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Enhancing 360° virtual laboratory safety training with linear learning pathway design: Insights from student experiences

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ABSTRACT

This paper investigates the role of learning pathway design in a web-based 360° virtual laboratory safety training. A linearly structured virtual laboratory safety training was designed and implemented. Student experiences with the linear learning pathway were compared with a previously implemented non-linear learning pathway. In the linear pathway, students complete the virtual laboratory tour in a predetermined order, while in a non-linear pathway the students can complete the virtual laboratory tour in any order. Student feedback was collected from over 900 students and the experiences from the linearly structured virtual laboratory were highly positive. Compared to the previously implemented non-linear learning pathway, the student feedback related to the learning experience improved significantly. The feedback also showed a difference between preferred learning styles, highlighting the importance of choosing the learning pathway based on the intended learning outcomes and offering different types of learning materials for different learners. Overall, the findings of this study indicate that the linearly structured virtual laboratory offers an effective and motivating learning environment for laboratory safety training.

1. Introduction

Laboratory safety training is an essential aspect of good laboratory culture. Well-planned safety training enables students to work safely in the laboratories and to avoid accidents that could cause injury or even death (Srinivasan et al., 2022). Traditional training methods, such as lectures, printed materials, and slidesets often provide limited interactivity and connection to practical aspects, leading in narrow or limited understanding of laboratory safety (Srinivasan et al., 2022). To address this limitation, virtual laboratories have emerged as an increasingly popular alternative training method, partly due to the general increase of online teaching methods (Levonis et al., 2021; De Jong et al., 2013; Glassey and Magalhães, 2020; Udugama et al., 2023; Shah et al., 2021).

Virtual laboratories provide a risk-free environment for students to learn and practice safety aspects of the laboratory environment at their own pace (Srinivasan et al., 2022; Kumar et al., 2021; Dado et al., 2013). Interactive virtual laboratories also provide students with feedback and self-assessment sections where students are able to reflect on their learning (Viitaharju et al., 2021; Kauppinen and Malmi, 2017). The focus here is on virtual laboratories based on 360° panorama images, accessible with a normal web browser. Such virtual laboratories can be considered as non-immersive virtual reality (VR) environments. 360° virtual laboratories can contain interactive tasks which allow the users to study a variety of materials such as text, images, videos, and interactive quizzes (Guzmán and Joseph, 2021; Potkonjak et al., 2016; De Jong et al., 2013). Users can navigate within the 360° panorama images, thus creating a sense of presence in the laboratory environment (Glassey and Magalhães, 2020; Potkonjak et al., 2016). While the 360° environment is not as immersive as headset-based VR, the benefit of 360° environment is that it can be accessed with a normal laptop or smartphone, not requiring any VR headsets or other special hardware (Srinivasan et al., 2022; Kumar et al., 2021). This makes the 360° environment a scalable solution for courses with hundreds or thousands of students.

A previous study by Viitaharju et al. (2021) presented an interactive, web-based 360° virtual laboratory as a scalable platform for laboratory safety training (Viitaharju et al., 2021). The training was completed by over 500 students, who also provided feedback on the training. Viitaharju *et al.* reported that the virtual laboratory training received positive feedback because students were able to learn about laboratory safety at their own pace, and practice as many times as they wanted with interactive videos and quizzes. However, one of the major criticisms in the

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student feedback was related to the learning pathway structure of the virtual laboratory which might have had a negative impact on their learning experience and motivation.

In the educational literature, a learning pathway refers to a route taken by the learner through a range of learning objectives, which are aimed to enhance students' knowledge or skills in specific subjects or degree programs (Méheut and Psillos, 2004; Scott, 1992). The learning pathway is an important part of the learning process, since it helps the students learn complex topics by building progressively from previously learned simpler topics (Méheut and Psillos, 2004; Scott, 1992; Biggs and Tang, 2007). Furthermore, the proper learning pathway can enhance students' understanding of the content and increase motivation to study (Derichs et al., 2022; Liu et al., 2017; Muhammad et al., 2016). In the literature, learning pathways are considered to be either linear or non-linear (Derichs et al., 2022; Klahr and Nigam, 2004; Chen, 2002).

Non-linear learning pathway refers to a pathway where students can choose the order at which they want to learn the materials (Chalmers and Hunt, 2012; Chen, 2002). Non-linear pathway is flexible, allowing students to design their own journey in the learning environment, and provides more opportunities for exploration and discovery (Chen, 2002). The earlier study by Viitaharju *et al.* (2021) was especially targeting non-linear pathway which allowed the students to explore virtual laboratories and learn the materials at their own pace and order. However, non-linearity can also lead to confusion and disorientation (Chen, 2002; Muhammad et al., 2016). This was also observed in the study by Viitaharju *et al.* (2021), where students could study the laboratory rooms and activities in the virtual environment in any order they wanted. Because of this, some students reported feeling lost in the virtual laboratory and even became frustrated with it. The same criticism has also been observed in another study by Levonis *et al.* (2020), where one of the future improvements was related to re-thinking of the learning pathway.

In a linear learning pathway, students study the learning materials in a certain order (Siren and Tzerpos, 2022; Lawless and Brown, 1997). For example, to learn content B, students need to first learn the content A. Textbooks and videos could be considered as linearly constructed learning pathways because the material is presented in a ordered manner (Robberecht, 2007; Lawless and Brown, 1997). However, learners still have the flexibility to change the sequence of their learning experience by selecting a specific section in the book or timestamp in the video that they want to learn (Lawless and Brown, 1997). The benefits of a linear pathway are that it is time-efficient, the student is able to learn the content in a logical order, and it assures that all learning materials have been presented to the student (Chalmers and Hunt, 2012; Lawless and Brown, 1997; Siren and Tzerpos, 2022). However, developing the content to be presented in a linear and logical structure can be more time-consuming for teachers, and from the students' point of view the linear structure can limit flexibility as they are not able to choose the order in which they want to study (Chalmers and Hunt, 2012; Viitaharju et al., 2023). The advantages and disadvantages of linear and non-linear learning pathways are summarized in Table 1. In addition to books and videos, laboratory experiments could be also considered linear, as they are typically completed in a certain order (Viitaharju et al., 2023). Laboratory experiments in for example analytical chemistry typically need to be implemented as linear virtual laboratories while for topics such as laboratory safety training, there is more flexibility for the design of the learning pathway.

