Scaffolding First Year Biology Undergraduates in a Problem Solving Approach for designing Experiments in Molecular Biology: An explorative design based study

Paulien A. Postma | 3384659

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Supervisor: Marie-Christine P.J. Knippels (Assistant Professor) | *Freudenthal Institute for Science and Mathematics Education, Faculty of Science, Utrecht University*
Coordinator: Arthur Bakker (Assistant Professor)) | *Freudenthal Institute for Science and Mathematics Education, Faculty of Science, Utrecht University*
Second examiner: Dirk Jan Boerwinkel (Assistant Professor)) | *Freudenthal Institute for Science and Mathematics Education, Faculty of Science, Utrecht University*
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RESEARCH REPORT

Scaffolding First Year Biology Undergraduates in a Problem Solving Approach for Designing Experiments in Molecular Biology: An Explorative Design Based Study

Paulien A. Postma

Freudenthal Institute for Science and Mathematics Education, Faculty of Science, Utrecht University, Utrecht, the Netherlands

The process of designing experiments is central in (life) science research, though rarely taught to undergraduate science students explicitly in educational practice. This explorative study aimed to learn about the characteristics and opportunities of an innovative educational approach to guide first year biology undergraduates in designing experiments in molecular biology. We focused on the process of designing an experimental work plan and choosing adequate techniques to a given experimental method. The approach employs general problem solving strategies – which are intuitive in nature – to domain specific knowledge about molecular biology techniques to scaffold students in designing experiments. We adopted a design based research approach for developing an extra-curricular lesson for first year biology undergraduates in designing experiments in expression cloning technology. The lesson was put into practice in a small scale exploratory study with six first year biology undergraduates (four males and two females, average age 19) and combined with a pre- post-test construction and semi-structured interviews. Results showed that the lesson can scaffold students in adopting a self-directed design approach based on general problem solving strategies. The presented approach can make students more aware of the 'why' and 'how' of steps in an experiment and to reason about the applicability of molecular biology techniques. These are considered relevant understandings for a scientist to prepare and conduct experiments efficiently, to trace errors and to analyse results critically. Therefore, it is recommended that already at the start of undergraduate science programs explicit attention should be paid to the skill of designing experiments.

Key-words*: Designing experiment; Problem solving; Scaffolding; Design based research; Molecular biology education.*

Introduction

According to Driver, Asoko, Leach, Mortimer, and Scott (1994) scientific knowledge or the process of acquiring scientific understanding is a process of experimentation. More specifically it is a process of choosing and experimenting with variables, making observations in order to test a hypothesis leading to extensive discussion about the results among members of the scientific community to explain natural phenomena.

Based on the idea of science as experimentally and socially constructed it was suggested that science education should shift its focus from merely transmitting factual knowledge towards instructional approaches that both equip and encourage students such that they are able to solve meaningful scientific problems (DiCarlo, 2006). This new focus gave rise to inquiry based science education (IBSE) which refers to the pedagogical approach modelling the general process of investigation that scientists use as they attempt to answer questions about the natural wold. In IBSE practises emphasis is given to experiment (European Commission, 2007).

The inquiry process can be modelled as an iterative cyclic process including central steps such as: diagnosing the problem, hypothesis generation, experimental design, carrying out experiments, analysing and interpreting data, modelling of data and evaluating and communicating results (Bell, Urhahne, Schanze, & Ploetzner, 2010; Schwarz & White, 2005; Windschitl, 2004). Depending on the type of inquiry instruction that is practiced varying degrees of freedom are allowed to students within this cyclic process. For example in guided inquiry students are given the materials and problem to investigate and need to devise their own procedure to solve the problem. In open inquiry students devise and carry out a complete investigation starting with developing their own research question, planning an investigation ending with evaluating and communicating the results (Colburn, 2000).

The process of designing experiments involves determining variables that are valid to test the hypothesis, choosing a reliable scientific method and designing an experimental workplan (Bell et al., 2010; Harms, Mayer, Hammann, Bayrhuber, & Kattmann, 2004). In other words: translating a research question into an appropriate experimental methodological work plan. Depending on the science domain one is working in different data are needed and as such, different types of experiments need to be conducted (Bell et al., 2010). This emphasizes the importance of being able to design experiments and to choose appropriate tools that can gather data needed to investigate the research question. Scientists have and use this skill frequently and the aim of academic science studies is to educate (under)graduate science students such that they develop this scientific inquiry skill too.

However, when it comes to designing experiments this process still reveals several difficulties for students (Wiegant, Scager, & Boonstra, 2011). Though there are technological tools that support students in the process of experimental design (e.g. Knowledge Integration Environment; Linn 2000, Web-based Inquiry Science Environment; Slotta 2004), students do not know which variables to focus on and find the search for appropriate tools difficult (Bell et al., 2009; Wiegant et al., 2011). Learning how to design experiments and choose appropriate tools for inquiry is underexposed in current educational practices (Coil, Wenderoth, Cunningham, & Dirk*,* 2010; Hoskins, Stevens, & Nehm, 2007; Hofstein & Lunetta, 2004; Neumann & Welzel, 2006; Wiegant et al., 2011).

This study focuses on how first year biology undergraduates can be supported in designing experiments. This will be explored in the field of molecular biology because especially in molecular biology numerous techniques exist that can be used as tools to collect data. Moreover, the body of potential techniques for experimentation in molecular biology is growing due to rapid technological advancements in this domain. Given the amount and potential of techniques available for scientific inquiry in molecular biology planning experiments and choosing appropriate tools isn't easy or straightforward. Instead, it requires creativity, domain-specific content knowledge about the topic at hand and knowledge about data collection methods (Windschitl, 2001). Designing experiments is therefore an important aspect of the education of undergraduate biology students that needs explicit attention in educational practice.

The goal of this study is gaining insight in an adequate educational approach to guide first year biology students in designing experiments in molecular biology. We will focus on the process of designing an experimental work plan to a given science topic and method. We adopt a design based research approach for developing and testing an extra-curricular lesson for first year biology undergraduates in designing experiments in molecular biology.

Theoretical framework

In search for a suitable educational approach for guiding students in designing experiments in molecular biology literature about IBSE has been consulted as well as experts (i.e. four experienced life-science researchers and teachers). In the following section the rationale is presented ending with concrete design criteria for a lesson in designing experiments.

Scaffolding

IBSE is grounded in the belief that learners should be engaged in self-directed knowledge construction. It is therefore a constructivist process (Hmelo-Silver et al., 2007). In IBSE students learn content knowledge, procedural strategies and self-directed learning skills through collaboratively solving problems and communicating ideas and results (Hmelo-Silver et al., 2007). These problems are typically authentic scientific problems or questions (Edelson, 1998).

Since inquiry requires a considerate amount of conceptual and procedural knowledge it is important students are provided with systematic and strategic instructional support to facilitate students' investigational practices (Hmelo-Silver, Duncan, & Chinn, 2007; Neumann & Welzel, 2006). In IBSE practices instructional support is given on a 'just-in-time' basis and aims to facilitate student's problem solving practices (Hmelo-Silver et al., 2007). This means that students experience a need to learn first and then are given instruction they experience as relevant or helpful for (continuing) their problem-solving or investigational practices.

The instruction in response to the content-based motive does not only take the form of direct instruction (for example a mini-lecture) where the teacher transfers factual knowledge needed for solving the problem. Instruction can also take less direct forms whereby the teacher guides the students in their problem solving process by means of scaffolding (Hmelo-Silver et al., 2007). Scaffolding aims to bring students gradually in a state of competence in which they can solve (scientific) problems individually (Smit, Van Den Eerde, & Bakker, 2012).

In literature several scaffolding strategies in the context of IBSE practices are mentioned. Most of these are based on teachers' use of particular reasoning strategies to give students guidance and support in their problem solving practices (Hmelo-Silver & Barrows*,* 2006). Often mentioned are: (re)directing students' attention to important learning goals, stimulate students to explain ideas, pushing students to think deeply, using metacognitive questions to encourage student's recognition of (knowledge) gaps, summarizing ideas to give structure to students' inquiry process and model the kinds of questions they need to ask themselves (Hmelo-Silver & Barrows*,* 2006). In IBSE practices the use of scaffolding strategies fades as students become progressively competent self-directed learners. This means that students take over the strategies that served as a scaffold earlier and thereby learn to solve scientific problems individually.

