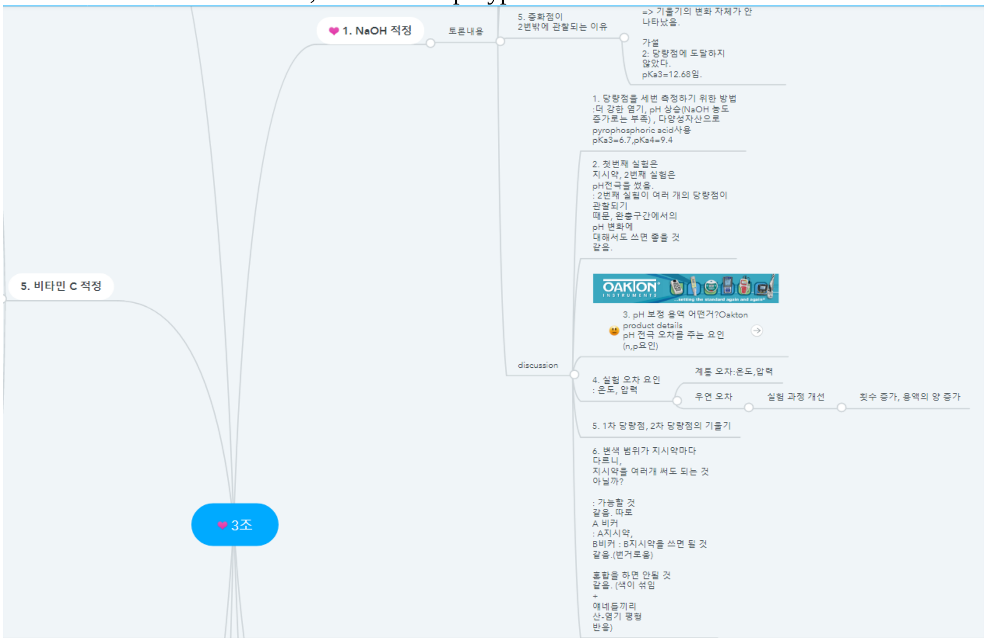
Week 2: EDTA titration

Week 5: Iodimetric titration of vitamin C and H_2O_2



F. Synchronous mind mapping activity and products

Week 1: Production and standardization of NaOH solution & determination of the concentration of a weak acid; Titration of polyprotic acid



Week 9: Applied electrochemical experiment 1

국문 초록

블렌디드 실험 및 이러닝 교수 설계 모형의 개발

: 대학 교수자와 학생들의 교훈으로부터 포스트-코로나-19 실험 교육을 향하여

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2020년에 발생한 코로나-19 사태와 이로 인한 사회적 거리두기 방역 정책은 대학 실험 수업들이 관습적인 대면 방식에서 익숙하지 않은 비대면 방식으로 갑작스럽게 전환되는 상황을 야기하였다. 코로나-19로 인한 세계적인 교육 결손이 예상되는 상황에서, 과학교육학자들은 비대면 원격 실험 수업이 가져온 실험 교육의 변화에 주목하며 그 전개와 결과에 대한 경험적인 연구를 촉구하였다.

이에 본 연구자는 다음과 같은 두 가지 목표를 지니고 연구를 수행하였다. 첫째, 원격 실험 수업이라는 초유의 상황에 직면하여 제기된 실험 교육의 본질(essence)에 관한 근본적인 질문들에 답하고자 한다. 그러한 질문들은 다음과 같이 요약될 수 있을 것이다. (문 1) 대학은 물론 K-12 과학교육에 이르기까지 실험 수업 경험의 본질은 무엇인가? 만족스러운 학습 결과가 어느 정도 보장된다면 원격 마인즈온 수업이 핸즈온 경험을 대체할 수 있는가? (문 2) 교수자와 학생의 시공간적 공동-존재(co-presence)는 필수적인가? (문 3) 우리는 어떻게 학생들은 자연 현상에 대한 탐구로 초대하고, 그것을 실험 보고서에서 과학적 글쓰기로서 표현하도록 할 수 있는가? (문 4) 위에 대한 답은 세계의 여러 문화 및 그에 따른 교수자와 학생 간의 상호작용의 특성에 따라 달라지는

가? (문 5) 우리는 어떻게 일반적인 상황뿐 아니라 긴급한 상황에서도 실행할 수 있는 효과적이고 적응적인 실험 수업을 설계할 수 있는가? 이에 대한 잠정적인 답을 연구의 이론적 틀과 함께 살펴보고, 보다 직접적인 답을 연구의 결과에 비춘 논의에서 제시하고자 하였다.