In this study, a virtual laboratory safety training with a linear learning pathway is described and the student feedback of the training is analyzed. Thematically, the work builds on a previous study where a virtual laboratory safety training with a non-linear learning pathway was implemented (Viitaharju et al., 2021). The virtual laboratory received positive feedback, but also criticism for the non-linear learning pathway structure. Here, the laboratory safety training with a linear learning pathway was implemented based on a recent study which observed linear learning pathway supporting students' learning in a virtual laboratory exercise (Viitaharju et al., 2023). However, the virtual laboratory described in Viitaharju et al. (2023) is related to a chemistry laboratory experiment, where it is natural to progress step-by-step in a linear fashion. The aim is to investigate how the linearly structured virtual laboratory affects the student's learning experience in the context of laboratory safety where materials could be presented in linear or non-linear learning pathway. In addition, the technical implementation of the virtual laboratory has been improved compared to Viitaharju et al. (2021) and Viitaharju et al. (2023) to make the content-hosting independent from any particular learning management system. The new technical architecture is presented and freely available step-by-step guidelines are offered so that anyone can utilize them to implement their own virtual laboratories.

Table 1
Summary of the advantages and disadvantages of linear and non-linear learning pathways.

	Advantages	Disadvantages
Linear learning pathway	• Easy to understand and follow • Fast and efficient training process • Suitable for handling a large amount of information	• Limits creativity and student initiative • Assumes a uniform progression of students from one level to the next • Takes time to determine the best linear order in the planning phase
Non-linear learning pathway	• Allows students to choose and explore topics that interest them first • Offers flexibility in the planning phase	• Can lead to confusion or disorientation • May take more time to study due to challenges in navigation • More repetition in the learning material may be necessary to establish context for the student.

This paper is structured as follows. First, the methodology section outlines the learning outcomes for the laboratory safety training. Second, a detailed explanation of virtual laboratory design is provided. Third, the Research Design section describes the methods which are used in this study to investigate the effectiveness of the learning pathway in virtual laboratories. Fourth, the Results and Discussion section presents and discusses the data obtained from students. Finally, conclusions are drawn in the last section based on the findings of the study. Overall, this study provides insights into the role of the learning pathway in virtual laboratory safety training.

2. Methodology

The starting point of the study was the student feedback received from a previously implemented non-linear virtual laboratory safety training (Viitaharju et al., 2021). The aim of the study is to enhance student engagement and learning outcomes by implementing a virtual laboratory safety tour with linear learning pathway. The following sections describe details of the learning outcomes, learning design, virtual laboratory design, and research methodology used in the study.

2.1. Learning outcomes

After completing the virtual laboratory safety training, the student will be able to:

1. **Identify** potential safety risks related to the working in laboratory,
2. **Choose** appropriate personal protective equipment and use laboratory safety equipment,
3. **Master** safe and accident preventive working in laboratory,
4. **Determine** appropriate safety measures,
5. **Know** how to act in the case of an accident,
6. **Be more aware** of their own and fellow students' safety,

7. **Handle** laboratory waste in appropriate manner.

The main objective of laboratory safety training is not to memorize all the details, but to develop an understanding of safe laboratory practices and the safety related factors to consider when working in a laboratory environment. By focusing on these objectives, students and other laboratory workers can be better prepared to work safely in the laboratory and promote a culture of safety and responsibility within the laboratory setting (Biggs and Tang, 2007).

2.2. Learning design

The linear learning pathway was chosen based on Wittrock's generative framework model (Wittrock, 1992). Wittrock's model, also known as the "Generative Learning Model," is a theoretical framework that outlines a process for learning that involves four stages: (1) recall of prior knowledge, (2) integrate new information to prior knowledge, (3) link the learned knowledge together, and (4) apply the new information to produce new information. Schematic presentation is shown in Figure 1. This model also has been connected to student motivation and student engagement (Anderman, 2010). Based on this model, the students were able to gain new knowledge and recall prior knowledge in the non-linear virtual laboratory safety training by Viitaharju *et al.* (2021). However, due to lack of linearity in the learning structure, students were not able to integrate the new information and link them together in an efficient way, which disrupted the learning experience. Therefore, by adopting a linear structure, the aim is to improve the integration and organization of information and prior knowledge, which could contribute to better memory encoding and recalling.