Overall, scaffolding could be a fruitful approach to guide students in designing experiments and gradually bring them into a state of competence in which they can design (similar) experiments. Therefore, the first design criterion for the lesson in designing experiments in molecular biology is: *the lesson should make use of scaffolding to adequately guide students in a process of designing experiments in molecular biology.*

Problem solving approach

During inquiry practices, students work on solving authentic scientific problems. In most general terms literature in the learning sciences specifies problem solving as two processes that interact, namely creation of a problem space (the problem solver's view of the problem) and a solution process (Dhillon, 1998; Zimmerman, 2000). When constructing a problem space the solver defines the initial and goal state and attempts to 'understand' the problem by connecting it to existing knowledge. The solution process involves the search for operators (elements of the problems' solution) that can bring the initial state of the problem space towards the goal state (Dhillon, 1998).

Several general problem solving strategies have been defined that can be recognized when solving problems. A general problem solving strategy is a technique that may not guarantee solution, but serves as a guide in the problem solving process (Mayer, 1983). Frequently mentioned strategies are *problem decomposition* and *means-end analysis* (Gick, 1986). Problem decomposition is used when the problem space is too large and is therefore transformed into a more manageable form by breaking down the problem into sub problems. Means-end analysis is an assessment made between the current (knowledge) state and goal state followed up by seeking and using new operators to reduce these differences (Dhillon, 1998; Gick, 1986; Jonassen, 1997).

General problem solving strategies are called general because they can be recognized in a wide variety of problems – both daily life and professional. As such, general problem solving strategies are not tied to specific (scientific) problems. In addition, general problem solving strategies seem to be used intuitively. Therefore, people might not be explicitly aware of the strategies they use. Klahr and Dunbar (1988) state that in the field of scientific discovery the same problem solving strategies are recognizable as when solving problems encountered in daily life. Problem solving in knowledge rich domains (such as physics, math and biology) involves the interaction between general problem solving strategies and domain-specific knowledge (Klahr and Dunbar, 1988).

So, since general problem solving strategies are already used intuitively, in educational context this means students should be encouraged to apply these general problem solving strategies when designing experiments in molecular biology rather than being given instruction how they can apply them.

Problem solving approach for designing experiments in molecular biology.

Experiments in molecular biology typically aim to collect data needed to answer a research question. In the experiment a series of molecular biology techniques are used with which from certain starting material (specific tissue or a cell culture) the desired end data can be gathered (hereafter referred to as *produced)*. For example, when setting up an experiment aimed to sequence a specific gene in a malignant lung tumour, the lung tumour tissue serves as starting material. The desired type of end data encompasses a sequence read of the gene of interest. The sequence read of the gene of interest can in turn be used to analyse what type of mutation has caused the tumour. This is modelled schematically in figure 1.

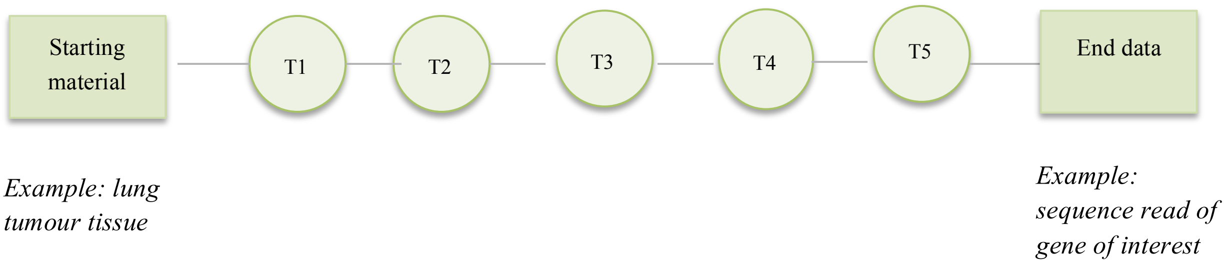

Figure 1. 'Start' represents the starting material with which you can start performing the experiment and 'end data' the desired end data of the experiment that can be used for subsequent analysis. Circles represent the molecular biology techniques (T) needed to produce the desired end data.

The molecular biology techniques to be used in the experiment all have the same features: they require specific input and produce - via a specific throughput (technical procedure or working mechanism) - certain output (hereafter referred to as *intermediate products* in the experiment). Usually, the output of technique 1 can serve or is needed as input for subsequent technique(s). This results in an experiment where various techniques follow each other up in in an input/output dependent manner. In the example of sequencing a specific gene in a lung tumour as intermediate products are needed (amongst others) isolated DNA and the Polymerase Chain Reaction (PCR) product of the gene of interest. The output of the DNA isolation technique can be the input for the PCR technique. These two techniques can thus follow each other up input/output dependently. Seen through the lens of problem solving it can be argued that an experimental work plan consisting of a series of techniques transcending from starting material to the desired end data relates to a set of operators transcending the problem space from initial state to goal state. This is modelled schematically in figure 2A en 2B.

Close analysis of the process of designing experiments with experts in molecular biology revealed that they engage in an iterative and cyclic process consisting of defining what intermediate products are needed, seeking for techniques that can produce these products (outputs) and checking whether the output of technique 1 can be input for the subsequent technique and so on and vice versa. In this process problem decomposition and means-end analysis can be recognized. In the example of the lung tumour it is assessed whether the output of the DNA isolation technique can serve as input for the PCR technique. This is modelled in figure 2C. Designing experiments in molecular biology thus builds for a large part on intuitive problem solving strategies.

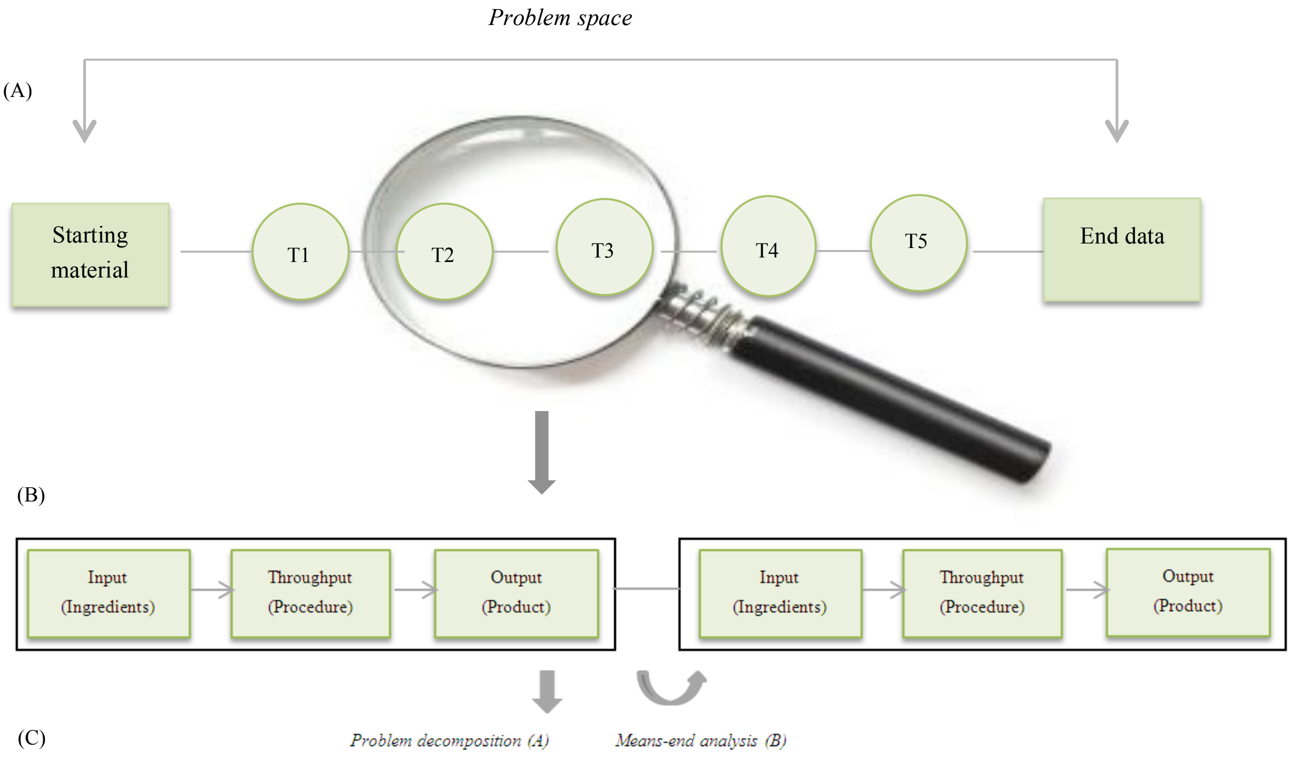

Figure 2. Applying the problem solving approach to the design of experiments in molecular biology. (A) The series of techniques that can transcend from starting material to the desired end data of the experiment are the equivalent of a set of operators transcending the problem space. Circles represent the molecular biology techniques (T) needed to generate the desired end-data. (B) Close-up of two techniques. Visualized are the input/throughput/output features of techniques and how these techniques are chained to each other input/output dependently (C) For defining what intermediate products (outputs) are needed in the experiments problem

decomposition is applied. For checking whether the output of technique A can be the input for technique B (assessing the application of techniques) means-end analysis is applied.