둘째, 본 논문은 2020년에 코로나-19로 인하여 촉발된 원격 실험 수업에 관하여 대학에서의 이공계열 교육에 어떠한 현상이 발생하였는지를 조사하고 향후의 대학 원격 실험 수업을 위한 실제적인 함의를 제공하는 일을 목표로 하였다. 보다 구체적으로, 본 논문은 대학 교수자들이 2020년 봄학기에 팬데믹을 직면하여 어떻게 원격 실험 수업을 실행(implement)하였는지를 합리적으로 설명하고(연구 1), 학생들의 반응을 통해 그 원격 실험 수업의 결과를 조사하며(연구 3), 미래의 대학 원격 실험 수업 설계를 위한 실제적인 지침(guideline)을 제공하고자 하였다. 본 연구의 현장인 한국대학교(가명)의 상황이 이러한 전반적인 연구의 시작과 수행을 가능하게 하였다.

이론적 틀로서, 대학 원격 실험 수업을 실험 수업과 이러닝(e-learning)의 각 요소가 교차하는 지점으로 이해하는 관점을 제안하였다. 우선, 실험 수업 또는 이러닝 수업을 실행하는 이유는 실험 수업의 목적 또는 이러닝의 가능성 및 요구에 놓여 있다. 교수 프로그램의 일종으로서, 실험 수업과 이러닝은 어떻게 내용을 전달하고, 학습자 간 상호작용을 촉진하고, 평가와 피드백을 제공하는지를 고려해야만 한다. 그리고 두 프로그램들에서 이러한 세 요소들은 서로 자연스럽게 대응한다. 2020년의 다양한 대학 원격 실험 수업들은 코로나-19 상황에서 이러한 두 교육적 전통이 만나서, 교호하며, 혼합된(blended) 지점이었다. 또한 2020년의 다양한 대학 원격 실험 수업들의 특성은 사회문화적인 요소를 포함하는 각각의 교수학습 맥락에서 형성되었다. 2020년의 대학 원격 실험 수업 교수자 및 학생들로부터 얻은 교훈은(연구 1 및 2) 본 연구자가 실험 교육을 위하여 확장된 블렌디드(blended) 러닝 이해에 도달하게 하였으며(2.3.4 참조) 대학 원격 실험 수업을 위한 교수 설계(instructional design) 모형의 필요성 역시 제기하였다.

과학교육에서의 실험 수업에 관하여, 실험 수업의 목적과, 핸즈온(hands-on) 및 마인즈온(minds-on) 논쟁과, 실험 보고서 쓰기 및 피드백 방법을 고찰하였다. 이러닝 및 효과적인 교수 전략에 관하여, 이러닝의 전망 및 요구와, 매체(media) 제시와, 온라인 상호작용의 양상과, 이러닝에서의 평가 및 피드백을 숙고하였다. 원격 실험 수업의 (재)창발에 관하여는 코로나-19 이전과 이후의 연구들을 돌아보고, 해당 용어의 의미를 도출하였다. 특별히, 원격 실험 수업을 확장된 블렌디드 러닝으로 이해하는 관점을 제안하였는데, 이는 첫째로 핸즈온 및 마인즈온 실험 경험을 혼합하고 둘째로 실험 경험들과 학습 공간들을 혼합하는 것이었다.

더하여, 과학교육에서의 교수자 행위주체성(agency)을 활용하여 대학의 이공계열 교수자들이 원격 실험 수업을 실행할 때의 적응적인 행동을 해석하였다. 우리나라 과학 교수자들의 행위주체성에 대한 사회문화적 시각은 연구자의 해석의 지평을 거시적(macro-), 중시적(meso-), 그리고 미시적(micro-) 수준의 구조(structure)들로 정교화하였다. 또한, 교육공학 분야에서의 설계 및 개발 연구 관점에 따라 유연하고(flexible) 반복적인(iterative) 교수 설계 모형의 유용성을 제안하였으며, 이는 외적 타당화를 위한 수업 모듈 도출 과정에서의 래피드 프로토타이핑(rapid prototyping)을 포함하는 것이었다.

연구 1에서, 연구자는 한국대학교에서 코로나-19 이전에 서로 비슷하였던 일반 물리학, 화학, 생물학, 지구과학 실험뿐만 아니라 2개의 전공 교과 실험 수업을 비교하였다. 연구자는 대학 원격 실험 수업 현상의 창발을 사회문화적 관점에서 해석하였는데, 이 때 코로나-19 팬데믹과 교육 당국에 의하여 부과된 구조 및 대학 교수자들의 행위주체성에 주목하였다. 거시적 수준의 한국 맥락, 중시적 수준의 한국대학교 맥락, 그리고 미시적 수준의 개별 대학 원격 실험 수업 맥락은 서로 뿐만 아니라 대학 교수자의 행위주체성과도 밀접하게 상호연관되어 있었다. 2020년 봄학기에, 교수자의 행위주체성은 이러한 다층적(multi-level) 구조들에 의하여 모양지어졌다(shaped). 그러나, 개별 교과(discipline)에 따라 실행된 대학 원격 실험 수업은 교수자가 투입한 노력에 따라 상당히 다양하게 되었다. 대학 교수자들의 고려사항은 동영상 자료, 실험 데이터의 특성, 자신들과 학생들 간의 제한된 상호작용, 평가의 어려움, 그리고