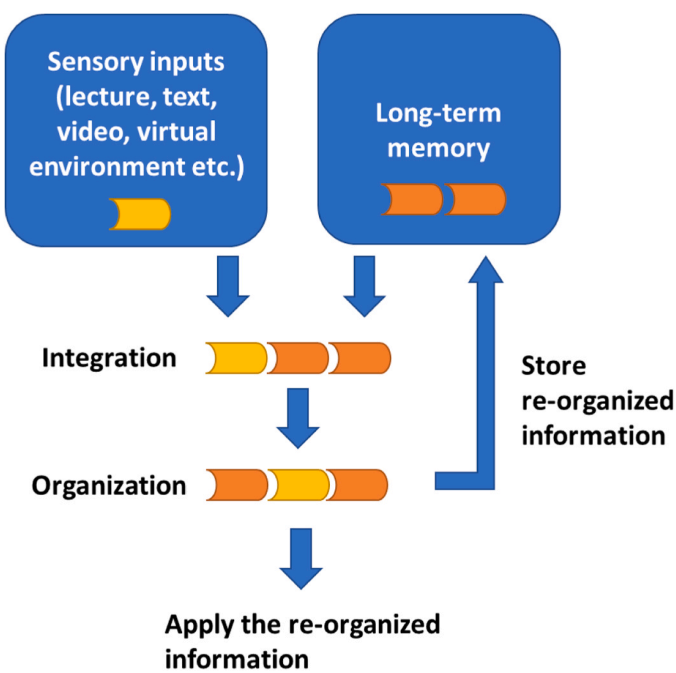


Fig. 1. Schematic presentation of the Wittrock's generative framework model. The model is based on the idea that learners can actively integrate new ideas into their memory to enhance their educational experience. From sensory inputs, the learners receive new information (yellow tile). The learners also recall prior knowledge from their long-term memory (orange tiles). For most successful learning, information is then integrated and organized together, and then either stored to long-term memory or applied. The aim is to enhance the integration and organization of the information, contributing to better long-term memory encoding and recalling by using linear learning pathway model in the virtual laboratory.

3. Virtual laboratory design

3.1. Description of the laboratory safety tour

The virtual laboratory safety training is mandatory for all students who take laboratory courses at the School of Chemical Engineering at Aalto University (Finland),which makes the participant list of the course rather heterogeneous. The training was also offered to students from the University of Eastern Finland. The primary target group is students studying chemical engineering, chemistry, biosciences, and materials science at the BSc and MSc levels. Students majoring in other fields such as electrical engineering or art and design also participate in laboratory-based workshops and multidisciplinary project courses, hence taking this same laboratory safety training.

The general laboratory safety training consists of two parts: virtual laboratory training and a digital exam. Overall architecture of the training is illustrated in Figure 2. The virtual laboratory safety training is composed of five rooms which each contain one larger theme of laboratory safety. Topics were divided among five rooms and chosen based on the safety guidelines of Aalto University and University of Eastern Finland. Topic separation helps students to grasp the overall picture of laboratory safety and understand the safety aspects to consider when working in the laboratory by providing organized and sequential learning path. The virtual laboratory safety training comprises of 235 slides of learning materials, including 13 slides with an interactive video and 23 game/quiz slides. The laboratory rooms are as follows:

1. **Before entering the laboratory:** Covers topics which need to be considered before entering any laboratory. These topics include laboratory clothing, getting familiar with the experiment to be carried out, and health-related aspects (pregnancy, contact lenses etc.).
2. **General safety:** Covers the general safety topics, such as cases of emergency, fire safety, first aid, and different types of washing stations in case of chemical spills.
3. **Chemical safety:** Covers the safety aspects regarding to chemicals, such as safety data sheets, glove types, powders, and gases.
4. **Physical safety:** Covers the physical safety aspects, such as different types of radiation, electricity, glassware, and heavy machinery.
5. **Waste management:** Covers the safety aspects related to waste management and what needs to be done before leaving the laboratory.

The order of the learning pathway has been designed to reflect an actual laboratory teaching scenario. The order has been designed by the responsible teachers of the laboratory safety courses, who have many years of teaching experience in this field. An example view of the virtual laboratory training is shown in Figure 3. Compared to a previous virtual laboratory with a non-linear learning pathway (Viitaharju et al., 2021), activities will appear to students step-by-step (after completing activity A, activity B will appear and so on). This helps the students to navigate in the virtual laboratory and helps them to comprehend the learning materials by building the knowledge incrementally. This way of learning is supported by Wittrock's model, as the student receives new information and is able to connect it to their prior knowledge (Wittrock, 1992). However, a disadvantage of the linear pathway is that it limits exploration and creativity, which could inhibit person's own learning strategies to connect new information to prior knowledge (Wittrock, 1992). Hence, investigating effectiveness of learning is crucial to find the right balance between connecting to prior knowledge and promoting creativity in education. Once all the activities in one room have been opened and studied, an arrow will appear which takes the user to the next room. During the training, students may revisit previous activities and previous rooms at any time. Instructions on how to move in and use the virtual environment are also provided to the students.

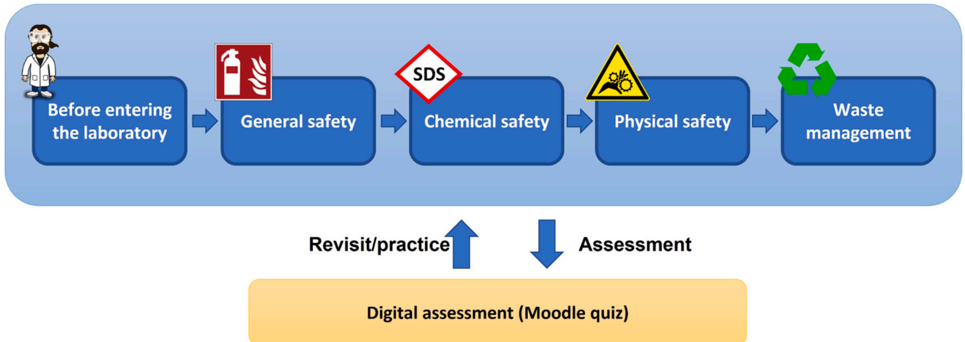


Fig. 2. Overall architecture of the laboratory safety training composed of five 360° virtual rooms. Each room is dedicated to a specific theme related to one of the aspects of laboratory safety: What to do before entering the laboratory, General safety, Chemical safety, Physical safety, and Waste management. Each room contains various multimedia resources, such as videos, self-assessment quizzes, pictures, and text. By dividing the topics into these five themes, students can gain a better understanding of the safety aspects in a logical order and comprehend the materials easier by building knowledge little by little.