So, when designing experiments researchers actually engage in a problem solving process that encompasses defining starting material and desired end data, seeking what intermediate products are needed, searching for appropriate techniques, assessing their potential in the problem space and using them to transcend the problem space from starting material to end data. Therefore, problem solving could be a suitable instructional approach to scaffold students in a process of designing experiments in molecular biology. This led to the second design criterion: *the lesson in designing experiments in molecular biology should make use of the problem solving approach, whereby students search for the required intermediate products, according appropriate techniques, assess their application and use them to set up a series of techniques that are chained to each other in an input/output dependent manner*

Hypothesis and sub questions

This study is explorative in nature aiming to gain insight how undergraduate biology students can be guided in designing experiment in molecular biology. Based on the literature study it is suggested that scaffolding and problem solving are promising for an educational approach. The hypothesis underlying this study is: *a problem solving based educational approach can scaffold undergraduate biology students in designing experiments in molecular biology.* In order to test this hypothesis, four sub questions are formulated, which are:

1. What are the features of a Hypothetical Learning Trajectory (HLT) and according learning activities that scaffolds students in a problem solving approach for designing experiments in molecular biology?
2. How do students progress through the different learning activities of the designed lesson?
3. What are the effects of the learning activities on how students design experiments in molecular biology?
4. What are students’ reflections on their learning process regarding the design of experiments in molecular biology?

Methodology

Design based research

For this study a design based research approach is adopted which involved roughly three phases: an exploration, design and test phase. During the exploration phase literature is used to determine learning and teaching problems in the research domain and to build ideas on how to deal with these problems. The exploration phase resulted in the aforementioned hypothesis and design criteria for a lesson in designing experiments.

The exploration phase is followed-up by the design of learning activities and accompanying learning materials and a set of expectations how students' thinking and understanding will evolve in the context of these tasks (Simon, 1995). The resulting HLT by interrelates the theoretically grounded design criteria with the designed learning activities and aims, predicts the learning outcomes and guides data analysis. The HLT can therefore be considered both an outcome of design based research as well as an instrument to test the underlying theory (problem solving, scaffolding) for designing experiments in molecular biology (Bakker, 2004).

In the last phase – the test phase – the HLT is used to research to what extent learning activities of the designed HLT can guide students in designing experiments. Usually in design based research this happens in a cyclic process in which the HLT is designed, tested, redesigned, tested again, and so on. The current study only includes the first cycle of design based research aimed to explore the characteristics of an appropriate educational approach based on problem solving to scaffold students in designing experiments in molecular biology. It is therefore a proof of principle: can it be done, is it within reach and meaningful for first-year biology undergraduates?

Design procedure

Expression cloning technology was selected as the central topic in this study. This experimental method is considered representative for typical experiments in molecular biology for example to study gene expression or protein function. In addition, it involves the use of a wide variety of basic molecular biology techniques. Choices made with regard to the target group and topic resulted in the selection of the course Biotechnology as an appropriate research setting for the context-specific design and subsequent testing of the lesson. This course is scheduled in the last semester of the first year of the bachelor Biology of Utrecht University (April 2013 – June 2013).

The design of the HLT was performed by the first author. The design process required reasoning back and forth between the two design criteria and continuously considering how students' thinking and understanding should evolve. Gradually this gave rise to a sequence of learning activities that characterizes the HLT.

Designing the leaning materials that were expected to elicit this thinking and understanding was done in an iterative way and in close collaboration with the coordinator and head teacher of the course Biotechnology. To match the learning materials with students' prior knowledge it was checked if and in what detail students of the course Biotechnology are taught about expression cloning technology. To this end the first author attended several seminars of the course Biotechnology and analysed the course reader. In addition, at two time points during the design phase meetings were organized between the first author of this study and the coordinator of the course Biotechnology. During the meetings the learning materials were evaluated, discussed and adjusted based on three criteria:

1. Scientific soundness and authenticity: to ensure that the content of the learning materials is scientifically correct.
2. Scientific content: to ensure the content of the learning materials match with student's prior conceptual knowledge regarding the experimental procedure and techniques.
3. Feasibility: to ensure that the tasks are logical and orderly and don't include sudden changes of difficulty.

To ensure the validity of the HLT various versions were discussed extensively with the second author of this study starting from the theoretical underpinning towards the tasks that were designed, coherence between the tasks and the expected outcomes.

The HLT in practice

The HLT was tested in a small-scale exploratory study with first year biology undergraduates engaged in an extra-curricular lesson. The exploratory study aimed to find out whether the HLT met the expectations and to reflect on the adequacy of the underlying design criteria (problem solving approach, scaffolding) for guiding students in designing experiments. This section elaborates on the design of the exploratory study and the participants.

Participants.

Selection of the exploratory study participants was done based on convenience sampling. Students of the course Biotechnology were addressed by the first author of this study during various seminars of the course Biotechnology. Students were told about the aim and topic of the lesson, duration and location and asked to participate in couples. This resulted in three couples (four boys, two girls, average age 19) willing to participate. The couples knew each other from the course Biotechnology but did not see or communicate with each other on a regular basis inside or outside the course Biotechnology.

Design of the exploratory study.

The HLT was put into practice in the form of a 60-minute extra-curricular lesson at Utrecht University. The extra-curricular lesson took place midway (5 weeks after the start) the course Biotechnology and just after students had finished the topic recombinant DNA technology. The lesson did not involve a teacher: the HLT was designed such that it could self-direct students in the tasks. The teaching method comprised students working on successive tasks. Students worked on the tasks in couples to stimulate them explaining and discussing their thoughts and answers. In addition, students were asked to fill in the worksheets that accompanied the tasks individually. The first author was present during the lesson taking field notes on students' progression and discussion. In addition, the first author was available for student's questions about the tasks only when this appeared to hinder students' progression. The lesson aimed to test the conjectures about students' learning as included in the HLT, which relates to sub question 2.

The extra-curricular lesson was preceded by a 20-minute pre-test with the same student couples. The pre-test aimed to document students' starting level concerning the design and content-based argumentation of an experimental work plan. The question used for the pre-test is adopted from the 2012 final exam of the course Biotechnology thereby ensuring alignment with students' prior conceptual and procedural knowledge regarding the design of experiments (see Appendix C). The topic central in the pre-test was the same as central in the HLT, namely expression cloning technology. Students were asked to describe and motivate as detailed as possible the steps needed for performing the experiment.

The extra-curricular lesson was followed-up by a 20-minute post-test conducted with the six students individually. The post-test took place 3 weeks after the extra-curricular lesson – just after students had finished the last topic of the course Biotechnology and just before the final exam would take place - and comprised the same task used for the pre-test. Together, the pre-test – extra-curricular lesson – post-test construction enabled to describe the effects of the lesson on to how students design experiments in molecular biology. This accounts for sub question 3.

Lastly, two 10-minute semi-structured interviews were held directly after the lesson (with the student couples) and after the post-test (with the students individually). The interviews aimed to gain insight in students' perception and appreciation of the tasks. Accordingly, the interview questions were motivated by the anticipations of the HLT. In addition, students were asked to what extent they experienced the lesson as new in relation to their regular biology education and useful for designing experiments in molecular biology. The results account for sub question 4. An overview of the design of the exploratory study is depicted in Figure 2.

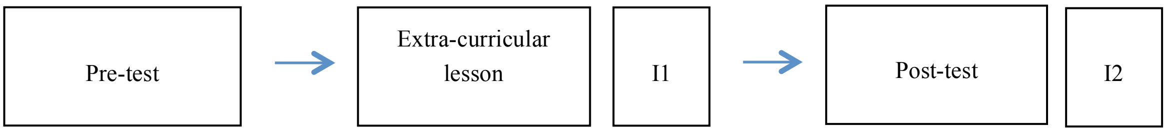

Figure 2. Design of the exploratory study**.** Consisting of a 20-minute pre-test, conducting the 60-minute extra-curricular lesson followed-up by 10-minute semi-structured interviews (I1) all held with three student couples. After three weeks the teaching experiment was followed-up by a 20-minute post-test ending with a 10-minute semi-structured interview (I2) held with students individually (n=6).

