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

JOERG ZUMBACH  
*University of Salzburg*  
Austria  
joerg.zumbach@sbg.ac.at

STEFANIE SCHMITT  
*University of Heidelberg*  
Germany  
stefanie.schmitt@psychologie.uni-heidelberg.de

PETER REIMANN  
*University of Sydney*  
Australia  
p.reimann@edfac.usyd.edu.au

PHILIPP STARKLOFF  
*University of Heidelberg*  
Germany  
starkloff@uni-hd.de

The life sciences, in particular molecular genetics, have become a pivotal area of research and innovation, and at the same time are amongst the most controversially discussed in today’s society. Despite this discussion, the demand for life science expertise increases rapidly, creating a growing need for life science education in particular and for science education in general, given that progress in this area depends on progress in biology, chemistry, computer science, and some others. In this article, an approach to science education is suggested that combines guided knowledge acquisition with hands-on experience in a computer-based learning environ-
ment. The pedagogical rationale for the learning environment are delineated and grounded in research in the learning sciences. The results of a first evaluation of the main features, comprising in addition to a virtual experimental workbench various scaffolding tools, among them a pedagogical agent, and a report/presentation tool, are reported. Findings indicate that students profited equally form working with the program, independent of differences in prior knowledge and interest.

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. This suggests that scientific literacy may be best developed within an authentic science-learning environment that resembles a scientific community.

Research practice in molecular biology is mainly based on testing theories and hypotheses by conducting experiments and interpreting their results. This kind of investigative and reflective activities should also be an important part of science education. Unfortunately, students rarely have sufficient access to appropriate science facilities where they may practice this way of 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. Under such conditions, teachers often cannot help but employ a “show-and-tell” approach in their classes, which leaves most students in a passive and receptive role. Students will acquire knowledge in such situations, but it will be mostly fragmentary, not integrated into a larger mental model (Linn, 1998), and too abstract and
unspecific to be flexibly used and transferred (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).

Computer-based learning environments in general and computer-based simulations in particular have been seen as being able to provide for authenticity and for “hands-on” experiences even in areas where schools cannot be expected to provide the respective “real” environment for learning (Alessi & Trollip, 2001). Our work starts from this assumption as well. However, many years of experience with and research into learning from simulations (de Jong & Joolingen, 1998) has shown that designing simulation environments that foster learning is not a trivial task, and that designers need to be very careful in their decisions about which aspects of reality to incorporate in their simulations. Furthermore, we have learned from this research that in addition to being provided with a model of reality, learners need carefully designed tools integrated into the simulation environment to be able to make best use of the information provided and to be able to cope with the demands of discovery learning (Reimann, 1991). In addition, we begin only gradually to understand the role of social interaction for science learning and how to incorporate group learning into simulations and discovery learning environments (Linn, Davis, & Bell, 2004). The study reported here is meant to inform designers of computer-based learning environments for life sciences about the effectiveness of combining a high-fidelity (three-dimensional) laboratory simulation with a number of “mind tools” (Jonassen, 1999a) for planning, analysis, and reporting. We start with an analysis of the kind of situations and the kind of tools such a simulation environment needs to contain to capture the pivotal elements of experimental laboratory work in molecular biology.

While some common teaching approaches still conceive learning and doing as separate, advocates of the situated learning approach point out that learning and doing are inseparable (Lave, 1996). 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 (Lave & Wenger, 1992). In math and science education in particular, the need for situated learning has been advocated (Linn & Hsi, 2004) 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.
According to McGinn and Roth (1999) scientific literacy is a grounding for competent participation in scientific laboratories and other locations or communities where knowledge 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). Experimental analysis of scientific reasoning processes (e.g., Kuhn, 1989) and in particular observational studies in laboratory environments (Dunbar, 1995; Kozma, Chin, Russell, & Marx, 2000; Lynch & Woolgar, 1990) contributed further to our current understanding of scientific competencies. This research has shown how important external representations, such as sketches, images, and the printout from instruments, are both for individual reasoning as well as for the coordination of work and the joint interpretation of findings. Kozma’s work, in addition, demonstrated that the ability to flexibly coordinate different representations of the same phenomenon is an important capacity that expert researchers have and that beginners often lack. We interpret Kozma’s representational fluency as being closely related to Linn’s (1998) concept of integrated science knowledge. The value of experimental activities for science teaching will be dramatically reduced if students do not succeed in integrating what they do with what they know on the conceptual level. It is our foremost goal to design a learning environment and provide tools that help students to bridge the gap between doing and reflecting, between hands-on experimental activities and the theories and models in the domain of molecular biology.