3.2. Technical design process

The virtual laboratory was designed in rather similar way as the virtual laboratory by Viitaharju *et al.* (2021), but some technical details have been improved for better scalability and technical robustness. Overall architecture of virtual laboratory safety tour is illustrated in Figure 4. The virtual laboratory is based on 360° panorama pictures which have been taken from actual teaching laboratories. The virtual environment has been created using 3DVista software (https://www.3dvista.com/). From 3DVista, the virtual environment can be exported as a collection of HTML5 and JavaScript source fíles that can be uploaded to any web server that can be accessed with a web browser. The virtual environment is compatible both with desktop and mobile devices, as long as the device supports HTML5 and JavaScript.

The activities inside the panorama pictures are created using free and open-source H5P framework (https://h5p.org/) and LUMI program (https://app.lumi.education/). Compared to the previous implementation by Viitaharju *et al.* (2021), the H5P activities of the 360° virtual lab are now independently hosted as static webpages instead of being embedded in Moodle or other Learning Management System (LMS) (as an example: Welcome H5P activity point https://lab.aalto.fi/safety/en/h5p/published/3000/). The activities are presented as slide sets and can include interactive videos, quizzes, text, and pictures (Figure 5). Activities are also exported as a collection of HTML5 and JavaScript source fíles that can be uploaded to any web server that can be accessed with a web browser. They are then embedded in the virtual environment created with 3DVista. This approach allows us to have more control over the virtual environment and enables anyone to use the virtual laboratory safety training without needing to use Moodle system. Step-by-step instructions for building virtual laboratories and implementing H5P activities on a static web server are provided openly in Aalto Wiki (Girmay, 2023).

After completing the virtual laboratory training, students are assessed with a Moodle-based digital exam. The integration of Moodle-based digital exam is described in more detail in the paper of Viitaharju *et al.* (Viitaharju et al., 2021).

4. Research design

The research design in this study involved the use of a virtual laboratory tour and digital exam, followed by a questionnaire with Likert-scale and open feedback questions. The purpose of the study was to explore the effectiveness of virtual laboratories as a means of enhancing students' learning experiences. The Likert-scale questions were designed to measure participants' attitudes towards the virtual tour and exam, while the open feedback questions allowed participants to provide additional comments and feedback on their experience. The used questionnaires are included as Supplementary material.

Ethical considerations: The research was conducted according to the ethical guidelines of Aalto University. The responses to the questionnaire were fully anonymous and no personal data was collected for the purposes of this study. Responding to the research questions was voluntary. Opting out of the questionnaire did not affect the intended learning outcomes of the course. The questionnaire was completed in the official Aalto University Moodle learning management system. The questionnaire data was analyzed by the first author of this study who was not part of the course staff.

5. Results and discussion

A total of 1005 students participated in the course. The feedback questionnaire was integrated into same Moodle platform as the exam to create a more accessible user experience. To avoid data duplication, the data analysis included only one feedback for each student if they completed the exam and questionnaire multiple times (the feedback from the exam completed with the highest grade was included). Since giving feedback was voluntary, the study omitted students who chose not to give feedback. Furthermore, only fully completed questionnaires were taken into account. Based on these criteria, responses from 942 students were included in the final analysis. The questions presented to the students are introduced in Supplementary material. The six statements or questions, and the distribution of answers in the student feedback are presented in Figure 6 and Table 2.

5.1. Previous learning experience

Students were asked about their prior experiences of virtual learning materials and virtual laboratories to determine their familiarity with both topics. Responses are presented in Figure 6. According to the responses from 942 students, 81% had no previous experience with virtual laboratories, while 18% had previous experience. This result indicates that virtual laboratories are still a relatively novel learning environment, and most students have not encountered them before. This lack of prior experience with virtual laboratories can affect students' learning experiences.

The lack of prior experience with virtual laboratories could increase students' cognitive load, requiring them to become familiar with the platform before studying the context (Sweller et al., 2011). Also, according to Wittrock's learning model, when learners have no prior experience with a particular learning material, they may struggle to integrate information obtained from this new type of material into their existing mental frameworks which could make virtual laboratory a slightly more negative experience (Wittrock, 1992). These findings highlight the potential challenges that learners may face when

Fig. 3. An example view of the virtual laboratory safety training. The training is designed to be linear, meaning that activities will appear in a predetermined order. **a)** In this view, only one activity (indicated by a blue icon) is visible at first. **b)** The user can click on the icon and H5P activity appears containing either text, pictures, videos or quizzes. Once they have completed the activity, they can close it by clicking the close icon. **c)** After the activity is closed, the next blue activity icon appears. **d)** After all activities in the room are completed, a blue arrow will appear, allowing the user to move to the next room. The user can also revisit previous activities and rooms from the bottom panel at any time during the training.

encountering new and unfamiliar ways of presenting information (for example, interactive videos, different types of quizzes, 360° environment).

However, if students have prior experience with some learning materials in the new learning environment (virtual laboratory environment), integration to the new setup could have a lower impact on the cognitive load (Wittrock, 1992; Mayer and Moreno, 2003). This effect has been seen in a previous study by Anderman *et al.* (2010), which found students to be less impacted by cognitive load and feeling more motivated towards the learning materials when they had prior knowledge with some of the learning materials in the environment (Anderman, 2010). Based on this, if there are familiar learning materials present, virtual laboratories could be then seen as a new and fresh learning experience compared to traditional learning methods such as lectures or textbooks (Van Merriënboer and Sweller, 2005; Choi et al., 2014).