Data sources

Students' discussions during the pre-test, post-test and extra-curricular lesson were audiotaped. The audiotapes were transcribed verbatim and used as primary data source next to the filled in work sheets. For the extra-curricular lesson these data sources were supplemented with the field notes from the observations. The semi-structured interviews were audiotaped and transcribed verbatim and served as the last data source collected in the exploratory study.

Data analysis

Data analysis included three consecutive steps: (i) analysis of the extra-curricular lesson, (ii) analysis of the pre- and post-test and (iii) analysis of the student interviews.

*Extra-curricular lesson***.**

Analysis of the extra-curricular lesson can be distinguished in two phases: an interpretative phase and reconstructing phase. The conjectures about students' learning in the HLT provided evaluation criteria. These were kept in mind throughout the entire analysis process. The transcripts of students' discourse during the teaching experiment contained the most complete information since they recorded every word of students' think aloud reasoning when working on the tasks. Therefore, this data source is used for the primary reconstruction of students' thinking and understanding as evolving during the tasks. This data source was triangulated with students' written answers in the worksheets and the field notes from the observations. Analysis in the interpretative phase included the following consecutive steps:

1. Close reading of all TAP's and highlighting striking phrases.
2. Describing in detail the students couples' reasoning per learning activity, distinguished per student couple and illustrated with quotations derived from the transcripts and students' written answers from the worksheets.
3. Combining, distilling and summarizing striking features in student couples' reasoning distinguished per learning activity and illustrated with quotations derived from the transcripts and students' written answers from the worksheets.

To validate the interpretation of the data these summaries were discussed with the second author of this study. Discussion was focused on interpretation of the quotations and relating these to the summaries of students' learning and continued until consensus was achieved.

In the reconstructing phase the focus was on analysing and describing students' progression in taking over de reasoning strategies that served as a scaffold for designing experiments as arising from the learning activities. In order to do so, the conjectures about students learning in the HLT were combined into four evaluative questions. These evaluative questions summarize the HLT in a sequence of four phases that scaffold students to a state of independency in designing experiments using a problem solving approach. Analysis included the following consecutive steps:

1. The evaluative questions were used as categories in which the summaries per learning activity (n=11) resulted from the interpretative phase were categorized.
2. Distilling common features and strategies in students' reasoning from the summaries.
3. Answering the evaluative questions by combining and summarizing common features and strategies into a description of students' reasoning as evolving during the extra-curricular lesson.

*Pre- and post-test***.**

Students' performance on the pre-and post-test were analysed and outcomes of the pre- and post-test were compared. Moreover**,** the post-test was compared to the outcomes of the extra-curricular lesson. The main data source used for analyses was the transcripts of the audiotapes during the pre- and post-test, since the written answers/ worksheets only showed students' final design of the experiment and not the process towards this design. Analysis focused on the problem solving process: so, to what extend do students define starting materials and end data and are they involved in a cyclic process of seeking intermediate products and according techniques, chaining them to each other in an input/output dependent manner and detecting and solving gaps. The outcomes of the post-test were compared with (1) the outcomes of the pre-test and (2) the outcomes of the extra-curricular lesson to reflect on differences and to what extent these could be ascribed to the extra-curricular lesson.

Interviews

Lastly, analysis of the pre-test, post-test and extra-curricular lesson was paralleled with students' reflections on the tasks in the semi-structured interviews. The interviews transcripts were analysed on 3 criteria:

- Students' recall of central steps and strategies practiced and applied in the lesson;
- Students' expressions about the added value of the lesson for developing skill in designing experiments in molecular biology;
- Students' expressions about the added value of the lesson in their bachelor education.

Results

The designed HLT

A detailed version of the HLT can be found in Appendix A. In the following section is explained how the two design criteria are interrelated ending with a general outline of the HLT. The two design criteria for the extra-curricular lesson are:

1. The lesson should make use of scaffolding to adequately guide students in a process of designing experiments in molecular biology towards a state of independency.
2. The lesson in designing experiments in molecular biology should make use of the problem solving approach whereby students search for the required intermediate products, appropriate techniques, assess their application and use them to set up a series of techniques that are chained to each other in an input/output dependent manner.

Criterion 1 aimed to gradually bring students in a state of independency in designing experiments. To this end it was decided to sequence the lesson in three phases with in each phase one experiment as the central topic. In the three subsequent phases scaffolding is gradually reduced while students are encouraged towards using the problem solving approach for designing experiments. Scaffolding is reduced towards independency. This means that in the last phase students are responsible for designing an experiment without guidance or support by the material but depending on their own problem solving strategies and conceptual knowledge.

Criterion 2 aimed to bring students in the position that they approach the design of experiments from a problem solving approach. In this way students' intuitive problem solving strategies would be called upon that would guide them in designing the experiment. The problem solving approach for the design of an experiment encompasses:

1. Defining starting material and desired end data
2. Seeking what intermediate products are needed and according appropriate techniques or technical operations
3. Checking the applicability of the techniques/technical operations by matching the output/input sequence (assessing whether the output of technique A can be input for the technique B and so on and vice versa)

Step 1, 2 and 3 can be performed in a cyclic process by repeating these steps back and forth meanwhile detecting and solving gaps to complement and complete the design. The lesson needed to guide students in this approach for designing experiments and to encourage students to adopt problem solving approach that suits them best. Therefore, interrelating the problem solving approach with scaffolding led to phase 1 in which students are modelled the approach for designing experiments using a visual model. To this end, students are given the experimental work plan of experiment 1 in the format of Figure 1. Learning activities encourage students to analyse this workplan as a series of steps (defined as an intermediate product produced by a separate technique or technical operation) chained to each other in an input/output dependent manner thereby transcending starting material to the desired end data. The tasks that are designed encourage students to use problem decomposition and means-end for this analysis. Thus, in phase 1 students are modelled how general problem solving strategies apply to the domain of experiments in molecular biology. However, they are not explicitly told about these strategies nor giving instruction how to apply them. As such, students are made familiar with the problem solving strategies and at the same are given freedom to internalize the strategies/approach as applicable and useful for designing experiments at their discretion.

In phase 2 students are encouraged to apply the approach – presented as a 'stepwise procedure' - as they have interpreted it from phase 1 for finishing the design of experiment 2. Scaffolding is reduced by giving students only the first step needed for experiment 2. Students are guided in finding the remaining steps by means of hints that require applying means-end analysis and problem decomposition.

In phase 3 students are directed towards a state of independency in designing experiments from a problem solving approach. Students are asked to design experiment 3 in the same stepwise way as practiced in preceding experiments. Students aren't given guidance or support in their design process. Instead, students have to rely on their own conceptual knowledge and are given the freedom to use the strategies they consider helpful for designing the experiment as a coherent and detailed set of steps.

Since this study is set within the course 'Biotechnology' a biotechnological application of expression cloning technology was selected as context for the learning materials. This led to the research topic *Folsomio Candida (F.candida).* Recent research identified a gene in this eukaryotic organism that codes for the enzyme isopenicilline N-synthase, which can produce isopenicilline-N. Expression cloning technology has been applied to construct the molecular clone of the gene of interest and introducing it into host organisms that can produce the protein product of the cloned gene on a large scale (Roelofs, Timmermans, Hensbergen, van Leeuwen et al., 2013). This research context was used as the context for the learning materials.

In the learning materials the following key experiments were distinguished: (i) isolating the gene – with unknown DNA sequence - of interest by preparing a cDNA library, (ii) screening the library for clones with the desired insert and (iii) retrieving the desired insert and using expression vectors to create a library of clones with each clone expressing the protein. These three experiments are central in each phase of the lesson. The lesson started with introductory learning activities to make students familiar with the research topic and research method central in the learning materials. In addition, it was made sure that the learning materials only included the molecular biology techniques students are taught in the course Biotechnology. Together, this led to the final design of the HLT of which a detailed version can be found in Appendix A. The lesson materials are included in Appendix B. A shortened version of the HLT is presented below.

Phase 1 Experiment 1 Creating a cDNA library

Scaffolding: building up the scaffold

LA1: Introduction to the research topic and research method

LA2: Introduction to the three successive experiments central in the learning materials

LA3: Defining starting material and desired end data of the three experiments

LA4: Directing students' attention to the input/throughput/output nature of the steps in the experimental workplan of experiment 1

LA5: Directing students' attention to the according techniques and technical operations of experiment 1 are how they are chained to each other in an input/output dependent manner.

LA6: Directing students' attention to the role and implications of specific control experiment in experiment 1.

Phase 2 Experiment 2 Screening the cDNA library

Scaffolding: reducing the scaffold

LA7: Recall experiment 2 and encouraging students to define starting material and desired end data of experiment 2

LA8: Encouraging students to finish the design of experiment 2 using the initial format and hints in the learning material and based on the stepwise approach modelled in experiment 1.

