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Be Prepared! How Pre-lab Modules Affect Students' Understanding of Gene Mapping

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Abstract
Lab activities are characteristic of life science education. In the current study, we investigate whether pre-lab modules can improve students' understanding of the theories and experimental procedures associated with lab activities. Such effects were studied in context of an expository lab on gene mapping in biology undergraduate education. An experimental group of 126 students had access to an online pre-lab module to prepare for the lab activity; a control group of 90 students did not have access to this pre-lab module. The data revealed that students who studied the pre-lab module had a better understanding of the gene mapping theory, at the onset of the class, when compared with the control group. Additionally, these students appeared to ask fewer questions on what needed to be done in the lab, suggesting more awareness of the experimental procedure. Further, students who studied the online pre-lab module showed greater understanding of the theory in their lab reports. These findings suggest that students' understanding of background theory and its relation to practice can readily be improved by enriching existing expository labs with pre-lab modules that contain information and questions on the complex conceptual information relevant to the lab experiment.

Keywords Pre-lab modules · Practical · Laboratory · Undergraduate · Conceptual understanding

Introduction

Lab activities form a distinctive type of learning process within life science education. Indeed, they are widely considered to be essential for learning practical skills and investigative skills and grasping related theoretical concepts (Reid and Shah, 2007). There exist various types of lab activities that differ in their suitability for meeting a given learning goal (Brownell and Kloser, 2015). Although their importance is clear, studies on lab activities have shown that students regularly fail to gain intended learning aims—especially those related to understanding theoretical concepts (Hofstein and Lunetta, 2004; Johnstone and Al-Shuaili, 2001; Kirschner et al., 1993; Reid and Shah, 2007).

The most common type of lab activity in large-scale undergraduate courses is expository labs or confirmatory labs in which research questions and methods are already set. Such classroom activities are often also referred to as "cookbook labs", given that, in such structures, students can follow preset procedures as a recipe, without understanding the discrete purpose of each step within the experimental procedure (Brownell and Kloser, 2015; McComas, 2005). Since both the experimental procedure and theoretical framework are already set, expository lab activities generally do not incorporate learning objectives such as posing research questions and designing methods to pursue them (Brownell and Kloser, 2015; Domin, 1999). Instead, they mainly stimulate students to develop practical skills, interpret data, and draw conclusions. In an explorative study, we asked bachelor-level life

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science teachers to delineate the main objectives of their lab activities. The most frequently mentioned learning objectives were to improve understanding of the theoretical framework and to relate this theory with practice—a set of goals that raise questions about the alignment of the learning goals and outcomes (unpublished results). However, studies that measure the efficacy of theoretical learning objectives in biology lab education still remain scarce. The present study aims to measure and improve these learning outcomes, applied to an expository lab activity on gene mapping.

The difficulty of improving theoretical understanding from lab activities is that students generally appear to be solely focused on the experimental procedure when working in the lab (Gunstone, 1991; Hofstein and Lunetta, 2004; Kozma, 2003; van der Kolk et al., 2012). Support for this statement comes from the observation that students almost exclusively ask questions in the lab regarding the experimental procedure (e.g. "where can I find …?" and "when can I do …?": Kozma, 2003; van der Kolk et al., 2012). This behavior may result from the limited working capacity of the brain and the large amount of new information they need to process in the lab (Johnstone et al., 1994). To clarify, students are required to recall information, make observations, search for materials, follow procedures, and analyze data, all at the same time. Thus, they are at risk of becoming cognitively overloaded—a condition that makes it more difficult to focus on the purpose and theoretical framework of the experiment (Johnstone, 1997). This can result in inconsistencies between intended and actual learning outcomes with respect to theoretical understanding (Hofstein and Lunetta, 2004; Johnstone and Al-Shuaili, 2001; Reid and Shah, 2007).

One solution to increasing the theoretical understanding, both of the experimental procedures and the relevant biological concepts, is to redesign expository labs into inquiry-based labs. In inquiry-based labs, students are required to design their own experiments; this can vary from setting up their own research question(s) to defining relevant theory and designing their own methodology (Zhang, 2016). It is thought that this format will keep students more engaged and focused on the actual purpose of the experiment (Brownell and Kloser, 2015). Previous meta-studies on inquiry-based labs (Furtak et al., 2012; Minner et al., 2010; Schroeder et al., 2007) have mostly revealed positive effects on students' learning outcomes. In addition, students in inquiry-based labs have appeared to ask more questions in the lab for which critical thinking is needed, suggesting that they better understand the purpose and theoretical framework of the lab activity (Hofstein et al., 2005).