According to the questionnaire responses about the familiarity of interactive learning materials, 62% of respondents had previous experience with interactive learning materials. These results suggest that students are familiar with some of the learning materials used in the virtual laboratory, which could potentially decrease cognitive load and increase motivation as previously described (Mayer and Moreno, 2003; Van Merriënboer and Sweller, 2005). Furthermore, in the open feedback section, discussed in more detail below, several students described the virtual laboratory as a new and fresh experience, while only a couple mentioned some difficulties. This supports the hypothesis that the increased cognitive load associated with a new learning platform did not negatively affect the overall learning experience.

Overall, these findings suggest that while lack of experience with virtual laboratories can increase cognitive load, students' prior experience with some learning materials in the new learning environment can make virtual laboratories a positive learning experience. Therefore, educators should be mindful of students' prior experiences and provide appropriate support to help them integrate virtual learning materials effectively into their learning processes. By doing so, educators can create a more positive and effective learning experience for students.

5.2. Students' learning experiences

The students were asked about their experiences with the virtual laboratory and digital exam. Results are summarized in Table 2. According to the questionnaire responses on the virtual laboratory learning experience and the digital exam ($N = 942$), over 95% of respondents considered virtual laboratories to be a beneficial learning platform for laboratory safety and over 90% considered digital exams as a suitable assessment method for the topic. Results show further improvement compared to the paper of Viitaharju *et al.* (2021) where 72% of students considered virtual laboratories to be a good learning environment for laboratory safety and 77% considered a digital exam to be a good assessment method. These results suggest that students were highly satisfied with the virtual laboratory and digital exam and they considered both as good approaches to learn about laboratory safety.

Statistical significant association between the students' learning experience from the virtual laboratory or the digital exam and their previous virtual laboratory experience was investigated. Pearson's chi-squared test was utilized and no statistically significant association between the variables was found ($p > 0.05$).

At the end of the questionnaire, open feedback question was presented to map different ways of improving the virtual laboratory in terms of technical functionalities, learning outcomes, and student motivation. The question was formulated as follows: "(voluntary) Here you can write your feedback regarding the course, positive or negative. We greatly appreciate all feedback as it allows us to improve the course!". In Table 3, the most frequent comments were categorized. Three major themes occurred multiple times in the open feedback:

> Majority of students enjoyed that learning was done in an ordered way and teaching was done by adding new information little by little. As seen also in Table 2, majority of students considered the virtual laboratory tour to be clear and logical. These results align well with Sweller's cognitive load theory, which states that learners retain information better when it is presented in a manageable and organized manner (Sweller et al., 2011). When information is provided in an organized manner, students are able to focus more on the content

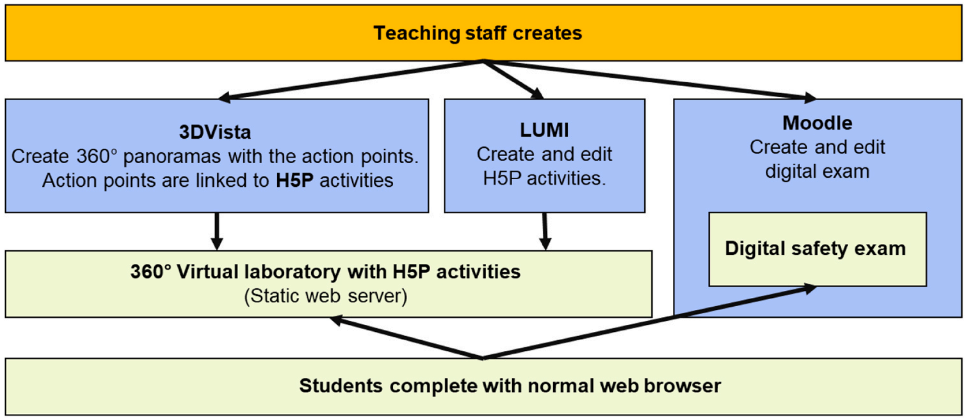


Fig. 4. Overall technical architecture of the virtual laboratory safety training environment. Details are described in the text. Step-by-step instructions to create and edit virtual laboratory environments are openly available in Aalto Wiki (Girmay, 2023).

rather than constructing a logical and connected presentation (Mayer and Moreno, 2003; Sweller et al., 2011). Logical order also has been shown to prove connectivity between topics, which was also mentioned by some students in the open feedback.

Students reported that they felt more motivated, engaged, and interested when videos and presentations included questions which students needed to answer before continuing. This is because interactive content increases active learning and challenges students to think critically and apply their knowledge. This approach also aligns with the behaviorism theory which state that interactivity increases the student motivation, enhances understanding, promotes retention and support more diverse learning styles for individuals who prefer hands-on activities (Dembo et al., 2007; Mayer, 2005; Bransford et al., 2000). Feedback also aligns with previous paper by Levonis *et al.* (2020), where students considered interactivity one of the main benefits of 360° virtual laboratory (Levonis et al., 2021).

One of the main problems that several students raised was the inability to save the current progress and continue later when they felt like it. The saving feature in a virtual laboratory presents a challenge in terms of managing user data. Saving option would require student to create a user account where progress can be saved and retrieved. This would increase the workload on the web server, and maintaining the data would become more challenging. One method to resolve this problem is to split virtual laboratory tour into several pieces and have a separate exam for each subtopic. However, this could affect the immersiveness of virtual environment (Jerald, 2015; Sherman and Craig, 2018). The degree of impact would depend on factors such as the size and layout of the virtual environment, the quality of the transitions between sections, and the activities taking place in each section (Jerald, 2015; Sherman and Craig, 2018). In some cases, splitting a virtual environment could enhance immersiveness by allowing for more detailed and focused experiences in each section (Jerald, 2015; Sherman and Craig, 2018). However, in other cases, it could detract from immersiveness by creating artificial barriers or disrupting the flow of the overall experience (Jerald, 2015; Sherman and Craig, 2018). Further studies are needed to investigate, how the splitting would affect the learning experience. In any case, the current implementation of virtual laboratory can simply be left open in a web browser and continued at any time, if the browser is not closed in the meantime.