To link experimental procedures with conceptually important biological principles, two kinds of knowledge need to be in place: knowledge about causal relationships (“causal knowledge”) that allows students to reason forward and backward in time (for instance, “probes in the gel sledge move from minus pole toward the plus pole because particles are charged negatively”). Moreover, knowledge that allows students to reason about (experimental) plans, about goal-subgoal relationships, about the function of laboratory instruments, and how experimental steps and the employment of certain instruments are related to goals (“planning knowledge”). Planning knowledge is not only essential to create experimental procedures, but—and in our context more importantly—to understand experimental procedures: for plan recognition. While causal knowledge is communicated extensively in textbooks and by teachers, planning knowledge is less often and less systematically communicated to students. It is our goal to foster both kinds of knowledge, because we believe that reasoning about complex experimental procedures, involving advanced technical instruments, is not fully possible
based on causal knowledge alone. The perhaps more mundane planning and plan recognition knowledge has not received sufficient attention in science education, a fact that may in part be due to a very limited notion of experimentation that underlies most of that research (Chinn & Malhotra, 2001; Lehrer, Schauble, & Petrosino, 2001).

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 currently not being realized to the extent required, 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 cofounded by the German Federal Ministry of Education and Research (BMBF) commenced in January, 2002. The multidisciplinary make-up of the project team, comprising expertise in IT, psychology, pedagogy and computer-based learning, was essential 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. This is to avoid that only students with high prior knowledge and/or high motivation and interest levels would profit from working with the lifelab®. Elements of several contemporary instructional design theories were incorporated into the design including Open Learning Environments (Hannafin et al., 1999), Constructivist Learning Environments (Jonassen, 1999b) and Learning Communities in Classroom (Bielaczyc & Collins, 1999). The elements of these learning theories were integrated into a normative model of expertise development, the different levels of which are shown in Table 1.
Table 1
Components and Methods of the lifelab® Approach

<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>

**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 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 et al., 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 et al., 2004). 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 experimental 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 learning 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 et al., 1999).

Guidance is provided in lifelab® by a pedagogical agent, represented in the interface by a figure called “Dr. Drop.” Dr. Drop provides onscreen text, not speech, and is rendered as a comic figure, not with a human-like appearance (Figure 1). We wanted to avoid that students interpreting Dr. Drop as being equipped with human-like conversational abilities because the current implementation does neither support speech output nor advanced social agent simulation. There is evidence that humans apply person-perception heuristics to animated conversational agents (Louwerse, Graesser, Lu, & Mitchell, in press) and that learning improves when agents provide speech comments (Moreno, Mayer, Spires, & Lester, 2001). Furthermore, in the current implementation as described here, guidance and scaffolding is provided in a static manner, that is, without the capability of gradually fading it out or adapting it to students’ needs. Students and teachers can decide, however, to use the program in one of two levels of difficulty (beginner or apprentice), with guiding and scaffolding reduced in the apprentice mode.
In addition to the acquisition of conceptual knowledge, experience-based inductive reasoning is pivotal for inquiry-based learning. Free experimenting is essential to understand, replicate, and transfer acquired knowledge and skills to develop scientific literacy. In this exploration phase, learners need resources that are changing dynamically. Using information-collection tools, learners can accumulate resources for their own purposes and objectives. Complex relationships between ideas, or interdependencies of experimental elements, can be elaborated using tools to organize and present information. 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. Secondly, strategic scaffolds help to make students aware of different approaches and techniques for problem solving by supporting analysis, planning, strategy, and tactical decisions (Hannafin et al., 1999; Brush & Saye, 2001).

**Level IV: Exchange.** Science is more than individual investigation. Science requires constant discourse. Within science laboratories, discourse is central to scientific understanding, sense-making, and negotiation within the research group (Latour, 1990; 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 Figure 1. In addressing the objectives described in Level I (see Table 1), learners are presented with challenging authentic problems that integrate molecular biology in questions that combine common knowledge with basic science concepts, for example, “How can bananas be used to produce sera?”

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 subtasks 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-ani-
mations 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 such as planning, monitoring, and evaluating an experiment in the virtual laboratory, students can plan an experiment with a “planning tool” (Figure 2). 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.

![Figure 2. Planning tool](image)

Another tool, the “laboratory report,” is illustrated in Figure 3. 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 lifelab® 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 a first evaluation of the effectiveness of the program we were primarily interested in the questions if working with lifelab® leads to learning gains at all, and to what extent the learning gains depend on prior knowledge. The second question is particularly important because discovery learning and simulation-based learning, like learning with hypermedia, suffer from the pedagogical analog to the Matthews Effect: Learners with high prior knowledge typically profit most from these kind of learning experiences. What we like to see, and what many of the features built into lifelab® should help to bring about, are *equal-sized* learning gains for students.
with varying degrees of prior knowledge. This is the main rationale for the median-split on pretest scores underlying the study reported next. Similarly, we assessed students’ motivation and interest to check if learning gains are confined to those students who are very interested in life sciences before working with lifelab®. Again, it is our expectation that lifelab® will cater to the preferences of less motivate/interested students because of its open and authentic approach to experimenting.