Nonetheless, inquiry-based labs have some practical implications that suggest they may not be efficient or feasible for all levels and settings. The first implication is that students need to have some knowledge of lab techniques (Gormally et al., 2009; Krajcik et al., 2000). Besides, some experiments are simply too complex for students to design themselves (an issue that is particularly true for the gene mapping experiment explored in this study). An additional implication is that inquiry-based labs often appear to be more expensive and require more lab facilities and lab space (Gormally et al., 2009; Johnstone and Al-Shuaili, 2001; Wei and Woodin, 2011). Most importantly, inquiry-based labs focus on the entire process of conducting research—meaning that students generally need to formulate hypotheses, solve problems, apply theoretical knowledge, design experiments, use practical skills, select data, interpret data, derive conclusions, and identify limitations of the procedure (Johnstone and Al-Shuaili, 2001). In other words, a great deal of time and effort is spent on objectives other than improving the understanding of biological concepts. Thus, inquiry-based labs may not be the best fit for lab activities designed to improve understanding of multiple biological concepts and procedures and taught to large groups of students with little lab experience.

An alternative method for increasing theoretical knowledge is to enrich expository labs with lab preparation activities. It is hypothesized that more preparation will result in less cognitive overload in the lab and thus allow students to focus more on understanding the experiment (Johnstone, 1997; Sweller et al., 1998). Better understanding can be readily obtained by handing out slides, videos, questions, and tests prior to the lab session(s) (Nadelson et al., 2015; Pogacnik and Cigic, 2006; Whittle and Bickerdike, 2015). A more modern method of preparing students for the lab is to use computer modules: a so-called pre-lab module.

Previous studies on pre-lab computer modules are mainly focused on the learning effects of experimental procedures (Johnstone, 1997; Jones and Edwards, 2010; Schmid and Yeung, 2005). For example, previous pre-lab modules have been shown to increase students' confidence in doing dissection-based lab activities (Jones and Edwards, 2010). Students appear also to perform better in the execution of chemical lab experiments when prepared with pre-labs (Johnstone, 1997; Schmid and Yeung, 2005). In addition, students who did pre-labs have been found to ask more theoretical questions (Winberg and Berg, 2007) and less "thoughtless" questions on the experimental procedure that, according to the teachers, they could have easily answered themselves (Johnstone, 1997).

Learning Objectives

In the current study, we scrutinized a lab activity with high theoretical complexity that is designed for a large group of undergraduate students with scant lab experience. In this specific lab activity, students must approximate the genomic location of a certain gene that results in a visible phenotype when mutated. This exercise was chosen because the underlying theory on genetics, recombination, and gene mapping is difficult for undergraduates (Makarevitch & Kralich, 2011). The learning objectives for this gene mapping experiment are that

students can (i) understand the biological principles important for gene mapping, (ii) understand (the purpose of) the methods used during the experiment, (iii) relate the theoretical knowledge of methods and biological principles to the research question, (iv) perform the experiments, (v) interpret the data, and (vi) identify the limitations of the experimental procedures.

We aimed to use pre-lab modules to improve the learning objectives on the understanding of the biological principles, the experimental procedure, and of how this procedure is related to these principles. In other words, the present study addresses the following main question:

Do pre-lab modules improve students' understanding of the theory from lab activities with high theoretical complexity?

More specifically, we aimed to examine students' understanding of the experimental procedure, theory, and obtained data through all stages: before, during, and after the lab activity. The current paper examines the following three specific questions:

1. *Do pre-lab modules increase theoretical knowledge before the lab activity, at the onset of the experiments?*
2. *Do pre-lab modules affect students' focus and understanding towards the methods, theory, and results during the lab activity, when doing experiments?*
3. *Do pre-lab modules affect students' understanding of the methods, theory, and results after the lab activity, when writing lab reports?*

The pre-lab considered in this study is designed to improve students' understanding of the theory behind a gene mapping experiment. The pre-lab includes videos, text, images, questions, and feedback on the theoretical background, experimental procedure, and interpretation of hypothetical data. Although the pre-lab studied herein is specifically designed for gene mapping, we expect the results of this study to be applicable to other lab activities with similar high theoretical complexity.

