Learning Life Sciences: Design and Development of a Virtual Molecular Biology Learning Lab

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Abstract

The consequence of some developments in the life sciences, for example genetics, have made them amongst the most controversial in today’s society. Despite the discussion about pro and contra arguments, the demand for life science expertise increases creating a growing need for life science education. In order to develop expertise in the complex domain of life sciences, learners need better access to science education. In this paper, an approach to science education is suggested that combines guided knowledge acquisition with hands-on experience. Although the need for authentic scientific learning is advocated by researchers, teachers, politicians and institutions, daily school practice, characterized by financial and organizational constraints, prevents holistic learning experiences. Technology partly helps to overcome such obstacles. In this
paper a learning environment is discussed that was developed to provide a virtual molecular biology laboratory and allows for authentic hands-on experience. Through this, students are introduced to concepts, skills and methods of the scientific domain with didactic support such as scaffolding, guided participation and the chance to explore experiments. Furthermore, by providing communication channels to exchange their understanding, learners are enabled to enter scientific discourse and build communities of scientific practice.

Learning Life Sciences - Pedagogical Considerations

Teaching students basic scientific literacy is one of the primary goals of contemporary high school and college education in the life sciences, the fields of biology, chemistry and physics (e.g. American Association for the Advancement of Science, AAAS, 1993). Scientific literacy includes cognitive as well as meta-cognitive knowledge and the ability to apply this knowledge in a scientific context. To be scientifically literate also means being able to collect information and data about specific concepts, schemata or domains. Scientific literacy requires the ability to recognize and develop scientific questions, then to draw conclusions from theoretical considerations and empirical findings (Prenzel, Carstensen, Rost & Senkbeil, 2002). In addition, scientific literacy demands interpersonal skills and capabilities to enable participation in scientific discourse. Thus, scientific literacy develops best within an authentic science learning environment that resembles a scientific community.

Research practice in life sciences is mainly based on conducting series of experiments. Accordingly, this is also an important part of science education. Unfortunately, students rarely have sufficient access to appropriate science facilities where they may practice experimental research. There are many reasons for the lack of experimental research
as an instructional method in science education including safety issues, the high costs of running a laboratory and time-consuming experiments that do not fit into school schedules.

Scientific literacy is difficult to achieve in a traditional instruction-based, teacher-centered environment, where students often take a passive learning role and acquire de-contextualized knowledge. The resulting abstraction and generalization can lead to learners’ understanding becoming less context dependent, but more general and unspecific (Lave, 1996). This does not necessarily imply that learning in traditional education is ineffective; nevertheless out-of-context learning often leads to students being unable to apply their knowledge (Edelson, 1998). While some common teaching approaches still conceive learning and doing as separate (Lave, 1990), advocates of the situated learning approach point out that learning and doing are inseparable. Throughout their development and adulthood people continually adopt the beliefs and behaviors of the social groups with which they interact. Where individuals are given the chance to observe members and practices of a culture in situ, they pick up relevant jargon and imitate behavior, even though the observed cultural practices are often abstract and extremely complex (e.g. Lave & Wenger, 1992). In life science education in particular, the need for situated learning has been advocated (Linn & His, 2000) suggesting that students acquire scientific concepts best through engaging in the practices of ‘real scientists’. It is also expected that authentic activities will engage learners and motivate them. Motivation is believed to be a precondition for learning success because it positively influences the willingness to learn (Zumbach, Starkloff & Schmitt, 2004).

According to McGinn and Roth (1999) scientific literacy is a grounding for competent participation in scientific laboratories and other locations or communities where science is created and used. Learners acquiring knowledge in a meaningful context develop
styles of inquiry and communication that enable them to develop life-long learning skills (Edelson, 1998; Hannafin, Land & Oliver, 1999).

**Rationale for an interactive life sciences laboratory**

So far it has been argued that development of scientific literacy is embodied in a set of activities and skills that are part of scientific practice. Scientific practice can be mainly characterized by identifying and rethinking theoretical issues, hands-on experimental hypotheses testing, integration of empirical data into existing theories and communication with other researchers in a community of practice. It is understood that in-depth science teaching is largely dependent on schools’ abilities to provide an adequate scientific environment. Given that these standards are not being realized at anything like the required scale, virtual science labs might be a viable alternative to real learning laboratories.

**lifelab® – learning in the digital lab**

Based on these considerations the lifelab® project (http://www.lifelab.de), led by the German Cancer Research Center (DKFZ) and co-founded by the German Federal Ministry of Education and Research (BMBF) commenced in January 2002. The project team comprising expertise in IT, psychology, pedagogy and computer-based learning was established to develop a learning environment which should enable high school students and laboratory apprentices to get a deeper and more authentic understanding of life sciences.