LA9: Asking students to reason what steps need control experiments.

Phase 3 Experiment 3 Cloning into expression vectors

Scaffolding: handover to independence

LA10: Asking students to design experiment 3 using the stepwise approach with which is practiced in experiments 1 and 2.

LA11: Asking students to include and motivate control experiments in the design of experiment 3.

Results of the exploratory study

*Students' progression through the different learning activities***.**

The results are presented per phase of the lesson and structured around evaluative questions that relate to the hypothesized learning outcomes of the learning activities. Table 1 describes phase 1 in the learning activities, the evaluative questions, and summarizes the achieved effects per duo.

Table 1. Learning activities, evaluative questions and achieved effects of phase 1 of the lesson.

Phase 1 Building up the scaffold Experiment 1: constructing a cDNA library	Evaluative questions	Duo 1 Paul &Jake*[1] Duo 2 Laura & Ian*	Duo 3 Chris & Mary*
LA1-LA2: General introduction to the research topic and research method central in the learning material. Students are asked to describe what cDNA libraries constitute and why this is a relevant experimental method for the *F.candida* research.	Do students understand what the three experiments in constructing a cDNA library encompass?	Students explain correctly what the three experiments yield and how these relate to each other.	Students have difficulty describing what the three experiments encompass. Students seem not to understand how they relate to each other.
LA3: Introduction to the experiments central in the learning material. Students are asked to describe what the three experiments yield and why these data are needed for the *F.candida* research goal.	Are students able to describe the three experiments in terms of starting material and desired end data?	Students give clear descriptions of starting material and end data. They also show how the three experiments are chained to each other in an input/output dependent manner.	Students have difficulty defining starting material and desired end data.
LA4-LA6: Analysing the input/output depended sequence of steps in experiment 1 via 3 strategies: - Students are asked to describe the role of every step in the experiment in terms of output and the relevance of that type of output. - Students are asked to describe the technical throughput of every step in the experiment guided by the question: how is this step performed in the laboratory? - Students are asked to describe the rationale for and implications of doing control experiments.	Do students understand that experiments constitute a series of techniques or technical operations that are chained to each other in input/output dependent manner?	Students' reasoning indicates LA4 is able to create awareness of the fact that the steps of experiment 1 are chained In an input/output dependent manner. Already in LA4 students describe the role of step 1 as "to produce output B", and the output B is "necessary for performing step 2", and so on.	Students' reasoning indicates LA4 was needed to call upon prior knowledge. LA5 pushed them to define more precisely the outputs of every step. This helped to reason how the steps are connected to each other in an input/output dependent manner.

Duo 1 and duo 2 – but not duo 3 – could easily call upon their prior knowledge concerning molecular cloning technology and therefore progress smoothly through LA1, LA2

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[1] * *Pseudonym*

and LA3. When analysing the experimental work plan of experiment 1 in LA4 and LA5 students' reasoning indicated they are aware of the fact that that the output of a step can be the input of the subsequent step, and what techniques or technical operations can produce the specific output. Quote 1 illustrates this reasoning.

Quote 1 Duo 1 (Experiment 1 R262-291)

Jake: *Step 1, RNA isolation. First, what product is produced with it. And why is this product necessary for the experiment. OK. Well, this one is given: you isolate total RNA.*

Paul: *Yes, and why is that necessary. Well, because you don't want all that other junk….*

Jake: *Yes, [you need to] separate it from the cell debris*

Paul: *Yes, because all those cell organelles and whatever are useless.*

Jake: *So we have total RNA. But we don't need total RNA, we only need mRNA. So, in step 2 we are going to purify mRNA [from the total RNA]. So what do we put into it? The solution with purified total RNA. What do we want to get out of it? Just the mRNA. And why? Well, because we are not interested in tRNA and micro RNA molecules etc. OK, then we continue with step 3: cDNA synthesis. What do we put into it? All the mRNA derived from the colon tissue. What do we want to get out of it? DNA of those mRNA molecules. So we can make a cDNA library out of that.*

Duo 3 had difficulties in interconnecting the steps of experiment 1 since they have difficulty recalling what cDNA libraries encompass. With a little help of the first author going through the tasks of LA4 plus LA5 that pushed them to define more precisely the outputs of every step, duo 3 seemed to understand how the steps of experiment 1 are connected to each other in an input/output dependent manner.

In LA6 the student duo's reasoned that control experiments are needed to check the output of certain steps. Results of the control experiments allow either to perform the subsequent techniques and technical operations needed for experiment 1 or to repeat previous steps. Students' discourse indicated they understand that the outputs of the steps in experiment 1 together form a chain that gathers the data needed to transcend from starting material towards the desired end data. This chain needs to be checked and possibly reinforced by repeating certain steps.

In phase 2 (LA7-LA9) scaffolding is faded. Table 2 summarizes the learning activities, evaluative questions and achieved effects. In LA7 duo 2 and 3 started designing experiment 2 with discussing what the starting material and desired end data are. Duo 1 immediately started seeking for the required steps in the experiment.

Table 2. Learning activities, evaluative questions and achieved effects of phase 2 of the lesson.

Phase 2 Fading the scaffold Experiment 2: screening the cDNA library	Evaluative questions	Duo 1 Paul & Jake Duo 2 Laura & Ian	Duo 3 Chris & Mary
LA7: Creating a problem space. Students are asked to define and write down starting material and end data of experiment 2 in the *F.candida* research.	Do students construct a problem space by defining starting material and desired end data?	Duo 1 immediately starts seeking for the steps needed in the experiment. Duo 2 defines starting material and desired end data.	Students define starting material and desired end data but do not write these two end-points down in their worksheets immediately.
LA8: Students are asked to design the experiment by setting up input/output dependent chain of techniques/technical operations that will allow editing the starting material to the desired end data.	Do students break the problem into a preliminary set of steps need for experiment 2 by building on the framework that has been given as a starting point and the hint included in the learning materials? Do students match the input and output of the preliminary set of steps in the experiment to detect and solve gaps?	Students focus on a central step in the experiment. Encouraged by the hint students consider the throughput of this central step. This results in students' defining in precise terms the required input of the central step. Students match the output of the first step with the input of the central step. This results in defining what intermediate products are needed and setting up a preliminary set of steps.	Students focus on a central step in the experiment. Encouraged by the hint students consider the throughput of this central step. This results in students' understanding the required input of the central step. Students match the output of the first step with the input of the central step. This results in defining what intermediate steps are needed.
LA9: Reflecting on the input/output dependent sequence of steps in experiment 2. Students are asked to describe what steps need be checked how and why and what steps need to be repeated when results are negative.	Do students reflect on the sequence of steps in experiment 2 by analysing the coherence of the input/output chain?	Yes, but not in LA9 partly due to design error. During LA8 students continuously compare the output and input of the preliminary set of steps to complement the initial design of the experiment. In this process students detect and solve gaps	Yes, but not in LA9 partly due to design error. During LA8 students continuously compare the output and input of the preliminary set of steps to complement the initial design of the experiment. In this process students detect and solve gaps

In the learning materials students are scaffolded in finding the intermediate steps by receiving a hint. The hint students received is to focus on the throughput of the hybridization step and the question: what hybridizes with what exactly? Students' discourse shows the hint encourages to set up a preliminary set of steps. Firstly, students defined what happens during the hybridization step. For example, duo 2 reasoned that hybridization concerns the binding of a single stranded DNA probe with a DNA strand of the cosmid. This enabled them to be more precise in the required input: the cosmid needs to be single stranded. This resulted in students reasoning that the bacteria need to be lysed and the cosmids need to be denaturized before being able to hybridize the cosmids with a probe. This two-step procedure between step 1 (transfer) and step 4 (hybridization) constituted duo 2's preliminary design of experiment 2. Quote 2 illustrates this reasoning.

Quote 2 Duo 2 (Experiment 2 R237-257)

Ian: *The last step is hybridization, obviously. You add the probe [to the bacterial colonies] and check what binds. No, the last step is checking what binds.*

Laura: *Yes, you just add the probe and the last step is selecting the bacterial colony that binds the probe, right?*

Ian: *Yes.*

Laura: *So the step before that is hybridizing with the probe.*

Interviewer: *So what steps need in between? (Points at the empty squares drawn by the students between the first and last step)*

Laura: *I don't know yet.*

Ian: *OK, well, before you can perform the hybridization step you need to prepare the nitrocellulose filter in such a way that…*

Laura: *We need to do something with single stranded and double stranded DNA probably…*

Interviewer: *(towards Ian) Could you finish your sentence?*

Ian: *I said, before you can perform the hybridization step you need to…you have to think backwards. What do you need to do before you can perform the hybridization step?*

Students continuously compared the output and input of this preliminary set of steps to complement the initial design of the experiment. In this process students used means-end analysis to detect and solve gaps. For example, duo 2 felt there was a gap between lysing the bacteria and denaturizing the cosmids. They reasoned that before denaturizing the cosmids the cosmids needed to be isolated from the bacterial cell contents by transferring the cosmids to a nylon membrane.