Methods

Participants

The participants in this study were students participating in the course, Molecular Genetic Research Techniques at Utrecht University. This course is one of the many electives within the second and third years of the bachelor-level study in biology. Based on ethical considerations (namely to avoid unequal treatment of students within the same course), the research was conducted over 2 years. Correspondingly, data for the control group and experimental groups were collected across two consecutive years. One hundred twenty-one students participated during 2016–2017 (control group) and 149 students participated during 2017–2018 (experimental group). The course set-up and lab activities remained the same for both years. Students were asked to sign an informed consent containing information on the research and gathering of data of the study. Only participants providing informed consent were included within the datasets on descriptive statistics, pre-lab tests, and lab reports (Table 1). Informed consent was provided by 90 students of the control group and 126 students of the experimental group. During the course, participants took an exam about topics unrelated to the one discussed in this study. The grade for this exam was used to compare the level of the control and experimental group.

Course Design

The course is divided in four segments of two part-time weeks that are related to a specific research field: microbiology, molecular plant physiology, cell biology, and developmental biology. Students have one optional lecture a week on the biological concepts important for the lab activities of that week. Each part contains mandatory expository lab activities guided by a specialized teacher in that specific field, of which none are (co)-authors of this study. The main teacher was usually assisted by two lab assistants: a master's student and Ph.D. student. The lab activities were taught in three groups of 30–40

Table 1 Descriptive statistics of participants who prepared a lab activity on gene mapping either with or without a pre-lab module

Group	Number of students	%male	%female	Average second exam grade[a]
Without pre-lab module	90	49%	51%	6.63 ± 1.52 ($N = 87$)
With pre-lab module	126	40%	60%	6.71 ± 1.14 ($N = 104$)

[a]The presented grade is the average grade for the exam of the second part of the course. This exam tested knowledge unrelated to the studied experiment in the first part of the course. Students are graded from 0.0 (lowest) to 10.0 (highest). Grades below 5.5 are considered insufficient. Note that some participants did not take the second exam

students and experiments were performed in pairs. For each part of the course, lab activities were followed by a mandatory in-class discussion on the experiments and results. After each part, students were also required to complete a lab report on each of the experiments. Both the lab report and students' attitude in the laboratory were graded.

Lab Activity on Gene Mapping

The study considered one of the expository lab activities during the part of molecular plant physiology and was performed in three separate sessions of 2 h and 45 min. Students had to approach the genomic location of a mutation causing a certain phenotype in sandrocket (*Arabidopsis thaliana*). The location of the mutation was determined with a so-called gene mapping approach. During these exercises, students needed to isolate DNA from plant material, perform polymerase chain reactions (PCR), and separate PCR products with gel electrophoresis. This procedure was done for two parental plants and for their F2 offspring with mutant phenotypes. The sizes of each of the PCR products were compared between parents and F2 offspring to determine how often crossing over occurred between a specific location and the mutation (and thus if the mutation could be expected to be near that location). Information on the theory and experimental procedure of gene mapping was included in a lab manual. Both control and experimental groups were asked to read this lab manual before the onset of the lab activities.

Pre-lab Module Design

The experimental group was also required to complete two mandatory online computer modules (about 90 min) at home before the start of the lab experiment (Online Resource 1). These pre-lab modules were specifically designed for this gene mapping experiment and aligned with the first five (theoretical) learning objectives of this exercise on (i) crossing-over, (ii) method of gene mapping, (iii) determining genotypes, (iv) calculating distances between genes and markers, and (v) reliability of gene mapping. The first module focused on gene mapping, which was also explained in the lab manual. The online module contained animations and short texts explaining homologous recombination, crossing over, and calculation of recombination frequencies. The information was alternated with questions on cross studies and gene mapping. This first module concluded with an explanation of the calculation of recombination frequencies needed for data analysis. The second module was mainly focused on the experimental protocol of gene mapping. This segment contained questions and explanations on the purpose of each protocol step. The module concluded with a possible outcome and questions on the interpretation of these data. The full protocol of gene mapping could be downloaded at the end of the second module. The modules were made with Xerte online toolkits (online software), exported as a SCORM 2004 3rd Ed package and uploaded in Blackboard (learning management system). Before the lab activity, students' use of the module was checked with records presented in Blackboard.