5.3. Student experiences on the learning design

The aim of the study was to investigate the preferences of students with respect to linear or non-linear learning pathways. Students were first provided with a linear version of the learning pathway and then given the option to use a non-linear version during the digital exam if they preferred it. Students can revisit either linear or non-linear version of virtual laboratory while taking the digital exam. Hypothesis was that students would prefer the structured and organized format of the linear learning pathway, as it would make their learning process easier.

In regards to the choice between linear and non-linear learning pathways, over 46% of respondents expressed a preference for the linear option while 25% of respondents preferred non-linear version. These findings suggest that significant proportion of students prefer when materials are presented in a linear and logical order. This was further supported by open feedback, where most commented feature was the clarity and logical structure of the virtual laboratory (See Table 3). However, response distribution was more mixed, with 28% of the participants providing a neutral response.

The statistical significant association between students' learning pathway preference and their previous virtual laboratory experience was also investigated. By using Pearson's chi-squared test, a statistically significant association between these two variables was found ($p < 0.05$). The relation between learning pathway preference and previous virtual laboratory experience is visualized in Figure S1 in the Supporting information and the data are available in Table S1. The analysis revealed that students who had previously experienced a virtual laboratory more than five times tended to prefer the non-linear virtual laboratory version. However, it needs to be noted that the number of students in this category was small ($N = 9$), in contrast to the larger group sizes in other categories ($N \geq 45$). Further research with a more balanced distribution of participants across different backgrounds is needed to validate and generalize these preliminary results.

For a more detailed comparison between different learning pathway designs, a between-groups experiment would be a more rigorous research design. In such experiments, groups are divided equally into two groups, where one group completes a linear virtual laboratory and other group completes a non-linear virtual laboratory. However, a similar research design could not be utilized here as the laboratory safety course is mandatory for all new students before they gain access to student laboratories, and equal learning opportunities for students with different learning preferences had to be provided. It was also considered that a between-groups research design could adversely affect the learning process amongst the students in a topic that is critical for laboratory safety and their future studies.

While another possible metric could be to investigate the statistical significance between received exam grades and learning pathway preferences, any grades were not included in the analysis. The students were allowed to retake the digital exam and improve their grades, introducing

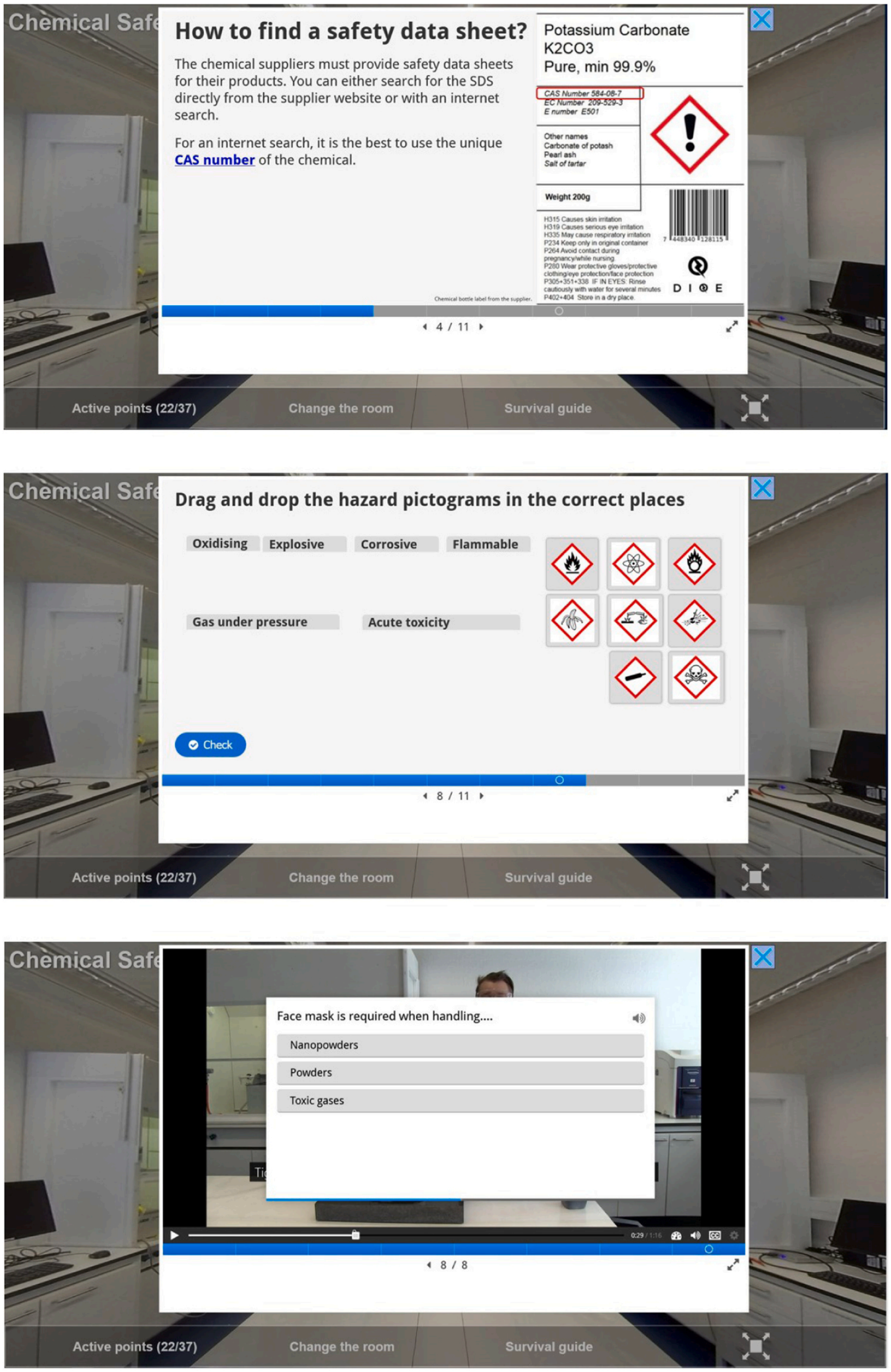


Fig. 5. Examples of H5P activities found in the virtual laboratory safety training. The H5P activities are presented as interactive slide sets that provide the possibility to add different materials such as text, games/quizzes and interactive videos.