Students' final design differs in detail between the student duo's caused by a difference in conceptual knowledge about the required techniques. However, the experimental workplan of all student duo's showed the steps they experienced needed to produce the desired input for the hybridization step, chained to each other in an input/output dependent manner.

In LA9 students are stimulated to reflect on the coherence of the set op steps in terms of input/output and the applicability of the according techniques. However, it appeared students reflected intuitively by continuously comparing the input/output chain to detect and solve gaps. Focusing on control experiments hardly attributed to this reflection phase. On the contrary, the choice to focus students on doing Sanger sequencing as a control experiment in experiment 2 confused them. Neither of the student duo's could reason why it is needed and what the implications are.

In phase 3 scaffolding is completely omitted. This means that students aren't given a starting point for designing the experiment nor any hints that guides them in finding the required steps. Table 3 summarizes the learning activities, evaluative questions and achieved effects.

Table 3. Learning activities, evaluative questions and achieved effects of phase 3 of the lesson.

Phase 3 Handover to independence Experiment 3: cloning in an expression vector	Evaluative questions	Duo 1 Paul & Jake Duo 2 Laura & Ian	Duo 3 Chris & Mary
LA10: Students are asked to design experiment 3 by setting up input/output dependent chain of techniques/technical operations that will allow editing the starting material to the desired end data.	Do students construct a problem space by defining starting material and desired end data? Do students break the problem into a preliminary set of steps need for experiment 3 by calling upon prior knowledge? Do students match the input and output of the preliminary set of steps in the experiment to detect	Student don't define desired end data Students define a preliminary set of steps by calling upon prior knowledge. These serve as stepping-stones. Students compare current status with input of stepping-stones. This leads to detailing the stepping-stones into a set of small successive steps.	Students define starting material and desired end data. Students define a preliminary set of steps by calling upon prior knowledge. These steps serve as stepping-stones.

	and solve gaps?		
LA11: **Reflecting** on the input/output depended sequence of steps in experiment 3.	Do students reflect on the sequence of steps in experiment 3 by analysing the coherence of the input/output chain?	Students chain intermediate steps input/output dependent. Students continuously compare output with input (and vice versa) thereby detecting and solving gaps.	Students chain the stepping-stones input/output dependent.

All students started with writing down the starting material, namely the bacterial colony that carries the cosmid with the desired cDNA insert. Duo 1 and 2 created problem representations by describing the problem and a solution direction. For example duo 2: *OK, so we need to come up with an experiment how this gene can be expressed [Experiment 3 R32]*. Followed by the other student of duo 2 saying*: So it [the gene] needs to be incorporated in an expression vector [Experiment 3 R46]*. Only duo 3 started designing experiment 3 by defining the starting material and desired end data precisely.

Duo 1 and duo 2 already had in mind – based on prior knowledge - a few steps that need to be included in the experiment. We call these ‘stepping-stones’. Considering the throughput of these stepping stones and comparing this with a current status of the starting material led to students detailing the stepping stone in a set of intermediate outputs all produced by separate techniques or technical operations. These intermediate steps were chained to each other in an input/output dependent manner. Thereby students bridged the stepping-stones via a set of small successive steps. In this process students continuously reasoned back and forth between input and output thereby monitoring whether the chain is coherent. Quote 3 illustrates this reasoning for duo 1.

Quote 3 Duo 1 (Experiment 3 R52-66)

Paul: *Ehm…starting material. What do we have? We have a cosmid with the desired cDNA insert.*

Jake: *Gen of interest (GOI).*

Paul: *GOI. And what do we need? Restriction enzymes to be able to cut that insert out of the cosmid.*

Jake: *So we can write that down as a subsequent step....*

Paul: *Yes. (…) We are going to isolate the cosmid. I assume it [the cosmid] still resides inside the bacterial colonies.*

Jake: *O yes, you're right. So that's an intermediate step.*

Paul: *Isolating the cosmid...How are we going to do that? By lysing the bacterial colonies...*

Jake: *And then purification.*

Paul: *By means of gel-electrophoresis*

Duo 3 worked forward by seeking and finding the steps (stepping-stones) needed to perform the experiment, not detailing them in small successive steps but directly chaining these steps in an input/output dependent manner. The fact that duo 3 didn't focus on the throughput of the stepping stones they experienced needed in the experiment – whereas the other duo's did – resulted in less detailed experimental design compared to the other student duo's.

Students' self-directed problem solving by formulating guiding questions, considering the throughput of stepping stones, thinking backwards, finding preceding steps and chaining them to each other in an input/output dependent manner faded as the design of experiment 3 progressed. This is probably due to fatigue that was observed among the students but also a lack of knowledge that hindered students in finding the intermediate steps thereby detailing their experiment.

Overall, in phase 3 it became apparent students had difficulties in defining what separate steps are. Where they interpreted and applied the concept 'steps' correctly as an intermediate product produced by a separate technique or technical operations in experiment 2 and at the start of experiment 3, this seemed to be difficult near the end of experiment 3. For example, near the end of experiment 3 all students experienced that cloning the gene in the expression vector is the last stepping-stone in the experimental work plan. Thinking about the throughput of this stepping stone seemed to be difficult for students and resulted in describing the step as 'constructing an expression vector' rather than breaking this step down in intermediate steps that leads to the construction of an expression vector. This resulted in experimental work plans showing a coherent set of steps at the start and a less coherent and detailed set of steps at the end.

The effects of the lesson on students' performance in designing experiments.

In the pre-test students started seeking what steps are needed without defining what the starting material is and what the desired end data. In this process students had difficulty defining what the separate steps must be. For example, a step could be 'using reversed transcriptase' or 'searching with a DNA probe'. Students – probably as a result of this difficulty in defining separate steps - did not pay attention to setting up a procedure consisting of a coherent set of steps resulting in experimental workplan showing large gaps in the central steps to be performed.

In the post-test students started with recalling what experiments need to be performed. All students reasoned that the major experiments to be performed encompass isolating the gene by means of constructing a cDNA library, screening the cDNA library and cloning the gene into an expression vector.

At the start of designing the three successive experiments in the post-test it appeared students constructed problem spaces. Instead of defining the starting material en desired end data as was practiced in the extra-curricular lesson students tended to start with defining the starting material and then formulate the question to be solved. The question students formulated themselves seemed to guide them in finding the steps (and according techniques and technical operations) needed to perform the experiment. For example, during the post-test Ian started with designing experiment 3 (cloning into expression vector) by saying: *The desired gene is now localized. How do I get that into an expression vector?[Post-test R133].*

Students continued their design process by detailing these experiments in small successive steps. Some students tended to define roughly the steps to be included while others were being very detailed in setting up the series of successive steps. In this process these latter students were also more attentive to detecting and solving gaps and reflecting on the coherence on the set of steps than the former students. For example, they were explicitly comparing the output of a certain step with the input of a subsequent step thereby detecting gaps in their experimental work plan that needed to be solved. It seemed that the students who defined roughly the steps to be included on the one hand were able to define the required intermediate products but had difficulty finding the according appropriate techniques or technical operations. However, they expressed explicitly the feeling that smaller steps needed to be included which they couldn’t come up with.

When comparing the post-test with the pre-test all students’ performance on the post-test contrasted their performance on the pre-test in favour of the post-test. That is, in the pre-test students did not pay much attention to setting up a procedure consisting of a coherent set of steps. In the post-test on the other hand students problem solving can be described as setting up a series of techniques or technical procedures with attention if and how these steps can edit the starting material towards the desired end data. Students focused on finding intermediate products and according techniques or technical procedures and chaining these to each other an input/output dependent manner.

Comparing the post-test with the extra-curricular lesson it appears students tended to work forwards in the post test in contrast to the backwards reasoning that what was seen in the extra-curricular lesson. In the extra-curricular lesson students were *seeking* for the steps needed to perform the experiments. These central steps – we called them stepping-stones – were broken down and set up in a series of small successive steps by considering the technical procedure (throughput) of these stepping-stones in detail. In the post-test students could recall much of the successive steps needed for constructing and screening cDNA libraries and how to construct expression vectors from a cDNA colony. Therefore, students' focus seemed to be on recalling these steps and how they can be chained to each other in input/output dependent manner.