The effects of the pre-lab module on understanding the theory and experimental procedure were measured with a pre-lab test, annotations of student questions, and lab report scores. A schematic presentation of this set-up is shown in Fig. 1.

Pre-lab Test

Students were asked to complete a theoretical test on gene mapping at the start of the gene mapping experiment. Students were not informed that they would receive this test on that particular day. It was explained that the test was only meant for research purposes and that students would not be graded for this test. Teachers did not receive individual test scores. The first two questions of the pre-lab test evaluated whether the student had read the lab manual and attended the lecture before the start of the lab activity. These items were followed by nine multiple-choice questions and true-false statements on the main principles of gene mapping (Online Resource 2). Each sub-question was scored with either one or zero points. The average

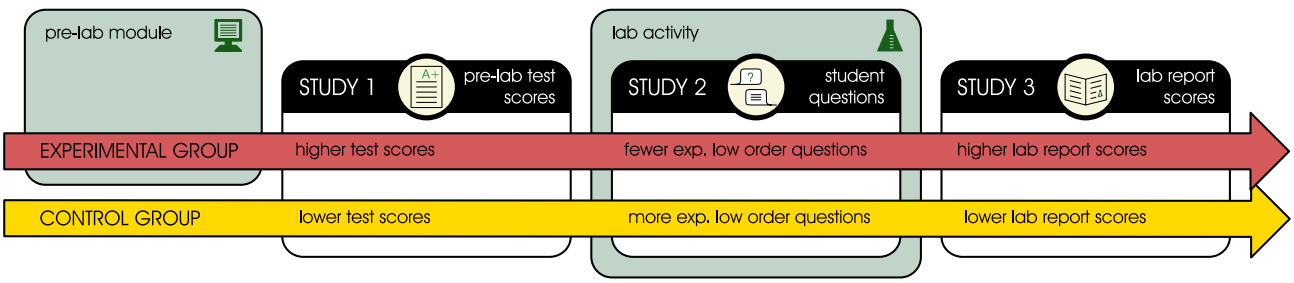

Fig. 1 Schematic presentation of the three studies on pre-lab tests scores, student questions, and lab report scores of the control and experimental group. The arrows present the sequence of activities and studies per group. The texts in the arrows show the general results of each study. Exp. low order questions = experimental low-order questions

test scores for the experimental and control groups were compared in IBM SPSS statistics Version 26.0 (statistics software) using an independent *t* test. Possible additional effects from reading the lab manual or attending the lecture on test scores were analyzed using a stepwise multiple regression, with the experimental group as first predictor and reading the lab manual and attending the lecture as second predictor.

Student Questions

Lab activities were taught in three classes of 30–50 students and students' questions were collected during the lab activity. The main teacher was asked to clip a voice recorder on his lab coat and make recordings during all lab activities on gene mapping. The teacher was informed that these recordings were only intended to record student questions and that his own explanations and instructions would not be analyzed. Recordings of only one of the three classes of each year were selected for analysis since other recordings were not complete, with 46 students in the control group and 39 students in the experimental group. All students' questions concerning the gene mapping experiment were transcribed except for questions that were repeated by the same student. Questions that were hard to decipher but clarified by the teachers' answer were still formulated and transcribed. The data were analyzed in several stages using Nvivo (qualitative data analysis computer software). Student questions were first coded in meaningful categories with an inductive coding approach (Creswell, 2007). The categories were then discussed with the research team and merged, deleted, or reformulated into new categories. These two steps were performed twice, after which agreement was reached (Thomas, 2006). The 386 transcribed questions were categorized in the following eight categories: *general organization*, *theoretical low-order*, *theoretical high-order*, *experimental low order*, *experimental high order*, *interpretation low order*, *interpretation high-order* or *other* (Table 2). Questions were categorized as low-order questions if they did not require understanding of the theory and/or experimental procedure. Questions were categorized as high-order questions if they could only be asked with some understanding of the theory and experimental procedure. Questions on the background theory were defined as theoretical questions, questions on the experimental procedure as experimental questions, and questions on the interpretation of the obtained results as interpretation questions. All questions on organization of the experiment, such as where to find or store materials, were defined as general organization questions. The assignations of the transcribed questions into these categories were performed blind by the first author (who is experienced in teaching biology). Afterwards, a selection of annotations was checked blind by

