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## **Virtual Laboratories as Preparation to a Practical Laboratory Course at the Example of Genetics**

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### **ABSTRACT**

A virtual laboratory is an abstraction of a real laboratory and allows for executing experiments in a computer-based simulation. Goal of virtual laboratories is to train the student's procedural knowledge that is needed for conducting experiments in a real laboratory environment. Students can train themselves comfortably in a secure environment using the computer and without wasting precious resources such as substances and devices. Different aspects of virtual laboratories in the field of genetics have been evaluated in the past. However, to the best of our knowledge there is so far no evaluation carried out that is investigating the impact of training with a virtual laboratory to the real-world laboratory course. In order to address this gap, we have conducted a comparative study using the photo-realistic virtual laboratory GenLab for genetics and genetic engineering. While one group of students (n=18) did receive a training using GenLab prior to real-world laboratory experimentation, the others did not (n=14). We recorded the students' own assessment of the experiments complexity and comprehensibility. For two experiments, we recorded more detailed information as they were trained using GenLab in the treatment group. In addition, we measured the time needed by the students for conducting experiments in a real laboratory course. The results show that there are some significant differences for the more complex experiment tasks, while this was not observed for the less complex ones. The differences might be explained by the amount of repetitive and rather simpler tasks versus some other tasks that are also repetitive but require higher concentration in order to avoid mistakes. Furthermore, the more complex experiment was reproduced more closely in the virtual lab. This indicates that procedural knowledge is best acquired when the experiment can be reenacted virtually step by step. Overall, working with the virtual lab was perceived positively by the students. Hence, its integration within the curriculum of genetics is considered to be beneficial for the students' motivation and their preparedness for the real-world lab.

### **Keywords**

Virtual Laboratories, Summative Evaluation, E-learning, Genetics, Molecular Biological Methods

### **INTRODUCTION**

E-learning has been an important and highly interesting research field over the last decades. Initially called computer-based training, its popularity tremendously increased since e-learning has reached the web. For example, significant media attention is currently drawn to so-called Massive Open Online Courses (MOOC) [Wal13a]. In this paper, we focus on a category of e-learning applications that are called virtual laboratories. A virtual laboratory is an almost photo-realistic depiction of a real laboratory in a computer-based simulation for the purpose of conducting experiments in virtual reality. A concrete example of a virtual laboratory is GenLab [OFF03] for genetics and genetic engineering. GenLab consists of two central components [Sch02]: The seminar room allows the students to gain knowledge about the theoretical foundations of genetic tools just like a traditional computer-based training application. In addition, it provides small, interactive e-learning units that allow for training individual skills such as

using specific laboratory devices. The virtual lab room allows for a highly-interactive and exploratory learning of procedural knowledge in the domain of genetics and genetic engineering. While the students are conducting the experiment, a tutor constantly tracks the experiment progress and provides feedback when the learner makes a mistake. Advantages of virtual laboratories are that the students can train the procedural knowledge arbitrary often. As the experiments are conducted in virtual reality, precious resources like reagents and samples are saved and experimental devices can be explored without risks. In addition, the students are not exposed to any hazards while being in the virtual training phase.

In this paper, we present the design and results of a study investigating if students using GenLab are actually better prepared for the practical course in a real lab. First, we present the related work in the field. Subsequently, we provide a brief introduction into the two experiments considered in this study, namely the agarose gel electrophoresis (AGE) and the polymerase chain reaction (PCR) [SR01]. We describe in more detail the seminar room and experimentation room of GenLab. Subsequently, the design of the study and its results are presented, before we conclude the paper with a discussion.

## **RELATED WORK**

We first introduce the notion of virtual laboratories in biology, with a special emphasis on genetics, and explain its difference to remote laboratories. Subsequently, we elaborate on related studies that investigated different usability aspects of virtual laboratories.

### *Virtual Laboratories vs. Remote Laboratories*

An interesting area of research in e-learning is on so-called virtual laboratories. Virtual laboratories in a narrower sense emulate a real laboratory with high fidelity in which one can move around and actually perform the experiments using virtual equipment and reagents. These allow for repeating practicals without any hazards, costs, or preparations [OFF03, PQN+11, Sch02] before going into a real world lab. An example is LabLife3D providing an immersive environment for conducting virtual experiments in the domains of biotechnology education and chemistry using the proprietary simulation environment Second Life [KOJ+13, PQN+11]. A virtual laboratory for genetics is GenLab [OFF03], which is used as apparatus in our study. GenLab allows for executing different genetic experiments in a computer-based simulation such as AGE and PCR (see also Section “Overview of GenLab”). It is specifically designed as being part of a physical curriculum (*blended learning*) and being used as preparation for a real-world (laboratory) training and experience phase, respectively. VIROLAB simulates a biology laboratory in which the student has access to different rooms with analytical instruments, lab journals, and a library in order to gain knowledge and succeed in multiplying defective viruses [SRD00].

In the literature, virtual laboratories are also understood as online platforms that enable distributed, virtual research. The materials provided online may be videos on laboratory procedures [MHC09, SD09], digitalized specimen such as virtual slides [NGB07] or agarose gels [CMP+06], lab protocols [BSP05, SLM+12], or patient laboratory reports [BFH+11]. Interactivity is achieved by quizzes or decision making along a storyboard flowchart. Another interesting approach is to simulate the process by a mathematical model as done by Gerlach et al. [GBG+14] in order to convey procedural knowledge on recombinant protein production in a bioreactor.