Students' reflection

In the two semi-structured interviews students were asked about their perception and appreciation of the tasks they worked on during the extracurricular lesson. Students reported they experienced the lesson as being a taught a strategy for designing experiments. In addition, they reported that the strategy for designing experiments in the way practiced in the tasks – being responsible for seeking the steps that are needed and being as detailed as possible what techniques could be used - is a skill that is hardly addressed in their bachelor education thus far.

All students reported that the strategy starts with defining starting state and goal state and then finding the intermediate series of steps needed to perform the experiment. An interesting finding is that all students experienced that defining a starting state and goals state can already help them considerably in their problem solving process. It gave them focus and a sense of direction, which they experienced as facilitating the design process.

It is reported by various students that the tasks stimulated them in seeking, finding and thinking critically about the steps needed for doing the experiments. They stated that in the pre-test it was easy to skip steps – either deliberately or unconsciously - whereas the strategy forces students to be as detailed as possible in every step needed for performing the experiment as quote 4 illustrates.

Quote 4 Duo 1 (Interview I R13-28)

Jake: *In this task [the pre-test] you're not guided in the steps needed to perform the experiment. It's just a matter of...well uhm…*

Paul: *In this task [the pre-test] it's much easier to skip steps.*

Jake:	*Yes. And it's also much easier to be descriptive by just saying: we are going to do this procedure. Whereas you really need to design the experiment in detail in these tasks [teaching experiment].*
Paul:	*Yes, and you're pushed to think more critical.*
Interviewer:	*Critical about what?*
Paul:	*What you're doing, so to say. Really think about what you're doing, what steps are needed after a certain step. And in this task [the pre-test] you would skip steps when you didn't know what to do.*

When students were asked in interview II how they experienced the tasks, they all reported having remembered the stepwise procedure of designing experiments. Some students called this stepwise procedure a *chain reaction [Interview II R278]* consisting of successive techniques and they reported having used this interpretation of experimental work plans as a framework when working on the post-test. It helped them to focus and structure their experiments, direct them in finding the required steps and to detect and solve gaps. Chris described his problem solving process along this framework as working on a chain of products as quote 5 illustrates.

Quote 5 Chris (Interview II R152-168)

Chris:	*I find it a useful framework. I kept that framework as a common theme in in the back of my mind.*
Interviewer:	*And what did you remember from that framework?*
Chris:	*The steps from start to end. Yes, I experienced that as a common theme that I could apply in this task.*
Interviewer:	*And how would you describe that common theme…?*
Chris:	*You continuously define an output and then…what you want next and how you can get that and what you want with that product subsequently until you get your end data.*
Interviewer:	*Ok. And you kept that framework in mind during this task?*
Chris:	*Yes, I thought it was useful. When working on the pre-test I didn't had a clue how to start. And this time I knew better what to do.*

Chris reported having remembered and applied a framework for designing experiments that encompasses defining what (intermediate) products are needed, how these can be produced and what subsequent steps are needed that lead to producing the desired end data.

All students described the tasks as being modelled and having practiced a stepwise procedure to design an experiment from starting material to desired end data. They experienced this stepwise procedure a useful framework for designing experiments in the pre-test. In addition, the majority of the students reported they think this framework is useful for designing experiments in other biologic topics too. However, they emphasized this framework still requires extensive conceptual knowledge about the scientific topic at hand and experimental techniques that could be used. Students thought this could be a limiting factor when designing experiments in new situations as Mary reported: *When designing a completely new experiment it would still be as difficult as in these tasks. Since it requires being very detailed in the required steps. [InterviewI R86].*

Interestingly, some students reported that the detailed way of designing experiments can help them when actually performing the experiment in the laboratory: both for elucidating the 'what', 'why' and 'how' of every step in the experiment and for reasoning what steps could have gone wrong when the experiment failed to produce the desired end data. This in turn could be valuable for being more hands and minds on when engaging in laboratory sessions as quote 6 illustrates:

Quote 6 Duo 1 (Interview I R66-81)

Jake:	*When designing experiments in this [stepwise and detailed] way it's easier to check what steps could have gone wrong. When I would only have this [points at pre-test] as a procedure for performing the experiment, (..) and it appears that the bacterial colony doesn't produce the desired protein, I wouldn't have a clue what steps could have gone wrong. So yes, I think a schematic overview like this could be useful.*
Interviewer:	*To analyse what steps could have gone wrong you mean?*
Jake:	*Yes, especially for that.*
Paul:	*Yes, and when having designed an experiment in this way you can more easily imagine what you have to do in the laboratory compared to the pre-test.*

Next to the reporting about the stepwise procedure for designing experiments as giving focus and structure and enabling to be more hands on minds on when actually working in the laboratory, students also proposed improvements. First of all students could be guided more in detailing their experiments in small successive steps and finding the appropriate techniques or technical operations. For example by being more precise in the level of detail that is expected from students by giving students the general steps (stepping stones) needed for performing the experiment and asking students to detail these steps in the smallest successive steps they can come up with.

Conclusion

This explorative study aimed to gain insight in how students can be guided in designing experiments in molecular biology. We suggested that a problem solving approach could scaffold students in designing experiments. Therefore, the hypothesis was: *a problem solving based educational approach can scaffold undergraduate biology students in designing experiments in molecular biology.* We approached this research question by means of four sub questions:

1. What are the features of Hypothetical Learning Trajectory and according learning activities that scaffolds students in a problem solving approach for designing experiments in molecular biology?
2. How do students progress through the different learning activities of the designed lesson?
3. What are the effects of the learning activities on how students design experiments in molecular biology?
4. What are students' reflections on their learning process regarding the design of experiments in molecular biology?

In general we may conclude that the educational approach can scaffold students in adopting a self-directed design approach based on general problem solving strategies. During the lesson and in the post-test students design experiments as a coherent series of steps that are chained to each other in an input/output dependent manner whereby they think critically about the 'why' and 'how' of steps to be included. Table 4 summarizes achieved effects, the bottlenecks in the design and remaining questions.

Table 4. Achieved effects, bottlenecks and remaining questions of the HLT

Scaffolding towards the problem solving approach for designing experiments in molecular biology	Achieved effects	Bottlenecks and remaining questions
Phase 1 Interpreting the intended problem solving approach for designing experiments in molecular biology	Modelling the experimental work plan and focusing students on explaining the role of every step (output and the technical procedure of the according technique) can make the input/output dependent chain of activities intelligible to students.	Question remains to what extend students grasp the concept of steps as an intermediate product in the experiment produced by a separate technique or technical operation.

Phase 2 & phase 3 Practising the intended problem solving approach for designing experiments in molecular biology	Students develop and adopt a self-directed problem solving approach that includes: 1. Defining starting material and desired end-product or formulating guiding questions 2. Recalling central steps to be included in the design 3. Subdividing central steps in small successive steps (step defined as an intermediate product produced by a separate technique or technical operation) by considering the throughput. 5. Chaining the set steps of to each other in an input/output dependent manner 6. Reflection on the coherence of the input/output chain thereby including additional steps.	Self-directed problem solving fades when complexity level of tasks increases. Scaffolding students to implementing control experiments does not lead to reflection on the input/output sequence. Reflection occurs naturally when designing the experiment. Confusion occurs near the end of experiment 3 what the definition of a step is (a step is an intermediate product produced by a separate technique or technical operation)
Overall	Post-test versus lesson and pre-test indicates students show more critical thinking regarding the set-up of a series of techniques or technical procedures with attention if and how these steps can gather the data needed to transcend starting material towards the desired end data.	In post-test students' focus seem to be on recalling the required steps rather than thinking critically what steps are needed and if they are applicable in the experiment. Progressive confusion about what defines a 'step' resulting in incoherent experimental work plans.
Students' reflections	Students experience the approach as useful for focusing and structuring the design of experiments. Students experience the approach new in relation to their bachelor education and a valuable preparation for doing the laboratory sessions more hands on and minds on.	The fact that the approach requires extensive body of factual knowledge is reported to be a limiting factor and a focus for improvement (in the form of more guidance)

The designed HLT and lesson

In answering the first sub question, the features of the HLT can be described as employing general problem solving strategies – which are intuitive in nature – to the domain of experiments in molecular biology. Students are guided in designing experiments as coherent series of techniques with which from specific starting material the desired type of end-data can be produced. In the design process students are encouraged to reflect on the applicability of certain techniques and on the coherency of the set of steps.