Table 2 Categorization of students' questions within the lab

Question category	Explanation	Examples
General organization	Questions on the general organization of the experiment	Where can I find ethanol? Where should I bring my sample? Can we get some new solution?
Theoretical low-order	Low-order questions on the theoretical background of the experiment	What do you mean with ecotype? What do you mean by Landsberger; a wild-type plant?
Theoretical high-order	High-order questions on the theoretical background of the experiment	So the mutation is nearby if they are homozygous for all mutants? Do you first search for primers complementary to the mutants because they may not be complementary to the wild-type?
Experimental low-order	Low-order questions on the procedure of the experiment	Do we also need to add loading buffer in here? What voltage do we need?
Experimental high-order	High-order questions on the procedure of the experiment	Wouldn't it be better to add Taq polymerase after making those PCR thingies? Something went wrong last time… so should we add more loading buffer?
Interpretation low-order	Low-order questions on the interpretation of the results of the experiment	Why did it fail? What can I interpret; Just whether it's homozygous or heterozygous?
Interpretation high-order	High-order questions on the interpretation of the results of the experiment	Is it possible that the primers were not mixed well enough? But the parents couldn't be heterozygous, right? Because it seems that they are…?
Other	Every question that does not fit in any other category	How expensive is one such tube?

the second, third, and fourth authors. Annotations that were disagreed upon were discussed to reach consensus.

Lab Reports

Each student pair was required to complete a joint digital lab report after the final in-class discussion. No interim feedback was provided on the lab reports and the reports were required to include an introduction, methods, results, conclusion, and discussion. Each of these five lab report sections were aligned with the first (comprehensive) learning objectives of the gene mapping experiment as students were expected to (i) understand the biological principles important for gene mapping, (ii) understand the methods used during the experiment, (iii) relate the theoretical knowledge of methods and biological principles to the research question, (iv) perform the experiments, (v) interpret the data, and (vi) identify the limitations of the experimental procedures.

All 91 lab reports were anonymized, and dates revealing whether students belonged to the experimental or control group were removed from the files. The reports of both the control and experimental group were given random numbers and blindly assessed by two examiners (second and third co-authors). A simple rubric was used to assess the reports on introduction, methods, results, conclusions, and discussion with either an insufficient, sufficient, or excellent categorization (Online Resource 3). Note that the rubric used in this study was a modified version of the actual rubric used in the course and was only created for the purpose of this study, merely focusing on students' understanding of the experimental steps and theory behind gene mapping. The actual rubric used for feedback and grading of students is more elaborate and also focuses on general content, lay-out, relevance, and completion. Report sections were not assessed if students left them entirely blank.

The examiners first assessed 10 reports and then came together to discuss their grading system. The rubric was fine-tuned and used by both examiners to assess the reports in three phases. First, examiners assessed all reports individually and equally scored 71% of all rubric categories equally which yielded a Cohen's kappa of 0.55, suggesting moderate agreement (Landis and Koch, 1977). Second, the examiners discussed their grading for reports they assessed differently and individually assessed these reports again. Third, final discrepancies in grading were discussed to arrive at a final consensus on the grading of each rubric category for each report. Examples of lab report sections and corresponding rubric scores can be found in Online Resource 4. The 2×3 contingency tables of rubric scores (insufficient, sufficient, or excellent) of the control and experimental group were compared with a Fisher exact test in IBM Statistics Version 26 (statistics software).

Results

Pre-lab Test Scores

The aim of the pre-lab modules was to increase students' knowledge in advance of the lab exercise in an attempt to reduce the cognitive load on students and connect the theory to the lab experiment. To test the assumption that the module indeed increases theoretical knowledge, a test was performed at the start of the experiment. The test was scored from 0 (lowest) to 9 (highest) (Fig. 2). The students who studied the pre-lab module indeed scored significantly higher ($M = 6.5$, SE = 0.14) than the control group ($M = 5.2$, SE = 0.17) ($t\,(197) = -6.10$, $p < 0.001$). Thus, this result demonstrates that students have more theoretical knowledge regarding the experiment at the start of the lab activity when prepared with the pre-lab modules.