In contrast to virtual laboratories, the term remote laboratory refers to the notion of real laboratories being controlled over the Internet like a robot that may inject various reagents into 100,000 different

Petri dishes via remote control [Wal13b]. In this work, we focus on virtual laboratories and their evaluation.

### *Evaluating Virtual Laboratories*

In the past, different experiments were conducted to evaluate specific aspects of virtual laboratories. While these are relevant and related to our works, there is – to the best of our knowledge – so far no evaluation that measured the impact of using a virtual laboratory for course preparation in a real-world laboratory. In the following we give an overview of different studies which have a certain focus on learning procedures and techniques within the field of genetics, molecular biology, and biotechnology. We present content, aim, and scope as well as the main findings of the evaluation.

The study by Maldarelli et al. [MHC09] investigates the effectiveness of using video material for explaining and demonstrating biology laboratory techniques on the learning outcome in respect to these techniques. The techniques included common skills, e. g., using a micropipette, as well as more specific skills like pouring an agarose gel. A total of 203 students participated in the experiment, from which 171 completed a pre- and post-test survey showing a significant difference regarding the students' perception on knowledge, confidence, and experience with the laboratory techniques before and after viewing the videos. Pre- and post-testing also included techniques which had been actually performed by the students in the real lab without viewing a video. Despite of this, the authors do not further discuss the effectiveness of video demonstrations in comparison to hands-on experience.

A comprehensive study with first year college students was carried out by Swan and O'Donnell [SO09], where the effectiveness of a virtual biology laboratory in botany/plant genetics in scope of an introductory biology course was investigated. A set of ten smaller virtual experiments were offered to the students such as operating a microscope, understanding plant evolution, investigating chromosome structure and meiosis, and others. In contrast to our study, the study by Swan and O'Donnell allowed the college students to freely choose whether or not they wanted to use any of the ten virtual laboratories. The college students were then classified as laboratories users (n=117), if they decided to use at least three virtual laboratories of the ten offered ones, and so-called non-users otherwise (n=666). The experiment was repeated in the following year with 146 users and 113 non-users. The free choice of using a virtual laboratory or not caused a skewed distribution. In addition, the threshold of having used at minimum three virtual laboratories of the ten offered ones seems to be rather arbitrary and low as members of this student group did conduct up to seven experiments not with virtual laboratories. The authors could observe statistical differences between the users of the virtual laboratories and the non-users with respect to hourly exam scores, laboratory practical exam scores, and the final exam scores. However, when users and non-users were matched based on their scores in the first hourly exams, only significant differences were observed in laboratory practical exams on items that were also covered in the virtual lab.

Polly et al. [PMM+14] propose a virtual lab for specific molecular biology methods (SDS-PAGE and Western Blotting) which is part of an undergraduate Pathology course and shall enable students to learn technical and diagnostic skills. The study was conducted with third year science students over three consecutive years. In 2011, n=80 students participated while 2012 there were n=73 and in 2013 the experiment was run with n=59 participants, respectively. The students were divided into two groups where one group was asked to attempt the virtual lab first and the other to complete the real lab. After

one hour the groups swapped having a second hour to work in the other lab environment. The authors found out through questionnaires that the virtual lab was at least equivalent to the real lab w.r.t. the perceived development of concepts, laboratory skills, and diagnosis of disease. While the experiment is similar to ours, it also has strong differences as the students had very limited time and it remains unclear which experimental steps exactly were carried out in the real lab and how much hands-on experience the students actually had. Furthermore, the evaluation was based only on questionnaires and hence the students' own perception.

The study by Gerlach et al. [GBG+14] also focuses very strongly on the acquisition of procedural knowledge. Here the virtual laboratory serves explicitly to train production personnel in the operation of bioreactors and auxiliary equipment. In contrast to our study, not a virtual lab in the narrower sense was used, but a mathematical model which simulates very accurately the growth of the recombinant bacterium and the production of the recombinant protein. Twenty biotechnology students received a two-hours training with this operation training simulator (OTS) whereas five students only prepared by reading written instructions and listening to verbal guidance from the instructor. The performance of the students while doing two cultivations in the real laboratory was evaluated by a standardized observation protocol. According to the authors, the OTS-trained students performed better as they adhered closer to the standard operation procedure, made fewer mistakes, and showed a better understanding of the whole process. The results, however, lack statistical analysis (most likely due to the small number of students in the control group).

In contrast to the studies presented so far, the following studies do not have the primary goal to use virtual labs for gaining procedural skills and to use them as pre-training for real lab practicals. Instead virtual labs are used as an alternative or additionally to traditional teaching methods and/or learning materials.

Shegog et al. [SLM+12] present a study with  $n=44$  high school biology students at the age between 17 and 18 years where a virtual laboratory was used to learn molecular biology techniques to construct a transgenic mouse model in order to study the causes and potential cures for human genetic diseases. The virtual laboratory is considered as a substitute for a real lab as the latter is logistically not feasible for high school students. The students were split up randomly in a treatment group of 23 students and control group of 21 students. The results show a significant increase in procedural and declarative knowledge of molecular biology compared to the control group. Furthermore, the authors repeat the stimulus and observed a continued significant increase of the knowledge. In addition, the students using the virtual model showed a significantly higher positive attitude towards using computers for learning. Most important limitation of Shegog et al. is that the treatment group had significantly better grades in biology than the control group. This may strongly influence the results. The work by Shegog et al. differs from our study in such way that our participants are university students in the field of molecular biology and thus much older. Thus, the learning behavior and attitude towards using computers may be very different then with high school students. In addition, the virtual laboratory space of Shegog et al. consists of photos taken from real laboratories. In contrast, the GenLab system used in our experiments uses photo-realistic rendered 3D objects, which allow for an immersion into the virtual world while still abstracting from specific real-world labs.