학생들이 핸즈온 경험이 없이 원격 실험 수업에서 무엇을 “얻을”(gain) 수 있는가 하는 점이었다. 2020년 가을학기부터 대학 교수자들은 상황에 적응하여 자신들의 원격 실험 수업을 개선하였으며, 더 많은 개선점들을 제안하였다. 연구 1의 결과는 대학 교수자의 행위주체성이 임박한 긴급 상황에서 다양한 원격 실험 수업 실행이 창발하는 결과를 낳았음을 보여준다.

연구 2는 연구 1과 발맞추어 한국대학교에서 수행되었다. 연구자는 대학생들이 서로 다른 교과의 다양한 원격 실험 수업 경험을 어떻게 인식하였는지를 조사하였다. 연구 2는 혼합 연구로서, 338명의 학생들로부터 온라인 설문 응답을 얻었으며 18명의 학생들과 인터뷰를 실시하였다. 분산분석(ANOVA)과 Bonferroni 사후 검정을 통해 원격 실험 수업 경험에 대한 학생들의 인식이 교과(물리, 화학, 생물, 지구과학, 다른 전공 과목)에 따라 통계적으로 유의미하게 다르다는 점을 발견하였다(p < .05). 더하여, 학생 인터뷰는 이러한 차이들이 개별 교과목에서 창발한 교수 전략에 의하여 발생하였음을 드러내었다. 향후의 효과적인 원격 실험 수업을 위한 전략으로서, 수업의 목적을 명확히 설정하기, 실험 동영상을 세심하게 설계하기, 동시적(synchronous) 온라인 협력 세션 제공하기, 실험 보고서 작성에 대한 피드백을 제공하고 보충적 평가를 실시하기 등을 제안하였다.

연구 3에서 연구자는 대학 원격 실험 수업을 위한 블렌디드 실험 및 이러닝 교수 설계(Blended Laboratory and E-learning iNstructional Design, BLEND) 모형을 개발하고 타당화하였다. 팬데믹에 의하여 요동하는 교수 환경에 대응하기 위해, 연구자는 교수 설계 모형을 신속하게 구축하여 실제적 학습 맥락에 적용하고, 참여자의 피드백을 통한 반복적(iterative) 모형 수정을 시도하였다. 연구 맥락은 예비 화학 교사들을 위한 분석화학실험 강좌였다. 초기 BLEND 모형은 문헌 리뷰 및 2020년의 연구 1과 연구 2의 교훈에 기반하여 도출되었다. 내적(internal) 타당화를 위해 6명의 이해당사자(stakeholder)가 사용성 평가(usability test)에 참여하였으며, 다양한 과학 교과 배경의 10명의 내용 전문가와 3명의 교육공학 전문가가 전문가 리뷰를 제공하였다. 외적(external) 타당화를 위해 해당 시기의 교수 설계 모형을 기반으로 대학 원격

실험 수업 모듈이 개발 및 실행되었고, 해당 강좌를 수강하는 7명의 대학생들이 온라인 설문 및 후속 인터뷰에 참여하였다. 2회기의 타당화 과정을 거쳐, BLEND 모형은 내적으로 효율적이며(efficient) 외적으로 효과적(effective)인 것으로 타당화되었다. 이 때 교수자 및 학생 간의 높은 상호작용이 특별히 주목되었다. 대학 원격 실험 수업을 위한 최종 BLEND 모형은 지속적인 형성 평가와 피드백을 중시하며, 주별 그리고 강좌별 수준에서의 원격 실험 수업 교수 체제를 구조화하고 시각화하였다. 연구 3은 과학교육에서 설계 및 개발 연구 방법을 적용한 드문 사례이다.

본 연구에서 모두 해결되지 않고 여전히 후속 연구를 요구하는 쟁점들은 다음과 같다: (1) 원격 실험 형식이 요구하는 바와 각각의 과학 과목(물리, 화학, 생물, 지구과학 등)의 특성 사이의 상호작용이 더 자세히 고찰되어야 한다. (2) 실험 동영상을 어떻게 설계하고, 촬영하며, 편집해야 하는지의 문제가 여전히 중요하다. (3) 개방형(open-ended) 탐구 실험 수업을 위한 교수 설계 모형이 향후의 중요한 연구 주제이다. 이 경우, 개방형 탐구 수업 프로그램을 어떻게 평가할 것인지 역시 반드시 먼저 해결되어야 할 연구 주제가 될 것이다.