In a first and small-scale evaluation study, data from 43 high school students (age 17-20) using the lifelab® learning environment were assessed. Some used the program during biology classes in their schools (external group), others participated in an evaluation session in rooms of the University of Heidelberg (internal group). Before starting the virtual experiments, the students completed a pretest questionnaire that included questions on socio-demographic data, on prior knowledge in genetics, on experiences with biology courses (e.g., grades, time, and effort invested) and on students’ motivation. The overall data acquisition lasted about two hours, and the interaction with the lifelab® program took about one and one half hours.

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 preknowledge 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 prior knowledge with those with low prior knowledge. To distinguish the prior knowledge of the students in the knowledge pretest, a median split was applied (ANOVA: $F(1,39) = 104.78$; $p<.01$, $\eta^2 = 0.73$).

The posttest (Figure 4) 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 pretest (ANOVA: $F(1,39) = 70.73; p < .01; \eta^2 = 0.65$). Even though there is a significant difference between the two groups (ANOVA: $F(1, 39) = 51.61; p < .01$, $\eta^2 = 0.57$), the knowledge increase is comparable (Table 2).

![Figure 4. Cognitive effects (knowledge test)](image)

**Table 2**

Prior Knowledge and Cognitive Effects

<table>
<thead>
<tr>
<th>Category</th>
<th>Mean</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Score Pretest</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low prior knowledge</td>
<td>0.51</td>
<td>0.05</td>
<td>21</td>
</tr>
<tr>
<td>high prior knowledge</td>
<td>0.71</td>
<td>0.07</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>0.61</td>
<td>0.12</td>
<td>41</td>
</tr>
<tr>
<td><strong>Score Posttest</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low prior knowledge</td>
<td>0.61</td>
<td>0.10</td>
<td>21</td>
</tr>
<tr>
<td>high prior knowledge</td>
<td>0.81</td>
<td>0.07</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>0.71</td>
<td>0.13</td>
<td>41</td>
</tr>
</tbody>
</table>

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 posttest ($r = .55$, $p<.01$; Table 3).

Table 3
QCM Factors (Motivation)

<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>

Students with low prior 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: $F(1,38) = 60.10$, $p<.01$, $\eta^2= 0.61$). Good performance in the knowledge test is associated with high interest in biology. However, both groups have about equal learning gains, which is promising because we don’t want to see only highly interested students profiting form working with lifelab® (Figure 5, Table 4).

Figure 5. Cognitive effects and interest
Table 4
Cognitive Effects and Interest

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

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

SUMMARY AND DISCUSSION

We have reported the design rationale and results from a first evaluation for a computer-based discovery learning environment (lifelab®) that aims at supporting learning about important experimental procedures and concepts in molecular biology. Based on a sequence model of learning goals for the domain, lifelab® incorporates a number of instructional measures and tools that support students in guided discovery learning. The findings from a first evaluation study support our expectation that lifelab® is a learning environment that is well suited for students with varying degrees of domain knowledge and varying interest in the field of life sciences.

The principal result is that students do, in fact, learn effectively by using the virtual lab. A second finding is that the learning gain is approximately equal irrespective of the level of prior knowledge. Third, both highly interested and less interested students profited from the interaction with the program.

The study reported is not sufficient to generalize far beyond the specific conditions and the specific students that participated. Other methodological issues such as random sampling and avoiding self-selection effects will need to be addressed in future work. We need to record process data in order to have a closer look at the use of the individual tools and design features, as well as classroom studies that look into how teachers and students use and appropriate the program under ecologically more valid conditions. We also have had little access to the details of knowledge acquisition processes that would allow us to substantiate our claim that indeed two kinds of knowl-
edge are developed in lifelab®: causal knowledge and planning knowledge. Much to our dismay, the state of the program at the time the evaluation was conducted did not allow us to make observations on the communication and presentation aspects that we find so very important.

The development of scientific literacy is a complex process that requires expertise development over several years. Clearly, a program such as lifelab® cannot just by itself provide the necessary challenges and support to such extended and sustained learning. However, the kind of learning exemplified in this environment will, if sustained, lead to considerable progress towards comprehensive science literacy in schools and should be a good preparation for university level courses. This because by working seriously with lifelab®, reasoning processes are instigated which bear many similarities with the reasoning of professional researchers. We would claim that lifelab® is authentic not only with respect to the problems posed to students, the simulated lab environment and the instruments, but also, and perhaps more importantly, it is authentic in an epistemological sense.