Cunningham et al. [CMP+06] conducted an evaluation of a virtual laboratory for teaching gel electrophoresis to high school students (n=20) and undergraduate biology students (n=38). The authors did not find significant differences between the two study groups in respect to their perception of the virtual laboratory itself which was overall positive. In respect to the learning outcome, undergraduate students significantly improved their scores for the more difficult questions in the quiz. The intention of the virtual diagnostic laboratory described by Bean et al. [BGH+11] was to draw medical students' attention to the relevance of genetics in medicine, to improve the understanding of genetic testing, and to train students' diagnostic skills. A comparative study with 140 undergraduate medical students on genetic testing was conducted and the same experiment was repeated with the same participants one year later. In anonymous evaluations, the students were asked among others about the educational value, the usefulness, and the suitability of the virtual laboratory towards their objectives. Overall, there was a majority in terms of supporting the new learning technique. Neither a statistical analysis of the results nor an objective evaluation of the learning outcome was carried out.

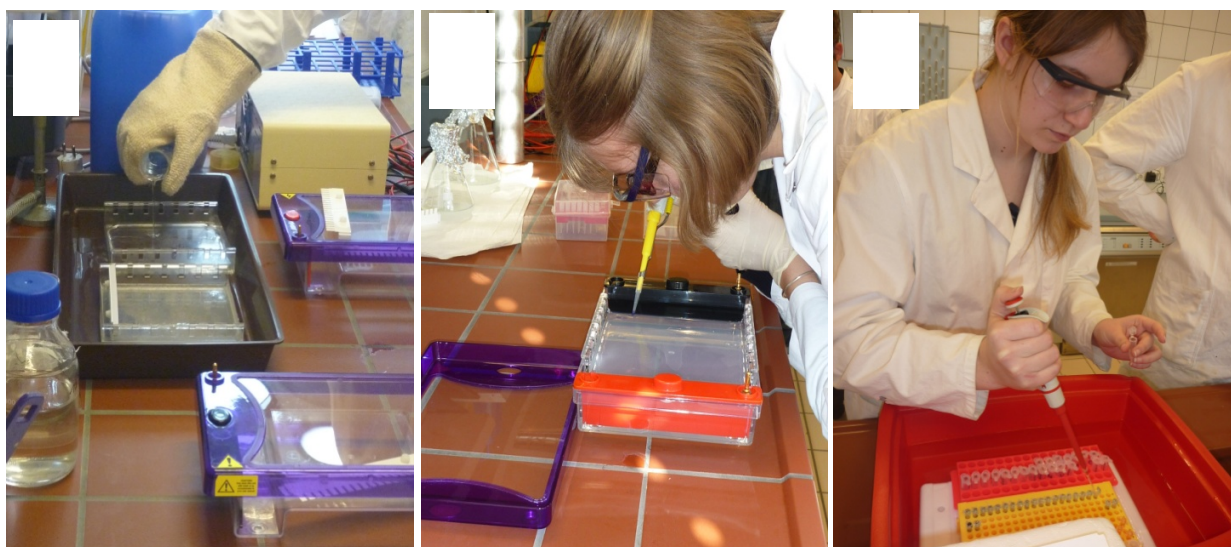
Boje et al. (2005) intended to fill a gap in the curriculum of undergraduate pharmaceutical biotechnology in an attractive way by launching a virtual lab on the research and development of recombinant peptides and proteins – a topic which was not covered by textbooks at that time. The three training conditions are weekly face-to-face classroom discussions, hybrid, and purely online course format. Unlike in our experiment, the participants could freely choose between one of the three options. While about half of the class choose the online course (n=14), the remainder participated in the hybrid of face-to-face and online (n=13). No participants choose entirely face-to-face training. Overall, the used software was rated very positive. However, when preparing for a (real life) exam, students often chose the traditional learning material, i. e., the hardcopy information, over interactive modules of the virtual lab. The authors could show that pre-test scores and post-test scores of the two groups, hybrid course vs. online course, did not differ significantly. Neel et al. [NGB07] investigated the attitude of students towards virtual microscopy in the domain of veterinary cytopathology. The result of the experiment with 62 students is that there is a strong preference for a continued use of traditional microscopy for graded experiments. At the same time, the students indicated a preference of using a virtual learning environment for studying exercises and take-home exercises.

## **BACKGROUND KNOWLEDGE ON GENETIC EXPERIMENTATION**

As example experiments for training in a virtual laboratory, we have selected in our study the agarose gel electrophoresis (AGE) and the polymerase chain reaction (PCR) [SR01]. First, these experiments represent essential molecular techniques which are fundamental to lab routines of the life sciences as well as to diagnostic applications in the food industry and the medical sector. Therefore, they are part of the genetics module's curriculum in both lecture (theory) and lab course (experimental practice) of the M.Ed. Biology program. Second, these experiments were very similar with respect to equipment and procedure for the real lab and the virtual lab. In the following, the experiments of the real lab course are summarized. In case of AGE and PCR, the procedures are described in more detail and differences in the procedure in the virtual lab are pointed out.