본 연구의 강점은 2020년 및 2021년의 한국대학교라는 연구 현장의 독특성에 기인한다. 본 연구는 코로나-19 초기 상황에서 창발한 원격 실험 수업에 관하여 상당히 많은 데이터를 수집한 연구 사례로 보인다. 그러므로, 연구 1에서 연구 3에 이르는 작업은 코로나-19의 초기 단계에서 나타난 원격 실험 수업 현상을 포괄적으로 보고하려는 시도라고 할 수 있다. 하지만 역설적으로. 본 연구의 강점을 만들었던 코로나-19 상황은 시간이 지나고 상황이 변화함에 따라 양날의 검으로 작용할 수 있다. 결과적으로, 포스트-코로나-19 시대에 원격 수업, 특히 원격 실험 수업의 지위가 어떠할지를 예상하기란 쉽지 않다.

만약 우리가 낙관적인 시선을 취한다면, 대학 원격 실험 수업에 대한 우리의 경험은 실험 교육에 대한 우리의 상상을 확장시켜, 시간과 공간을 넘나들며 다양한 학습 양상을 통합하는 블렌디드형식을 향해 전진하게 할 것이다. 실제로, 실험 교육을 위해 확장된 블렌디드 러닝 이해는 핸즈온 대 마인즈온, 동시적 대 비동시적, 현장 대 원격 등의 오랜 이분법을 넘어 더 나은 실험 교육으로 나아

가는 길을 비춘 면이 있다.

이와는 반대로, 만약 우리가 비관적인 시선을 취한다면, 원격 실험 수업에 대한 우리의 심각한 고찰 역시 언젠가 사라질 수 있으며, 이는 교육사에서 많은 교수 방법들이 그러했던 것과 마찬가지이다. 그러므로, 상기하였듯 코로나-19로 인하여 우리가 경험한 원격 실험 수업을 통해 재발견된 실험 수업의 본질에 관한 근본적인 질문들(문 1-5)에 답하는 일이 요청된다. 여기서 이러한 질문들에 답하는 가장 편리한 방법은 각 실험 수업에서 정하는 학습 목표의 특수성에 의존하는 것이겠지만, 이러한 단순한 해결책은 포스트-코로나-19 실험 교육을 위한 더 심화된 고찰로 나아가는 길을 열어줄 수 없다.

그러므로, 위에서 제기된 5가지의 질문들에 대해 본 연구의 참여자들의 목소리로부터 보다 구체적인 답을 해보는 일이 의미 있을 것이다: (답 1) 학생들이 실험 기능(skill)을 함양할 뿐만 아니라 예상하지 못했던 현상과 함께 암묵적 지식(tacit knowledge) 및 과학의 본성(nature of science)을 직면할 기회를 제공하기 위하여, 학생들에게 최소불가결의 핸즈온 경험을 제공해야 한다. 블렌디드 러닝 형식은 핸즈온 경험과 마인즈온 경험을 모두 갖게 하는 대안이 될 수 있다. (답 2) 교수자와 학생들은 시간적인 측면에서는 반드시 동시적 상호작용을 해야만 한다. 다만, 그 들이 공간적으로 함께 있는 일이 필수적인지는 명확하지 않다. (답 3) 만약 가능하다면, 학기 단위의 개방형 실험 수업을 진행하는 것이 학생들을 깊이 있는 탐구적 사고로 초대하는 가장 좋은 기회가 될 것이다. 하지만, 현실적으로 요리책(cookbook) 형식의 실험 수업들에서는 이론적 예측과 실제 실험 데이터 사이의 간극만이 탐구가 일어나게 되는 유일한 지점일 수 있다. 그러므로, 예비실험(pre-lab) 활동, 데이터 특성, 동료 토론(discussion)이 주의 깊게 설계되어야 한다. (답 4) 만약 실험 수업 현장을 둘러싼 문화가 인지적 경로로서의 손(hand) 또는 마음(mind)을 강조하거나, 교수자와 학생 간의 상호작용을 수직적으로 또는 수평적으로 만든다면, 그렇다고 할 수 있다. (답 5) 교수 체제에 대한 형성 평가라는 개념이 실험 수업을 더 적응적이고(adaptive) 유연하게 만드는 방법일 수 있는데, 이것은 연구 3에서 개발된 BLEND 모형에서 잘 드러난다.

2020년 한국대학교의 교수자와 학습자들은 대학 원격 실험 수업을 실행하고 수강하기 위해 노력한 진정한 행위자들(agents)이었다. 그리고 그들이 남긴 교훈이야말로 포스트-코로나-19 실험 수업을 향하는 BLEND 모형의 개발 및 실험 수업의 본질에 관한 고찰을 가능하게 하였다.

주요어: 원격 실험 수업, 대학 과학 교육, 이러닝, 교사 행위주체성, 설계 및 개발 연구, 코로나-19
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