a potential bias in data selection. Some students pursued the highest possible grade through multiple attempts, while others were satisfied with their initial passing grade.

These results highlight the differences in learning methods, as some students prefer structured materials, while others prefer more exploratory approaches to learning. Differences between learning styles has also been highlighted by the paper of Seifan *et al.* (2020), where they implemented virtual laboratory as part of laboratory course (Seifan et al., 2020). This is in line with the learning style theory, which suggests that individuals have their own unique learning styles and preferences (Terry, 2001; Romanelli et al., 2009; Phavadee, 2022). It is important for educators to recognize this diversity and provide a variety of learning materials and formats to meet the needs of all students. This can be done by incorporating different teaching methods, such as videos, group discussions, more descriptive pictures, and self-assessment quizzes into virtual laboratory platform.

Furthermore, when designing a virtual laboratory, educators should also consider the desired learning outcomes with respect to the pros and

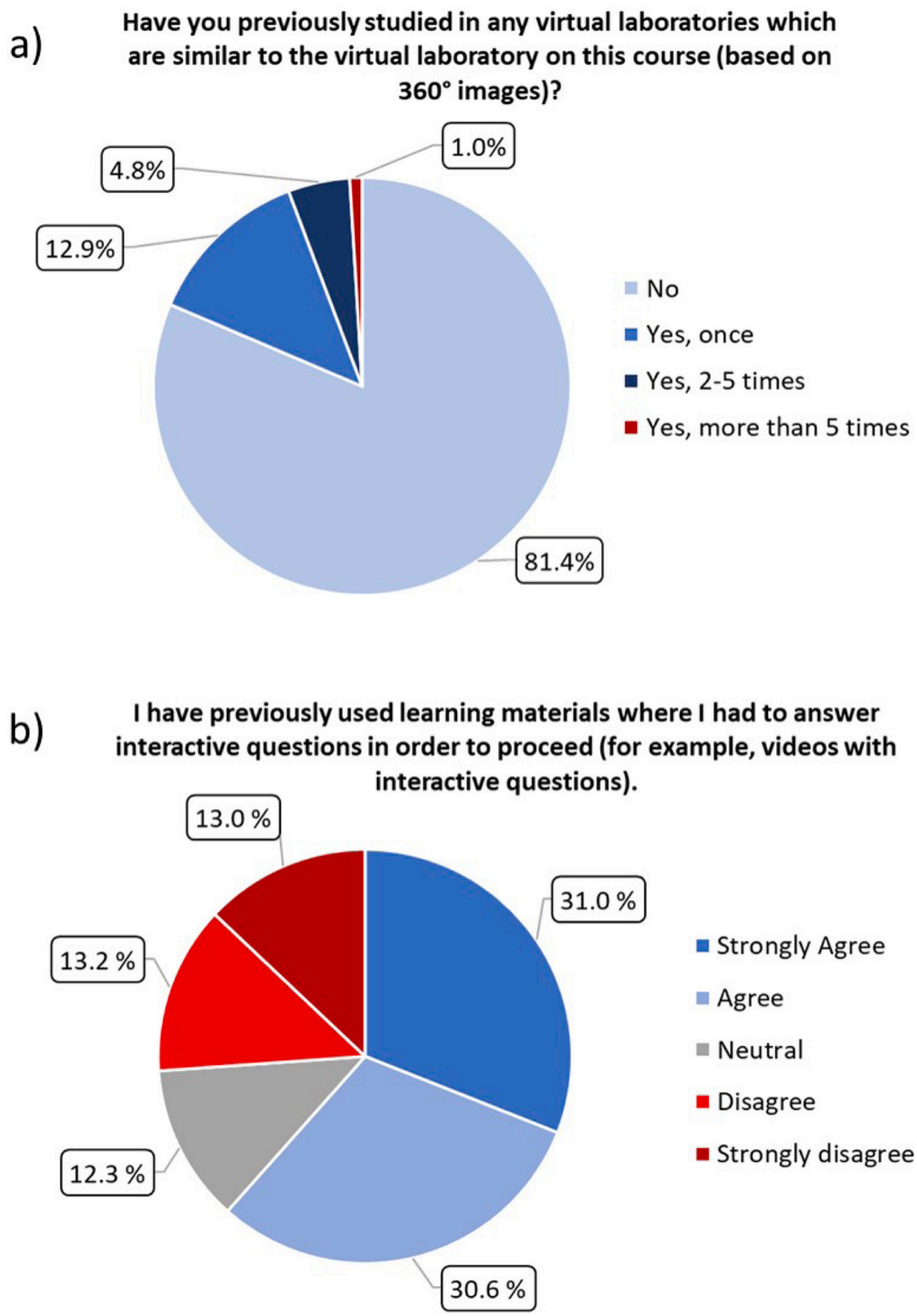


Fig. 6. Previous learning experience responses from the students ($N = 942$). Students were asked about their previous experience related to a) virtual laboratories or b) interactive learning materials.