Agarose gel electrophoresis (AGE) allows the separation of DNA molecules based on their migration velocity within an electric field through a porous matrix (the agarose gel). The procedure of AGE consists of several steps which are very closely reenacted in the virtual lab. First, the students had to make their

gels, including the weighing and mixing of components, the melting of the gel solution in the microwave, the addition of the nucleic acid stain as well as the preparation of the gel trays prior to the pouring of the gel (Fig. 1a). In the virtual lab, only the step of sealing the tray is not included. Once the gel had solidified, it was transferred to the electrophoresis chamber and covered with the electrophoresis buffer. Now, the samples could be loaded on the gel. For this purpose, the samples were mixed with the loading buffer and each sample was carefully applied with a micropipette to the gel slots (Fig. 1b). In the virtual lab, the samples were already mixed with the loading buffer and could be directly loaded on the gel. The chamber was closed with the lid putting the electrodes in place. Current and voltage were adjusted and electrophoresis was started. Finally, the gels were placed on a UV-transilluminator and imaged for documentation purposes and subsequent analysis.



**Figure 1. Activities during the practical course in genetics: a) pouring the agarose gel, b) loading the gel with the samples, and c) pipetting the PCR assays.**

By means of the polymerase chain reaction (PCR), specific sections of a DNA molecule can be amplified millionfold *in vitro* within a very short period of time. The preparative steps for PCR are less numerous than for AGE, which was also the case for the virtual version. The students first had to calculate – depending on the numbers of samples – the volume of each component of the so called ‘mastermix’. The components of the mastermix were water, reaction buffer,  $MgCl_2$ , the four dNTPS, two primers and the Taq-DNA-polymerase. The appropriate volumes of each component were then pipetted into a reaction tube (Fig. 1c) and mixed. The mastermix was distributed into new reaction tubes according to the number of samples and the samples were added. After brief mixing, the reaction tubes were placed into the thermocycler and the program was started to conduct the PCR. In the virtual lab, the PCR was performed only on one sample. In contrast to the real lab, the thermocycler needed to be programmed first.

Further experiments included the preparation and microscopic investigation of mitotic cells in root tips, the crude extraction of DNA from tomato, the conjugation between bacterial strains and the transformation of bacterial cells. Whereas the procedure of mitotic cell preparation and staining is rather simple, the other experiments involve more steps which in case of conjugation and transformation span several days.





makes a mistake such as waiting too long and letting solidify the gel before pouring it into the gel tray during the AGE experiment.

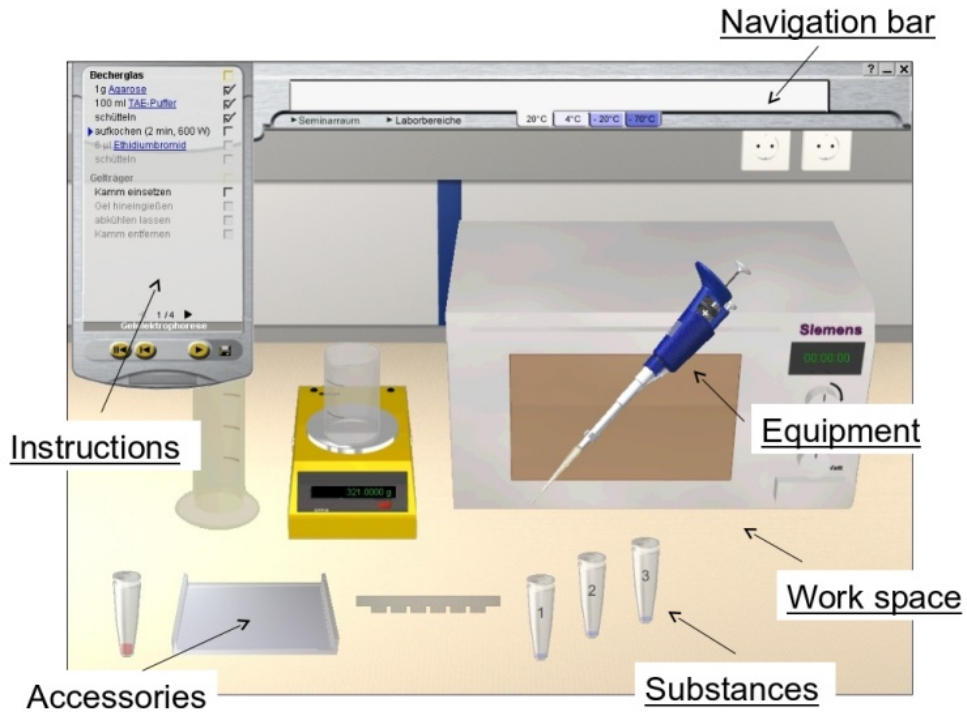


Figure 3. Screenshot of the laboratory bench for preparing the agarose gel in GenLab (captured from [OFF03]).