It was considered crucial to introduce naïve and/or novice learners to the life sciences by allowing a high degree of self-directed learning in combination with instruction elements like coaching and scaffolding. Elements of several contemporary instructional design theories were incorporated into the design including Open Learning Environments
(Hannafin, Land & Oliver, 1999), Constructivist Learning Environments (Jonassen, 1999) and Learning Communities in Classroom (Bielaczyc & Collins, 1999). The elements of these learning theories may be recognized in the different levels of expertise development shown in Table 1.

<table>
<thead>
<tr>
<th>Level of Expertise: Objective</th>
<th>Instructional Component</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: Be able to activate prior knowledge, understand basic concepts of new domain</td>
<td>Enabling Concepts, Motivate Learners, Generate or activate needs</td>
<td>Analogies, Authentic scenarios, Challenging missions</td>
</tr>
<tr>
<td>II: Be able to acquire domain specific declarative/procedural knowledge</td>
<td>Static Resources, Processing/Search Tools, Conceptual/Procedural Scaffolding</td>
<td>Guided experiments, Tutorials, Information kiosk</td>
</tr>
<tr>
<td>III: Be able to explore and to experiment</td>
<td>Dynamic Resources, Collecting/Organizing Tools, Meta-cognitive/Strategic Scaffolding</td>
<td>Own Experiments, Background information, Planning &amp; reflecting</td>
</tr>
<tr>
<td>IV: Be able to exchange research questions and findings</td>
<td>Design Tools, Exchange Scaffolds</td>
<td>Report Research, Establish Community of Practice, Collaborative Planning &amp; Reflecting</td>
</tr>
</tbody>
</table>

Table 1: Components and methods of the lifelab® approach.

**Level I: Activation of prior knowledge and introduction to basic concepts of the new domain**

To introduce learners to a new domain, learning materials are needed that address a learner’s prior knowledge. This can be realized through the presentation of explicitly situated problem statements or questions, through scenarios, missions, cases or analogies. Introductory materials have to orient the individual to a need or problem and guide them to recognize or generate problems to be addressed and to frame their own learning needs (Hannafin, 1999; Hannafin, Land & Oliver, 1999). In making science accessible to learners, their learning experiences have to be connected to their existing science concepts. The presentation of (authentic) problems and cases that individuals can relate to brings science to life and motivate learners to carry out lifelong investigations (Linn & His, 2000). To facilitate investigative exploratory learning, not only are challenging tasks necessary, but also, learners need information resources to enable their construction of
conceptual models, to formulate hypothesis, to understand (hidden) processes during experiments and to communicate results; in short to perform scientific inquiry.

**Level II: Guided knowledge acquisition**

Inquiry-based approaches to science education emphasize the process of inquiry, such as generating research hypothesis, collecting and interpreting data, constructing explanations and arriving at conclusions (Sandoval, 2003; Reiser, 2002). To adapt scientific practice to a classroom environment, in addition to learner-appropriate resources, tools and scaffolds, a supportive underlying school curriculum and teacher preparation is needed (Edelson 1998). For novice learners guided experiments are often indispensable. Without guidance and support the iterative process of planning, performing and documenting an experiment process would be out of reach for most. To overcome basic problems in experimenting and domain-specific problem solving, as well as reflecting on recent learning experiences, special tools and scaffolds should be provided for the learners. Tools such as keyword searches, topic maps, or semantic search engines, support detection and selection of relevant information helping learners locate and filter relevant resources and information. Conceptual scaffolds facilitate learners to focus by recommending the use of certain tools, by providing explicit hints and prompts or by offering topic maps and content trees. How to use available resources and tools is embodied in procedural scaffolds (Hannafin, Land & Oliver, 1999).

**Level III: Exploration**

In addition to theoretical knowledge acquisition, hands-on experience is the core of inquiry-based learning. Free experimenting is essential in order to understand, replicate and transfer acquired knowledge and skills and finally, to develop a scientific literacy. In this exploratory phase, learners need resources that are changing dynamically. Using collecting tools, learners can accumulate resources for their own needs and objectives.
Complex relationships between ideas, or interdependencies of experimental elements, can be understood using tools to organize and present resources. Exploration requires two types of scaffolding: Meta-cognitive scaffolding provides guidance in how to think during learning and supports the underlying processes of individual learning management. Strategic scaffolds help to make students aware of different approaches and techniques for problem solving by supporting analysis, planning, strategy and tactical decisions (Hannafin, Land & Oliver, 1999; Brush & Saye, 2001).

**Level IV: Exchange**

Science is more than investigation. Science requires constant discourse. Within science laboratories, discourse is central to scientific understanding, sense-making and negotiation within the research group (McGinn & Roth, 1999). To establish a community of science practice in a classroom, learners need different kinds of social support. With the aid of design tools, learners are able to create graphs, text, presentations or complete entire research reports. Synchronous and asynchronous communication tools provide learners with the means to convey discourse, share ideas, review work, ask questions and discuss work and results. Furthermore the establishment of collaborative planning and reflection becomes possible. The collaborative construction of knowledge and domain-specific skills are supported through enabling learners to exchange knowledge.