The theoretical background information on gene mapping was also discussed in a lecture and included in the lab manual. The aim of the lab manual was similar to the pre-lab modules: to improve understanding of the theoretical background and method of gene mapping. Both the control and experimental groups were asked to read the lab manual before start of the lab activities, but the main teacher had strong doubts as to whether students actually read the lab manual prior to the lab. We therefore included a question on reading the lab manual in the pre-lab test. Only 47% of the experimental group and 66% of the control group answered this question. Interestingly, these students

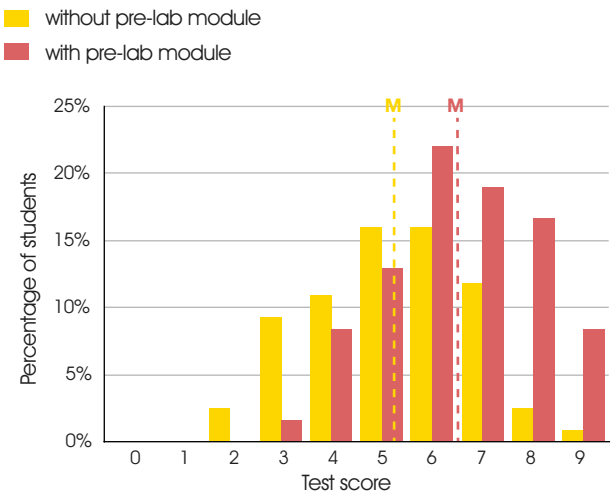

Fig. 2 Test scores on gene mapping for students who did ($N = 116$) or did not ($N = 83$) prepare with a pre-lab module. The theoretical test was performed at the start of the mapping experiment. Students received scores from 0 (lowest) to 9 (highest). The dashed lines represent the mean adjusted test scores for the control and experimental group

claimed to have read the lab manual significantly more often in the experimental group (56%) than in the control group (13%) (χ^2 (1, $N = 110$) = 23.158, $p < 0.001$) (Online Resource 5). Nonetheless, reading the lab manual does not have significant additional effect on the variance in test scores (Online Resource 6). Similarly, no significant additional effect on the variance in test scores is found in relation to lecture attendance (Online Resources 6 and 7).

Students' Questions During Lab Activities

Teachers of the present course stated that students usually almost exclusively ask what they need to do at that specific moment of the lab activity. If students have more prior knowledge on the theoretical background of a lab activity, it is expected that students are better aware of what needs to be done during the lab exercise and thus ask fewer of these types of questions. Similarly, it is expected that these students will change their focus towards the actual purpose of the experiment. These hypotheses were tested by recording, transcribing, and annotating student questions within the lab for one class of both the control group and experimental groups (Table 2).

The recordings show that only 4% of all student questions are high-order questions that display comprehension of the theory, experimental procedure, or data (Fig. 3). In fact, 111 out of 179 student questions in the control group were questions on what needs to be done during the lab activity. Remarkably, students in the experimental group only asked 64 of such experimental low-order questions. Similarly, low-order questions on how to interpret the data are asked only once by the experimental group, compared with nine times by the control group. Questions on the general organization such as where to find or bring lab material are asked roughly as often for both groups.

In summary, the number of high-order questions is relatively low for both the experimental and control groups. Nevertheless, the number of low-order questions on the experimental procedure is lower for students who used the pre-lab module for preparation. More specifically, students in the control group asked 1.7 times as often what they needed to do at certain moments during the lab activity.