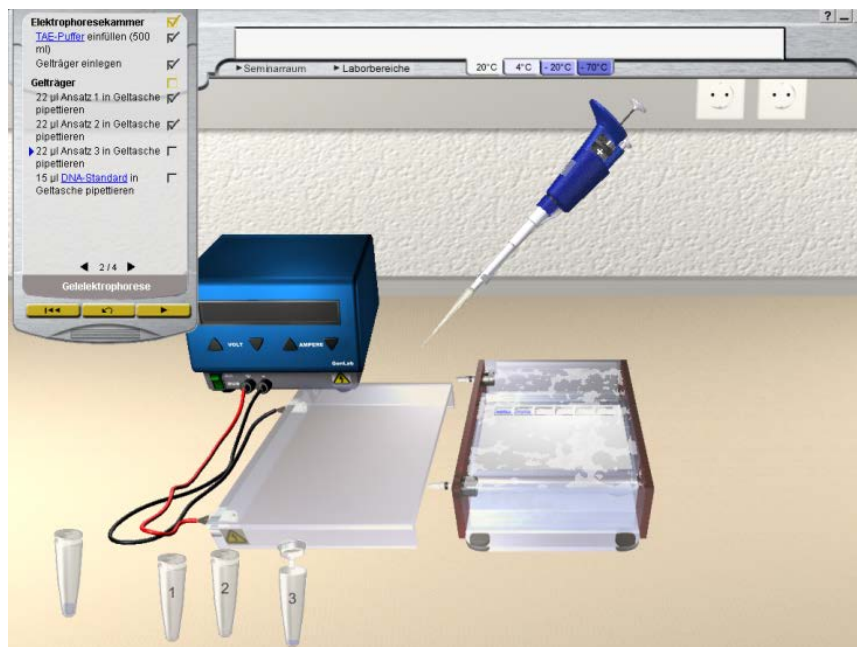
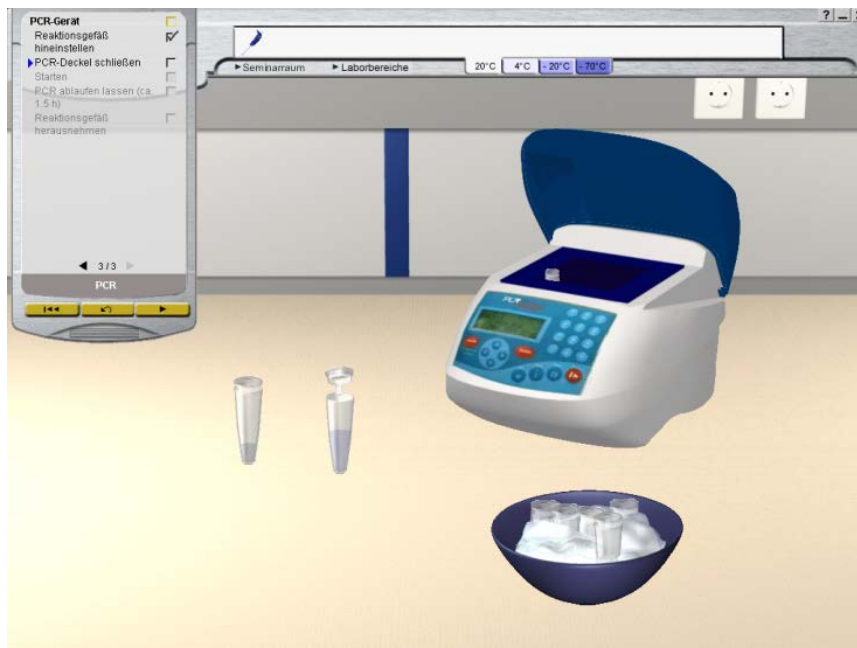


Figure 4. Screenshot of the electrophoresis chamber in GenLab (captured from [OFF03]).



**Figure 5. Screenshot of the thermocycler and the components of the mastermix on ice of the PCR module in GenLab (captured from [OFF03]).**

Two weeks in advance to the practicals, the course script was made available to the students. It provides for each experiment i) an introductory part on general theory and background information, ii) a list with required materials and equipment, iii) a step-by-step description of the experimental procedure, and iv) a guidance for analysis with questions to consolidate the learning subject matter. The traditional training material covers among others the two experiments AGE and PCR used in our study. Thus, the traditional training material allows the same preparation to the practicals using paper-based information as the interactive and simulation-based virtual lab GenLab.

## **STUDY DESIGN**

### *Participants*

32 students of the M.Ed. Biology program at the University Koblenz-Landau in Koblenz, Germany, took part in our study. The laboratory course in genetics is organized as a 5-day block course and is part of the set curriculum. Two parallel block courses are held per study period which allowed us to perform a summative evaluation. The training with GenLab was obligatory for all students. However, only the first group received the training before the practical course. The students enrolled in the two laboratory courses of genetics during winter semester 2012/2013 were invited to participate in our study. Participation in the study was voluntary. No compensation for the effort in participating in the experiment was given.

### *Procedure*

We conducted a summative evaluation with the two groups. The first group was trained using GenLab prior to the practical course (treatment group: n=18, 10 female). Besides GenLab, this group also had the traditional learning material as preparation. The other group served as control condition and was not trained prior to the practical course (control group: n=14, 9 female). This group had only the traditional

learning material as preparation. In our study, we focused on two example experiments that are supported by GenLab. We selected the agarose gel electrophoresis (AGE) and the polymerase chain reaction (PCR) [SR01] described above. However, also further genetics experiments were conducted by the participants in the practicals and served as baselines in our study.