To provide such an integrative and holistic approach to science teaching and to enable learners to become members in a community of practice in the domain of molecular biology the computer-based learning environment lifelab® was developed.
Implementation of design principles in the lifelab® environment

The main objective of the lifelab® learning environment is to make authentic life science research accessible to students and to support students (and teachers) in scientific reasoning and discourse and, thus, to develop expertise in scientific practices. By means of adapting authentic activities in molecular biology, students become active participants in the process of scientific reasoning. The core of the virtual learning environment is an interactive 3D-laboratory shown in screenshot 1. In addressing the objectives described in Level I (table 1), learners are presented with challenging authentic problems that integrate molecular biology in questions that combine common knowledge with basic science concepts, e.g. “How can bananas be used to produce sera?”

Figure 1: Virtual laboratory

To accomplish these challenging missions, students receive different kinds of support (e.g. introductory animations) depending on their prior knowledge. Different difficulty
levels allow students to participate in guided experiments, to receive remedial lessons between the steps of an experiment or to experiment on their own (see Levels II and III in table 1). While experimenting, several opportunities are available to undertake sub-tasks of the experiments (e.g. to make predictions, to control or manipulate, or to recognize and to communicate dependencies, coherences etc.). The generic task in each mode involves the compilation of a thorough and informative report about the accomplished experiment. To support students’ learning, several instructional tools and scaffolds and information resources were developed. These help to provide background information, domain-specific knowledge and skills. In addition, there are extracts of encyclopedia articles and video clips of real laboratory work (e.g. how to use a pipette) as well as 3D/animations illustrating hidden biochemical processes. In addition, a virtual assistant, Dr. Drop is available to guide learners through the experiment.

Specific tools are available to scaffold and provoke planning and reflection, as well as document and present learners’ experimental progress. To enhance the acquisition of meta-cognitive skills like planning, monitoring and evaluating an experiment in the virtual laboratory, students can plan an experiment with a “planning tool”. The planning tool consists of different pages that label the partial stages of the experiment and have to be arranged in correct order. During the course of the experiment this plan should be compared to the real experiment and, if necessary, revised. Another tool, the “laboratory report” illustrated in screenshot 2. This report automatically records information about the stages of each experiment including parameters such as time, abundance and temperature, information about visible and invisible processes and the results of the tasks. Any optional remedial sessions visited are also shown. Like a real laboratory report, the tool allows learners to make annotations. Furthermore, it is possible to add external as well as internal hyperlinks to any material available in the learning environment.
In addition to these basic functions, the laboratory report tool can be used to prepare a presentation that allows learners to demonstrate their results to peers and teachers. The laboratory journal can also be used to communicate and exchange research findings, problems and further research plans over the internet (see table 1, Level IV). The life-lab® learning environment provides asynchronous and synchronous communication tools where research reports can easily be shared, annotated and improved. This enables the building of peer groups overcoming traditional classroom borders and enables special interest groups to build communities of practice.

Cognitive effects of learning in the digital lab

In an evaluation study, 43 high school students (age 17-20) used the life-lab® learning environment. Some used the program during biology classes in their schools (external group), others participated in an evaluation session at the University of Heidelberg (in-
ternal group). Before starting the virtual experiments, the students completed a pre-test questionnaire which included questions on socio-demographic data, prior knowledge in genetics, experiences with biology courses (e.g. grades, time and effort invested) and the student’s motivation.

After obtaining initial instruction in the lifelab® environment, the students conducted the experimental unit “Vaccines in Plants” where they had to follow experimental steps of inserting an external gene, transformation, isolation and restriction analysis. At the end of the experiment, a post-test was applied that tested students’ knowledge in genetics and their current motivation.

**Results**

The data reveals that the sample of students performed quite well in biology with grades of an average of 2.2 (SD = 0.79; 1=first, 6=failed), possibly due to the fact that participation was voluntary and explicitly targeted at fairly experienced students. The score for the pre-knowledge assessment was on average 0.6 (SD = 0.14) on a scale of 0 to a maximum of 1.

Because there was no significant difference between the results of the external and the internal group, the group membership of the students was disregarded. Comparisons were made between the results of students with high previous knowledge with those with low previous knowledge. To distinguish the prior knowledge of the students in the knowledge pre-test, a median split was carried out (ANOVA: F (1,39) = 104.78; p< .01, eta² = 0.73).
As can be seen in figure 3, the post-test revealed a score of 0.7 (SD = 0.13) on a scale from 0 to 1. This result represents a significant knowledge increase (learning effect) by comparison with the pre-test (ANOVA: F (1, 39) = 70.73; p<.01; eta² = 0.65). Even though there is a significant difference between the two groups (ANOVA: F (1, 39) = 51.61; p< .01, eta² = 0.57), the knowledge increase is comparable.