We use “epistemological” here in the sense as introduced by Chinn and Malhotra (2001): “…the basic principles that guide decisions about when and how to change one’s knowledge in response to evidence” (p. 378). We would argue that when working lifelab®, which has been built in close interaction with molecular biologists from one of Europe’s leading life science research centers, students are engaged in activities of experimentation and interpretation which bear close resemblance, on the epistemological dimension, with what real scientists are doing and how they are thinking. This argument for the importance of epistemological fidelity is so important that it merits further elaboration.

The main argument by Chinn and Malhotra (2001) was that simulated experiments are not flawed because they are simpler than authentic experiments; the real problem is that many simulated experiments (by which they are not only referring to those delivered in computer-based simulations, but primarily to the experiments that are described in textbooks and are discussed in classrooms) oversimplify the experimentation process to an extent that alters essential epistemological features of real experimentation: “Many current simulated tasks (…) do not simply create a simpler version of scientific experimentation; they create a profoundly altered version of scientific experimentation” (p. 379).

The main form of experimentation that students are introduced to in school is the simple multivariate experiment: One dependent variable, such as speed of a car rolling down a ramp, and a few, but typically not more than 2-4 independent variables, such as size (mass) of the car and the steepness
of the ramp. Each of the independent variables can be varied, typically in a limited manner (small and big car, three different degrees of slope) while the other variables are held constant. The problem is solved when the factors have been identified that affect the dependent variable, and simple interactions may be considered as well. The simple multivariate experiment (SME) is not only typical for science education, it is also the drosophila for the vast majority of psychological studies into scientific reasoning (our own included, e.g., Reimann, 1991, see also Schauble, Glaser, Duschl, Schulze, & John, 1995). Chinn and Malhotra (2001) went to some length to elaborate the differences between a typical experiment in the life sciences, such as a medical drug test, and the SME. For instance, there are multiple interventions by the experimenter in real experiments, the simple experiment knows only one. The space of possible variables to consider and the values these variables can take is much larger in real experiments than in the SME. In real experiments, the there are typically many causal paths between a sequence of events, whereas the SME can be explained with a single causal link between two events.

Because of the many differences, the cognitive demands of SMEs are different, and in general lower than when working with real experiments. For instance, there is almost no planning required for designing an SME, but a lot of planning goes into real experimental design. Also, SME can be comprehended by taking only into account what is immediately visible, whereas in real experiments most of the causal processes are hidden. What is most worrying, however, is that students acquire the wrong epistemology. For instance, they begin to see the purpose of science as being essentially a mechanistic, algorithmic process, a “…Baconian enterprise of accumulating simple observations and drawing simple generalizations.” (Chinn & Malhotra, 2001, p. 379). Furthermore, students get little chance to reflect on the theory-ladenness of methods (Collins & Pinch, 1993), gain no awareness of the social construction of “data” (in particular when complex instrumentation is involved, see Latour & Woolgar, 1986), and have no exposure to the many ways scientists react to anomalous data (Chinn & Brewer, 1993). Any sense of that science in general and experimentation in particular requires a great deal of creativity to make sense out of confusing data of the real world is lost.

Maybe that the effects on students epistemological beliefs about the purpose and nature of experimentation aren’t always quite so devastating, but there is ample evidence that should motivate teachers and instructional designers to be very careful in their attempts to reduce the complexity of real experimentation. The baby is easily thrown out with the bath water, it
appears, when we read, for instance in a study by Germann, Haskins, and Auls (1996) that most out of 90 biology laboratory exercises in the US K-12 curriculum are of the simple kind. Epistemological beliefs are hard to change once acquired, leading us to the conclusion that students should be exposed early on to real science rather than simplified science. Instead of reducing the complexity to avoid confusion and frustration in learners, a better strategy is to offer beginners sufficient scaffolding and guidance, and all the information they may need ready at hand. Computer-based and web-enabled learning environments such as lifelab® have the potential to deal with the complexity of real science in a manner that can be adapted to the needs of students at various stages of scientific literacy.

To continue the development of this approach, it is desirable to extend and broaden the model to other domains and areas. Furthermore, there is need for more empiric evidence for the benefits of the proposed four stages. This includes laboratory research as well as applied field research. Both should include quantitative as well as qualitative data analysis to describe more precisely underlying process of acquiring scientific literacy.

Since a few months, the lifelab® learning environment is 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. This will also be made easier by the fact that an English version of the program is being developed.

References