The treatment group received a two-hours training in the procedures of genetics using the virtual laboratory the week before the real laboratory course. The students were allowed to use the software as they like. However, it was mandatory to read the theory on PCR and AGE in GenLab, to learn the use of the micropipette with the software, and to conduct the virtual experiments AGE and PCR using the software. Subsequently, the students participated in the real laboratory course where they conducted experiments in pairs of two. Among the experiments conducted in this course were AGE and PCR. The students were asked to measure the time they needed for certain steps and among others provide a subjective rating of the difficulty and comprehensibility of conducting the individual experiments. The latter were captured using a post-test questionnaire to be filled in at the end of the laboratory course. The students were also asked to indicate their age, gender, second subject next to biology, as well as to quantify and qualify their previous lab experience.

The control group did not receive training prior to the real laboratory course. Except from this difference, both treatments were the same. The control group conducted the same set of experiments in the same laboratory and equal conditions like the treatment group. In order to enable also the students of the control group to investigate the usefulness of the virtual laboratory GenLab and to guarantee similar study conditions, the students received their GenLab training the week after the laboratory course.

## **RESULTS**

First, we investigated the comparability of the two groups with respect to age, second subject, and previous lab experience. The average age of the students was 24.5 years ( $SD=3.63$ ). The differences in age between the two groups were not significant ( $U=145$ , ns,  $z=0.72$ ). In the treatment group, 56% of the students indicated a second subject within the natural sciences (9/18 chemistry, 1/18 geography), while in the control group only 21% of students had a second subject within the natural sciences (3/14 geography). In addition, we asked the students if they took part in a practical course prior to participating in this practical course. The practical course in microbiology, which alternates with the practical course in genetics and which is similar in respect to organization as well as in respect to basic techniques and tools, had been completed by only 22% of the students of the treatment group and by 43% of the students of the control group. All students of both groups indicated that they had participated in practical courses beforehand. However, the total number (including the practical course in microbiology) varied from 2 to 15 accomplished courses. Students with chemistry as second subject had an average of 11.8 practical courses while all others had an average of 3.4 practical courses (treatment group 3.1, control group 3.6). This explained the significant difference between the two groups with respect to the total number of prior practical courses (treatment group 7.6 and control group 3.6;  $U=183$ ,  $p<.02$ ,  $z=2.17$ ). Accordingly, the participants' self-assessment regarding their experience in laboratory work was significantly higher in the group that had conducted more practical courses ( $U=170$ ,  $p<.05$ ,  $z=1.67$ ). A value of 1 refers to totally unexperienced and 7 to totally experienced. Only few students in both groups indicated laboratory experiences outside school or university (3/18 in the treatment group, 1/14 in the control group).

The students in the groups did not differ significantly regarding their self-assessment of how well they felt prepared to the real practical course ( $U=122.5$ , ns,  $z = 0.22$ ). The self-assessment of the treatment group on a 7-point-Likert scale was on average 4.44 ( $SD=0.92$ ) and for the control group on average 4.38 ( $SD=1.19$ ), where a value of 1 meant totally unprepared and 7 referred to totally prepared. In addition, we could not observe a significant difference in the students' rating regarding the difficulty of the experiments, except for the AGE experiment. In detail, the results of the statistical analyses for the level of difficulty were: investigation of mitotic cells (treatment group 5.33 and control group 5.00;  $U=158$ , ns,  $z = 1.22$ ), DNA extraction from tomato (treatment group 4.39 and control group 4.64;  $U=133.5$ , ns,  $z = 0.28$ ), conjugation (treatment group 4.50 and control group 4.93;  $U=152.5$ , ns,  $z = 1.01$ ), transformation (treatment group 4.17 and control group 4.64;  $U=148$ , ns,  $z = 0.84$ ), AGE (treatment group 3.83 and control group 4.79;  $U=172$ ,  $p<.05$ ,  $z = 1.75$ ), and PCR (treatment group 4.33 and control group 4.36;  $U=126$ , ns,  $z=0$ ). A value of 1 rated an experiment as very difficult and 7 as very simple.

Further, the participants were asked to assess for each of the experiments mentioned above, if the order of tasks they had to conduct in the experiments was understandable. Again we used a 7-point- scale with a value of 1 indicating a very low comprehensibility and a value of 7 indicating a very high comprehensibility. Again, the results were that the assessments for all experiments did not differ significantly, except for AGE. In detail, the results for assessing the comprehensibility of the experiment tasks were: investigation of mitotic cells (treatment group 5.78 and control group 6.07;  $U=152.5$ , ns,  $z=1.01$ ), DNA extraction from tomato (treatment group 5.22 and control group 5.93;  $U=157$ , ns,  $z = 1.178$ ), conjugation (treatment group 4.72 and control group 5.29;  $U=150$ , ns, $z=0.912$ ), transformation (treatment group 5.06 and control group 4.93;  $U=132.5$ , ns,  $z = 0.25$ ), AGE (treatment group 5.72 and control group 4.71;  $U=172$ ,  $p<.05$ , $z= 1.75$ ), and PCR (treatment group 5.56 and control group 4.93;  $U=155.5$ , ns,  $z= 1.12$ ).