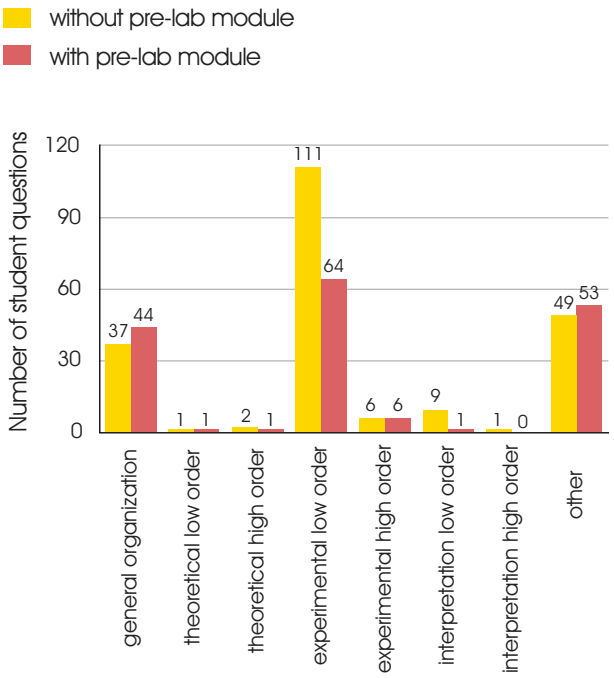

Fig. 3 Number of student question types asked to the main teacher during the lab activity for students prepared with ($N = 46$) and without ($N = 39$) a pre-lab module

Lab Report Scores

The previous results show effects of pre-lab modules at the onset and during the lab activity. We also determined whether students were better able to process the theory, procedure, and results during a later stage when reporting their experiment. The students in the course were asked to write a lab report that was expected to contain an introduction, methods, results, conclusions, and discussion. Each of these sections were expected to reflect one of the

Table 3 Percentage of lab report scores for students who prepared the gene mapping experiment either with or without a pre-lab module

	Without pre-lab module				With pre-lab module						
Criterion	*N*	Insufficient	Sufficient	Excellent	*N*	Insufficient	Sufficient	Excellent	FE	*df*	*p*
Introduction	37	11%	81%	8%	52	10%	42%	48%	17.76	2	< 0.001***
Method	34	3%	41%	56%	52	0%	38%	62%	1.61	2	0.546
Results	37	32%	41%	27%	52	2%	35%	63%	20.35	2	< 0.001***
Conclusions	26	38%	38%	23%	52	6%	31%	63%	16.52	2	< 0.001***
Discussion	26	65%	23%	12%	52	35%	29%	37%	7.643	2	0.023*

The number of scores differs per lab report criterion; some lab report sections were left blank by students

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

main theoretical learning objectives of the gene mapping experiment. The sections were scored blindly for both the control and experimental groups using a simple rubric to specifically assess students' level of understanding. Students who received the pre-lab module had significantly higher scores for four of the five lab report sections; only the Method section was scored similar for both the control and experimental group (Table 3). Thus, students who had the pre-lab module were found to be better at connecting the lab activity to the theory (i.e., presenting the theory needed to clarify the research question, presenting the results needed to answer the research question, interpreting the results correctly, and proposing future experiments).

Discussion

The main purpose of this study was to increase students' understanding of the complex theory of gene mapping and its relation to practice. The investigation demonstrates that pre-lab modules can improve students' understanding of gene mapping during an expository lab activity. More specifically, students who studied the pre-lab module showed better understanding on the gene mapping theory at the start of the experiment, as compared with those who had not received that module. Secondly, students who studied the pre-lab module posed few questions about what they were required to do in the lab. Thirdly, lab report scores revealed that students who studied the pre-lab module could better relate the background theory with the research aim, select the relevant results needed to answer the research question, understand how the obtained results were related to the background theory, and understand the limitations of the data analysis and procedure. In other words, students who studied the pre-lab module knew better what to do in the lab and could better connect the background theory with practice.

Limitations

It should be noted that the data of the control group were collected 1 year prior to collecting the data of the experimental group. This has possibly led to subtle differences in lab instruction between the control and experimental groups. The main teacher has indicated that they set stricter deadlines for the lab reports in the second year of this study, which explains the small sample sizes of the control group for the analysis of lab reports. Nonetheless, other lab manual instructions, the main teacher, the lecture on gene mapping, and the setup of the experiments remained identical for the two groups. No data are available to investigate that the experimental and control groups were comparable prior to this study.