The lesson starts with modelling the experimental workplan of experiment 1 in phase 1. Separate learning activities intend to let students interpret this experiment as a series of steps - defined as a certain output produced by a separate technique or technical operation – chained to each other input/output dependently. In phase 2 and 3 students are encouraged to apply the approach as they have interpreted it from phase 1. The learning materials scaffold students in finding the required steps by means of hints that encourage students to apply means-end analysis and problem decomposition. In phase 3 students aren't given any support thereby handing over independence in designing experiment from a problem solving approach.

Achieved effects

The second sub question addresses the question to what extent the lesson is effective to scaffold students in designing experiments using a problem solving approach. In general we see that students' intuitive general problem solving strategies are called upon effectively. Students quite easily get grip on the input/output chain of steps as an approach for designing experiments and they apply this same approach for designing the experiments in phase 2 and 3. As the lesson progresses students adopt a self-directed design approach based on general problem solving strategies. They formulate guiding questions in finding the required steps and to keep track on their progression in designing the experiment. Central steps identified to be needed are subdivided into smaller successive steps. These small steps are distinguished – if possible - as intermediate products produced by a separate techniques or technical operation. These small successive steps are chained to each other in an input/output dependent manner.

A few bottlenecks appeared in the lesson. For example, students show progressively difficulty in defining what accounts as a separate step to be included in experiments. As a result students tend to include central steps in the experiment without reference to a technique or technical procedure and/or without detailing these central steps in small successive steps as they are explicitly encouraged to. It is questionable if the lesson should give students direct instruction about the definition of a step as an intermediate product produced by a separate technique or technical operation.

In addition, designing experiments requires extensive conceptual knowledge about the scientific topic at hand and experimental techniques that could be used. Though the designed lesson built on students' prior knowledge and scaffolds students in finding the required intermediate steps, it appeared – especially in phase 3 – this wasn't implemented adequately enough. It is questionable how and in what way students could be provided the relevant content knowledge to enable them to apply general problem solving strategies more effectively and steadfastly.

In answering the third sub question it can be concluded that the lesson seems to be adequate in encouraging students to apply general problem solving strategies to their prior knowledge for designing more detailed and coherent experiments. Though, the effect of the problem solving approach is highly dependent on students' prior conceptual and procedural knowledge. Students intend to set up a series of steps that from starting material can be transcended towards the desired end data. However, lack of conceptual and procedural knowledge limits students design process leading to experimental work plans that are far from a coherent set of step. It is interesting that students themselves acknowledge the presence of gaps, feel dissatisfied with their design and keep searching for intermediate steps.

The fourth and last sub question addresses students' experiences with the educational approach for designing experiments. The approach appears to be effective to give students focus and structure for designing experiments and pushes them to be as detailed as possible about the required steps to perform the experiment. To design experiment in this detailed and stepwise way improves students' understanding of the 'what', 'why' and 'how' of every step in an experiment. This in turn could be a valuable preparatory exercise for laboratory sessions for being more hands-on and minds on. However, the approach requires a considerate amount of conceptual knowledge about molecular biology techniques. Students experienced being left alone too much in finding appropriate techniques. They report they needed more guidance in this.

In general, we can say that the lesson based on problem solving approach can position and guide students such that they can adequately self-directed themselves in designing experiments in molecular biology. The approach leads to students designing more detailed and coherent experiments and showing more critical thinking about the steps to be included. The approach is introduced in a meaningful way, meaning students experience it as helpful for designing experiments, new in contrast to their bachelor education, and valuable in future laboratory work for elucidating the knowing behind the doing.

Discussion

The overall goal of this explorative study is to learn about the characteristics, opportunities and pitfalls of an appropriate educational approach to guide students in designing experiments in molecular biology. Accordingly, we reflect on the adequacy of the theoretical underpinning of the designed lesson, consider and suggest modifications and points for future research.

Since general problem solving strategies are used intuitively we wanted to create the conditions in which these strategies would reveal themselves to students as applicable and useful to design experiments. Thereby we intended to give students freedom in adopting a problem solving approach for designing experiments that suits them best. We have shown that students – when modelled the intended approach visually - easily seem to pick up and apply general problem solving strategies in the context of design experiments as a detailed input/output chained set of steps. More importantly, when scaffolding is reduced students seems to take over this approach. However, it appears students are getting more confused about what defines a 'step', especially when experiments are getting more complex. This is probably due to a design error in the lesson that can be traced back to LA4 and LA5 and described as pursuing a dual and therefore confusing aim. LA4 and 5 intended to acquaint students with the concept of steps defined as a specific output with a particular role in the experiment, produced by a separate technique or technical operation. In addition, LA4 and LA5 intended to let students interpret the input/output chain of steps in the experiment. The latter hypothesized outcome was achieved effectively, but this probably led to students not getting grip on the intended definition of a step. In a revised form of the lesson students should be given direct instruction about the definition of a step used in the lesson. The learning activities can then more effectively focus students on the input/throughput/output chain of steps in an experiment.

Though the lesson built on students' prior knowledge and skills and intended to encourage students applying problem solving steps to design experiments in the intended input/output way, content knowledge still appears to be the bottleneck of the strategy. To tackle this problem a revised form of the lesson should not implement the gradual reduce of scaffolding as omitting any form of guidance or support. Instead, it could be fruitful to shift scaffolding from providing structure and guidance in phase 1 – to make students familiar with the problem solving approach - towards equipping students with the relevant content knowledge when students need in their design process. Obviously, adapting scaffolding to the changing needs of students requires interaction between teacher and student. Now we know that the problem solving approach can adequately position and guide students in a self-directed way for designing experiments in molecular biology we suggest a revised form of the lesson by implementing the suggested revisions in the learning activities. In addition, an explicit role for a teacher should be included to give students either structure and the relevant content knowledge (on a just-in-time basis) to facilitate students' design process.

Though the positive results of this study are encouraging, it must be emphasized that designing experiments is a skill and therefore most probably not something to be learned in a single lesson. Future research could explore the usefulness of this framework in different topics, settings and throughout different stages of students' bachelor education (year 1, year 2, year 3).

Limitations of the study

First of all, it must be emphasized that the lesson is tested for the experimental method *expression cloning technology* and with a group of 6 students that participated voluntarily (and thus may be more motivated). This limits the knowledge claims and generalizability of the theory underlying the presented educational approach strongly. Secondly, we do not present a ready-to-go educational approach. Instead, the explorative nature of this study limits our claims to presenting the approach as seemingly adequate for guiding students in designing experiment, though much more research and practice is needed.

This study does not allow us to claim this educational approach can be useful for designing experiments in other molecular biology topics too nor can we provide a proof that all students will automatically interpret and adopt the intended approach. More research is needed both by testing the approach in other biological topics and methodologies and with more students.

Recommendations for practice

In this study designing experiments is limited to the set-up of a series of techniques with which the type of data can be gathered from which the answer to a research question can be inferred. One could argue whether this is the most important aspect of designing experiments since the heart of the skill encompasses selecting variables that are valid to investigate the research question and choosing a reliable scientific method. Moreover, experimental work plans (protocols) can be found in books, articles etc. and thus – as one could argue - it is not important to give it extensive attention in educational practice.

We acknowledge that this study only includes a small aspect of the skill ‘experimental design’. However, we think that the presented approach focused on the process of choosing adequate techniques and designing an experimental work plan for an experiment in molecular biology can have valuable application in educational practices. A solid understanding of the ‘what‘, ‘why’ and ‘how’ of every step in an experiment – in which the presented approach seems to be effective - are relevant understandings for a scientist to prepare and conduct experiments efficiently, to trace errors when performing the experiment and to analyse results critically. This aspect is underexposed in current educational practices though included as an explicit learning goal in the examination program of undergraduate science programs.

Based on the results of this study we recommend that already at the start of students’ bachelor education explicit attention should be paid on the skill of designing experiments. First year biology undergraduates could be scaffolded in using the problem solving approach for designing experiments as set-up of a series of techniques with which the type of data can be gathered from which the answer to a research question can be inferred.It can make students more aware of the ‘why’ and ‘how’ of steps in an experiment and to reason about the applicability of certain techniques. This approach could be implemented in for example seminars and presented as a preparation for laboratory sessions. This in turn can ensure student being more hands-on as well as minds on when actually performing experiments in the laboratory (Hofstein & Lunetta, 2004). The presented approach can be expanded in complexity level in subsequent years of education e.g. by encouraging students to select variables and scientific methods themselves. Together, in this way an explicit learning goal of undergraduates science education is translated in concrete educational practice. Moreover, it can pave the way for promoting higher level learning goals (metacognitive learning goals) in other educational practices such as laboratory sessions.

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