For the two experiments, that were trained using GenLab, i. e., AGE and PCR, we conducted a more detailed investigation of the single experimental steps. Regarding AGE, we measured the time that was needed to prepare the agarose gel as well as to load the agarose gel. Measurements were taken by the students using a clock (like it was conducted in [GPR+14]) and the measuring units were minutes. While the treatment group required for preparing the agarose gel on average 24.76 min ( $SD=9.48$ ), the control group needed for the same task on average 29.77 min ( $SD=5.69$ ). However, the difference was not significant ( $U=152$ , ns,  $z= 1.31$ ). The time needed to load a sample on the gel was again on average lower for the treatment group (3.00 min per sample,  $SD 1.96$ ) than for the control group (4.08 min per sample,  $SD 3.17$ ). Here, we found a significant difference among the groups ( $U=174.5$ ,  $p<.02$ ,  $z=2.20$ ).

For the PCR experiment, we measured the time needed to calculate the PCR mastermix and the time needed to prepare the PCR mastermix and to pipett the individual PCR reaction tubes. The treatment group needed for the calculation of the PCR mastermix on average 5.65 minutes ( $SD=5.69$ ) and the control group on average 7.00 minutes ( $SD=5.95$ ). The difference was statistically significant ( $U=160.5$ ,  $p<.05$ ,  $z=1.65$ ). However, regarding the time required for actually pipetting the PCR assays, we could not observe a significant difference (treatment group 4.79 min per sample,  $SD 2.39$ , and control group 4.95 min per sample,  $SD 2.62$ ;  $U=121$ , ns,  $z=0.08$ ).

Finally, we asked the two groups how good their estimates were regarding the time needed for conducting the AGE and PCR experiments. The differences between the groups were non-significant for

AGE (treatment group 4.44 and control group 4.58;  $U=111$ , ns,  $z=0.13$ ) as well as for PCR (treatment group 4.56 and control group 4.58;  $U=116$ , ns,  $z=0.34$ ). A value of 1 referred to very poorly assessable and a value of 7 referred to very well assessable.

The treatment group was also asked some questions regarding the use of computers and the virtual lab as preparation. The students were asked if using a computer to prepare for the practical course was fun. The answer the students gave was on average a 4.89 (SD=1.45) on a 7-point-Likert scale, where a value of 1 referred to totally disagree and 7 corresponded to totally agree. More specifically, we asked if using GenLab as preparation to the practical course helped. Here, the assessment for AGE was on average 3.94 (SD=1.86) and for PCR the score was on average 3.72 (SD=1.78) using a 7-point-Likert scale where a value of 1 meant not helpful at all and a value of 7 meant very helpful.

## **DISCUSSION**

### *Main Insights from the Study*

The results of our study show that the treatment group needed on average less time conducting the AGE and PCR experiments. For both experiments, we could find for one step a significant difference while for the other we did not. In the case of AGE, the difference was not significant for preparing the gel while we did observe significant differences for loading the samples on the gel. We explain these results from the fact that preparing the gel is comparability simple, although it consists of multiple steps such as preparing the agarose solution and pouring it into the tray. In contrast, to load the sample onto the gel a pipette needs to be used multiple times and pipetting needs to be conducted carefully in a specific order while not to forget to change the pipette tip. For the PCR, we observed a significant difference for calculating the mastermix. However, when comparing the time needed for pipetting the PCR assays, we did not observe significant differences. In summary, it is quite interesting to see that for some steps in the experiments we did observe significances while for the others we did not. It seems like that specific parts and activities in a practical can benefit from a preparation in a virtual laboratory while others not.

We aimed to obtain a more detailed picture by asking the students to rate the level of difficulty and the comprehensiveness of six individual experiments conducted during the real laboratory course, including AGE and PCR that were specifically trained with GenLab. Here, we made the very interesting observation that the participants of the treatment group did understand the procedure of the AGE and PCR experiments better, based on their subjective judgment. However, a clear conclusion cannot be drawn from the results as the ratings of the comprehensiveness of the AGE experiment showed significant differences while the results for the PCR experiment did not. We tend to explain this observation by the fact that the AGE experiment is more complex than the PCR experiment, at least for the steps that were trained by using the virtual lab. Thus, the implementations of the AGE experiment and PCR experiment differ in the level of detail in GenLab. For AGE, more individual steps are shown and trained in GenLab than for PCR. Thus, the students might additionally benefit from the fact that the virtual AGE is a better representation of the real-world AGE compared to the virtual PCR experiment is for the real-world PCR. Accordingly, the level of difficulty for AGE was rated significantly higher in the treatment group than in the control group. Anticipating a higher complexity as a result from executing the experiment first in a virtual lab may also trigger a higher commitment and a more intensive preparation in the real-world lab. For the other experiments that were not part of the training in the virtual laboratory GenLab, we did not observe any significant differences. This result is insofar expected as both groups had the same

traditional learning material for preparation of these experiments and the treatment group could not benefit from any additional simulation-based training in a virtual world.

As discussed in the related work, the importance of training in a virtual lab for the performance in the real lab has also been shown by the comprehensive study of Swan and O'Donnell [SD09] with college students, which are of a much different age group than our students. Users outperformed non-users in practical exams on items that were covered in virtual labs but not on non-covered items or in the final exam. Gerlach et al. [GBG+14] observed less mistakes and confusedness while operating the bioreactor and auxiliary equipment and a better ability to recognize and interpret biological key events for those students which had been trained with the model-based simulation of the cultivation process. However, in contrast to GenLab their work is focused on a more abstract simulation engine for training rather than a photo-realistic immersive virtual environment. This indicates that an understanding of the processes and principles underlying the procedure is crucial for practical performance and that functional fidelity of the virtual laboratory is equally important to its physical fidelity. Polly et al. [PMM+14] confirmed that students appreciated the step-by-step explanation in the virtual lab and helped them in the real lab performance. However, in contrast to our study Polly et al. collected only feedback about the students' perceived improvement regarding the understanding, confidence, technical skills, and diagnosis skills of the experiment. The high rating of virtual laboratories in the study of Polly et al. was probably strongly influenced by the apparently unfavorable conditions under which experiments had to be performed in the real world (a too narrow time schedule and crowded labs).