cons of the learning pathways. For instance, if the desired learning outcomes encourage students to explore the laboratory environment extensively, a non-linear pathway may prove to be more advantageous. In the study of Derichs et al. (2022), they implemented two non-linear virtual environments for students to explore freely. The first one was a university-level business course to encourage students to explore the local microbrewery as a business case. The second environment was a non-linear virtual laboratory for a Swedish language course, where the purpose is to learn Swedish names of the items found in a chemical laboratory. They found both implementations to have high levels of student engagement as well as improvement in learning outcomes. These findings highlight the importance of aligning the learning pathway type with the desired learning outcomes. For exploration-type learning, a non-linear learning pathway can offer various approaches to learn and find solutions. However, if there is a risk that the students become confused or disoriented in the virtual environment, as found in the case of Viitaharju et al. (2021) and Levonis et al. (2021), a more structured or even linear learning pathway can a more suitable option.

In addition to considering the design of the virtual laboratory, educators also need to think about the assessment methods used to evaluate learning. The results showed that multiple choice exam was considered a good method to evaluate the learning (See Table 2). However, assessment methods need to be chosen based on the type of virtual laboratory and there are currently limited number of assessment methods which

Table 2
Likert-scale statements and responses from the students ($N = 942$). According to the questionnaire responses on the virtual laboratory learning experience and the digital exam, over 95% of respondents considered virtual laboratories to be a beneficial learning platform for laboratory safety and over 90% considered digital exams as a meaningful assessment method of the topic. The results suggest that students were highly satisfied with virtual laboratory and digital exam and they considered both as good learning methods regarding to laboratory safety.

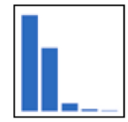
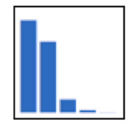
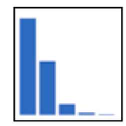
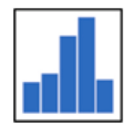
Statement	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Column chart	Mode
I think that a virtual laboratory tour is a good way to learn about laboratory safety.	57.2%	37.5%	3.7%	1.3%	0.3%		Strongly agree
I think that this kind of digital exam is a good way to assess learning on this course.	52.2%	40.4%	5.9%	1.2%	0.2%		Strongly agree
I think that the virtual laboratory tour proceeded clearly and logically.	60.2%	32.4%	6.2%	1%	0.3%		Strongly agree
I would rather explore the virtual laboratory completely freely instead of following a linear, predetermined path.	11.1%	14.2%	28%	34.7%	12%		Disagree

Table 3
Most frequent open question feedbacks given by students ($N = 942$).

Categorized response	Amount of responses
Easy to understand / Logical / Clearly structured	**40**
Videos were good/fun/nice	**33**
Possibility to save the progress in the virtual laboratory needed	**16**
Virtual laboratory was fun/humorous	**13**
Interactivity	**11**
Refreshing experience compared to traditional learning materials (such as lectures or books)	**8**

have been used to evaluate learning as well as learning experience (Chalmers and Hunt, 2012; Chan et al., 2021; Seifan et al., 2020). Therefore, further investigation needs to be done to inspect other assessment methods that allow students to demonstrate their learning. By exploring alternative assessment methods such as practical assessments or written assignments, students' learning and understanding of laboratory safety can be better evaluated. This will not only improve the accuracy of assessments but also help to identify areas of improvement in the virtual laboratory design (Biggs and Tang, 2007; Chalmers and Hunt, 2012).

Accessibility is another crucial aspect to consider when designing virtual laboratories. This aspect has been highlighted in previous study where the number of students was smaller but there was feedback related to accessibility (Jeffery et al., 2022). It is vital to design the virtual laboratory environment with accessibility in mind, incorporating features such as closed captioning, audio descriptions, and keyboard navigation, to ensure individuals with different abilities or disabilities can engage with the material and achieve the learning objectives. Although 3DVista and H5P are not fully accessible currently, the aim is to improve virtual laboratory accessibility in future versions by providing alternative learning materials such as text with audio description into the training.

Overall, by recognizing and addressing the diversity of learning styles and needs, educators can help to create a more engaging and effective learning experience for all students. This can lead to improved laboratory practices and safer working environment, better academic outcomes, as well as greater sense of satisfaction and achievement amongst learners.

6. Conclusion

As hypothesized, the implementation of a virtual laboratory with linear learning pathway received more positive feedback from students compared to non-linear learning pathway. Based on students feedback and literature, the interactivity and clear structure of virtual laboratory were major contributing factors to increased student motivation and engagement for learning laboratory safety. While significant proportion of respondents preferred linear pathway over non-linear version, there was still variation in their preferences. The results highlight the importance of providing a variety of learning materials by incorporating videos, text, images and self-assessment quizzes and aligning the learning pathway type with the desired learning outcomes of the virtual laboratory.

Alongside variability, accessibility is another crucial aspect to consider when developing virtual laboratories. Making virtual laboratories accessible to everyone is essential to ensure that virtual laboratory is more inclusive learning environment for all students. In future versions, the aim is to improve virtual laboratory accessibility by providing alternative learning materials such as text with audio description into the training. Enhancing accessibility in virtual laboratories is crucial to promoting inclusive education and ensuring that all students have the opportunity to succeed.

Overall, the positive feedback from students highlights the effectiveness of the linear learning pathway design of the virtual laboratory in promoting motivation, engagement, and understanding of laboratory safety. However, the study also opened new questions that need to be investigated to improve the design further. Therefore, future studies will focus on enhancing the design of the virtual laboratory as well as design of the learning assessment. By continuing to improve both designs, more effective, inclusive, and engaging learning experiences can be provided for the students.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ece.2024.02.002. The virtual laboratory safety training described in the paper is openly available at https://lab.aalto.fi/.

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