Better Preparation

It is interesting to find out that only a minority of students in the control group appear to have read the lab manual before the lab activity. This is in agreement with previous research of Jones and Edwards (2010) showing that, when pre-lab modules are not used, only 15% of biology students claim to do a substantial amount of preparation before they enter the lab. In our study, viewing the pre-lab modules was mandatory; it is not certain the same results would be obtained if use of the modules had been optional. However, it has been shown that students prefer to prepare with computer modules with animations and tests than to read long texts such as from lab manuals (Bouwmeester et al., 2016; Jones and Edwards, 2010). Moreover, online modules facilitate the monitoring of students' activities enabling teachers to make the pre-lab modules mandatory if needed. Another expected advantage of monitoring students' activity is that teachers could adapt their lab instructions to the individual needs of the students. Besides, interactive questions in pre-lab modules required students to stay more actively involved with the theory. It is likely that the alternation of such questions with theory increased students' focus and understanding of the presented (Haagsman et al., 2020).

It should be recalled that students who studied the pre-lab module claimed to have read the lab manual more than four times more often than the control group. Since other factors have remained the same, we hypothesize that the increased reading might actually be an effect of doing the pre-lab module. A possible explanation is that students are indeed more actively involved and that the pre-lab module might have triggered additional reading of the manual. Another explanation is that students might look for information in the manual to answer the assignments in the pre-lab module. One way or another, this result raises the question whether the presented results are direct effects of the pre-lab module itself or indirect effects of just reading the lab manual. Nevertheless, we found no significant additional effect of reading the lab manual on the test scores between the groups. This result implies that the improved results on students' test scores were not an effect of the lab manual. We have no reason to believe that this is different for the presented lab report scores or students' questions.

Improving Understanding

In this study, we systematically explored students' insight into the experimental procedure by recording all questions from students and categorizing them in different question types. In general, students most regularly asked simply what they needed to do in the lab. This is consistent with previous studies on student questions in the lab (Johnstone, 1997; Kozma, 2003; van der Kolk et al., 2012). Most importantly, we showed that these types of low-order questions are asked

less often by students who studied the pre-lab module. One advantage of fewer students' questions is that it reduces the workload for teachers and teaching assistants in the lab. This is especially relevant for labs with few assistants per students. Moreover, fewer low-order experimental questions suggest that students know better what needs to be done in the lab and have more confidence in that knowledge—a finding in agreement with previous results on pre-lab materials (Johnstone, 1997; Jones and Edwards, 2010; Schmid and Yeung, 2005).

However, the number of questions students ask on the background theory in our study remains scarce for both students with and without pre-labs. This result may be caused by the fact that there was no time scheduled for discussion during the lab activity and students are too occupied with the experimental procedures to reflect on the theoretical background. However, despite the fact that the number of theoretical questions did not increase in the experimental group compared with the control group, the theoretical understanding appeared to be clearly improved in the experimental group. The students that studied the pre-lab module scored better on the lab journal assessment, including their ability to discuss the results and to indicate limitations.

Recommendations and Future Studies

This study shows that the introduction of pre-lab modules results in better performance in a lab report and fewer low-order experimental questions in the lab, which we expect to be the result of improved understanding of the link between theory and practice. However, since reflecting on the theory during the lab exercises appears to be limited, we recommend that teachers use extra time in the lab to ask scaffolding questions and even further improve students' understanding of the experiment. Post-lab activities such as in-class discussions or post-lab computer modules might, similar to pre-lab modules, guide students to reflect upon their obtained results and improve students' understanding of the experiment (Reid and Shah, 2007). We support the conduction of studies on the effect of such post-lab modules on students' understanding of the background theory and its relation to practice. Finally, we should note that this study was specifically performed to align lab activities with learning goals on understanding the theory and its relation to practice. We highly recommend that teachers and researchers investigate how to align their lab activities with their learning objectives.

This study started from an exploratory investigation showing that the main aim of lab activities of most undergraduate life science teachers is to improve students' understanding of background theory and its relation to practice. Students' understanding of the theoretical framework can be improved with inquiry-based labs, but such activities are not always feasible when multiple concepts are taught, lab space and time is limited, and students have limited lab experience. This study shows that students' theoretical understanding and its relation to practice can already simply be improved by enriching existing expository lab activities with pre-lab computer modules.

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Compliance with Ethical Standards

Informed Consent All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee at Utrecht University (Review Board of Beta and Geosciences at Utrecht University, approval number S-19290). An informed and signed consent was obtained from all individual participants.

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