Although on average students of the treatment group did not rate the training with GenLab as specifically helpful for real-lab preparation, individual rating scores ranged from very helpful (a value of 7 on the Likert scale) to not helpful (a value of 2). This may also reflect individual preferences of students to work with computer simulations or computers in general, which has been also shown by studies referred to in the related works. Nevertheless, working with GenLab was on the whole perceived as fun which does imply a stimulating effect on learning and study habits and as investigated by Xu et al. [XHT14] results in higher grades by students.

While the treatment group and control group were comparable in respect to age and gender ratio, they showed differences in lab experiences, especially regarding the total number of previously completed practical courses. The highest numbers of prior practical courses were reported by students who had chemistry as second study subject indicating that these courses were completed in chemistry labs. One could assume that this gives the students a higher self-confidence in general lab routines but not necessarily more in depth knowledge on genetic experimentations and the procedures involved here. Labs in inorganic and organic chemistry consist mostly of the analysis of substance formulation and/or compound synthesis. This kind of experimentation is completely different from the genetic lab. Working in genetics and microbiology means the handling of biological agents (bacterial cultures, enzymes etc.) and working in sterile conditions. Devices such as microscopes, micropipettes, centrifuges, PCR-reaction tubes, Petri-dishes, electrophoresis chamber, and thermocycler were not used in chemistry labs. As our results above show both groups felt equally well prepared according to their self-assessment. This indicates that neither previous lab-experience nor the additional two-hour training with GenLab had an influence on the general self-assessment regarding the perceived level of preparedness to the laboratory work as well as the participants' self-assurance. The issue of comparability of treatment and reference

group has also been addressed by some studies mentioned in the related work [SD09, SLM+12] while others disregard this issue completely [GBG+14, PMM+14]. The problem of differences in respect to students' grades has been encountered especially in those studies where the participation is voluntary [SD09, SLM+12]. In our study, the application of the virtual lab was compulsory for the treatment group (while the control group did not know or use GenLab for preparation at all). This should at least circumvent the bias towards very engaged students. Swan & O'Donnell [SD09] solved the problem by searching for matches in the non-user group which was possible because of the large number of non-users. Similarly to Shegog et al. [SLM+12] the number of participants in our study is comparable small. However, in both studies students were randomly assigned to either the treatment or the control group. In addition, the sizes of the groups in our experiment are still sufficiently large to conduct statistical analyses and to find significant differences between the treatment and control conditions. While Shegog et al. randomly assigned the students to either the treatment group or control group, we have assigned a whole course of students to either of the two groups. Please note, unlike the studies discussed in the related work, the composition of our groups cannot be influenced by the instructors as the students choose one of the two parallel blocks provided for the practicals according to individual study programme schedules.

### *Summary*

Overall, we assume that the students have gained from using the virtual laboratory as preparation for the real-world lab. However, this result needs to be investigated in more detail in the future. It would be interesting to investigate if next to an improvement of the procedural knowledge also an increase in declarative knowledge can be achieved. Furthermore, certain points should be considered in order to increase the effect of virtual labs on the learning outcome. Training within a virtual lab should be extended in respect to both time and scope. It should at its best include all experiments that will be conducted in the consecutive real lab. Virtual experiments should be depicting as closely as possible the single steps of the experimental procedures. Finally, as discussed in the literature [YCL+14, VTR+14], virtual labs should be solidly integrated into the course curriculum and included in the course assessment.

### **CONCLUSION**

In this paper, we have conducted a study measuring the influence of the use of a virtual laboratory like GenLab on the time needed when conducting experiments in a real laboratory course and the subjective assessments of the comprehensiveness and difficulty of the experiments. We have compared the impact of using GenLab for preparing to the real-world laboratory versus plainly using traditional paper-based learning material as preparation. Overall, we can state that virtual laboratories may play a significant role in better preparing students in real laboratory work and thus have the potential to save precious resources when conducting experiments in the real world. We are well aware of the limitations of this work and that a clear answer on the impact of virtual laboratories can yet not be made. However, we still believe that the results are of high value to the research community as they provide first insights into the effect a virtual laboratory may have when being used as preparation to real-world laboratory work.

However, more extensive user studies are needed in the future. These user studies need to particularly investigate the usefulness of virtual laboratories as preparation for real laboratory courses. Thus, we need to integrate virtual laboratories like GenLab into the curricula of microbiology, biotechnology,



genetics and genetic engineering, and conduct some longitudinal studies. For the case of the practicals in genetics at the University of Koblenz-Landau, GenLab has become integral part of the curriculum of the practical course. This allows us to repeat the study and report further insights regarding the effect of using virtual laboratories as preparation for real-world laboratory work. Here, it will be interesting to investigate if knowledge acquired additionally through the virtual laboratories is more sustainable than traditional learning methods.

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