Table 2: Previous knowledge and cognitive effects
As previously stated, motivation may be seen as a precondition for learning success because of its positive influences related to willingness to learn (Zumbach, Starkloff & Schmitt, 2004). To quantify current motivation in the results, the German version of the Questionnaire on Current Motivation (QCM; Rheinberg, Vollmeyer & Burns, 2001) was used to assess motivational factors of anxiety, probability of success, interest, and challenge on a seven point scale. Of the four QCM factors, only Interest correlated with performance of the knowledge post-test ($r = .55$, $p<.01$).

<table>
<thead>
<tr>
<th>QCM scale</th>
<th>Challenge</th>
<th>Interest</th>
<th>Probability of success</th>
<th>Anxiety</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>4.74</td>
<td>4.47</td>
<td>4.81</td>
<td>3.12</td>
</tr>
<tr>
<td>SD</td>
<td>1.21</td>
<td>1.32</td>
<td>1.17</td>
<td>1.47</td>
</tr>
<tr>
<td>N</td>
<td>43</td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 3: QCM factors (motivation)

Students with low previous knowledge showed a significantly lower interest in biological education (ANOVA: $F (1, 39) = 14.34$, $p<.01$, $\eta^2 = 0.27$).
To ascertain if a student’s interest in bioscience is linked to their performance in the knowledge test, the sample was split in two groups: students with high - and students with low interest in bioscience. The groups differ significantly at both measuring times (ANOVA: F (1,38) = 60.10, p< .01, eta²= 0.61). Good performance in the knowledge test is associated with high interest in biology.
Figure 5: Cognitive Effects and Interest

<table>
<thead>
<tr>
<th>Category</th>
<th>Score Pretest</th>
<th>Mean</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>low interest</td>
<td></td>
<td>0.56</td>
<td>0.10</td>
<td>21</td>
</tr>
<tr>
<td>high interest</td>
<td></td>
<td>0.67</td>
<td>0.11</td>
<td>19</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.61</td>
<td>0.11</td>
<td>40</td>
</tr>
<tr>
<td>Score Posttest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low interest</td>
<td></td>
<td>0.64</td>
<td>0.12</td>
<td>21</td>
</tr>
<tr>
<td>high interest</td>
<td></td>
<td>0.78</td>
<td>0.10</td>
<td>19</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.70</td>
<td>0.13</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 4: Cognitive effects and interest

Gender differences were not observed neither in terms of motivation nor performance assessment.
Summary and discussion

The development of scientific literacy is a complex process that requires expertise development over several years. To introduce naïve and novice learners to scientific reasoning in a meaningful way, hands-on experience seems to be a necessary element. Unfortunately, prevalent conditions in schools allow only minimal scientific inquiry and experimenting in the life sciences. The lack of equipment, time and, sometimes, teaching skills diminish the chance of active enrolment e.g. in molecular biology.

The lifelab® learning environment aspires to overcome these impediments by providing access to authentic science problems in a virtual laboratory. To meet different learners' needs and to foster life science expertise through different stages, a four level approach for teaching scientific literacy is proposed. Starting with enabling contexts, the activation of prior knowledge, followed by guided participation and scaffolds, it is suggested that continuous scientific practice permits evolution from an individual viewpoint and becomes collaborative.

The summative evaluation study by the Instructional Psychology research unit at the University of Heidelberg provided valuable feedback on the effects of the lifelab® learning environment. The principal result is that students do, in fact, learn effectively by using the virtual lab. Even though the lifelab® learning environment does not lead to any compensation in individual knowledge differences, knowledge gaps between students with high and low previous knowledge do still exist after using the lifelab®, the level of knowledge acquired is equal irrespective of the level of previous knowledge. It may be seen, then, that the core objective of the project – to develop a learning environment to teach the life sciences (molecular biology) – has been mainly achieved.
Looking in detail at students’ motivation, it was demonstrated how important the influence of interest is on the actual performance of students. Interest, therefore, is an important factor in learning and schools and teachers should be encouraged and assisted in gaining and maintaining students’ interest.

Currently, a technically enhanced version the lifelab® learning environment is already being used in several German schools both in addition to, and as substitute for traditional, primarily lecture based science teaching. While cognitive and motivational benefits of the approach could be demonstrated in a short-time, intervention-learning laboratory research, the outcomes of a long-time intervention in schools compared to other instructional approaches will be the subject of future analyses.

Current developments of the software also include an English language version so that not only classroom borders, but also national borders are not longer barriers to future young life scientists’ communities.

Acknowledgement:

We thank Michael Lawrence-Slater for helpful comments on an earlier version of this paper.
References


