Learning in virtual physics laboratories assisted by a pedagogical agent

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Abstract. We present the concrete realization of a virtual laboratory equipped with a pedagogical agent. Its functionality and media didactics takes into account the results of an usability test on a prototype system, and the students’ demand on such an automated assistance as obtained from a preliminary survey. The pedagogical agent mediates between the content and the learner by activating him or her. To provide information about the learner’s skills, we propose a pragmatic and simplified competence model that is based on fundamental representations in physics (experiment, figure, text and equation). Moreover, an automated feedback relates the student’s self-assessment with the submitted answer to the correctness of the respective task. In consequence, the pedagogical agent enables mental reflection for a crucial review of the own learning process. Interestingly, learning pathways can be envisioned, thus, giving valuable insight into individual strengths and weaknesses.

1. Introduction

Pedagogical agents are lifelike characters presented on a computer screen that guide users through multimedia learning environments. They are defined in relation to the context of their employment as “learning partners” or “virtual tutors” in educational software. Therefore, they can be distinguished from other agent applications such as “embodied conversational agents”, “anthropomorphic interface agents”, “virtual characters” or “non-player characters” [1]. Pedagogical agents can demonstrate complex tasks, employ locomotion and gesture to focus students’ attention on the most salient aspect of the task at hand, and convey emotional responses to the tutorial situation. They offer enormous promise for interactive learning environments by broadening the bandwidth of communication to include many of the modalities of human-human tutoring [2].

In addition to providing problem-solving advice in response to students’ activities in the learning environment, these agents may also be able to play a powerful motivational role. Lester et al [3] stated in their seminal paper more than twenty years ago: “To design the most effective agent-based learning environment software, it is essential to understand how students perceive an animated pedagogical agent with regard to affective dimensions such as encouragement, utility, credibility, and clarity. Their study revealed the so-called persona effect, which is that the presence of a lifelike character in an interactive learning environment – even one that is not expressive – can have a strong positive effect on student’s perception of their learning experience. As a result, students may choose to use interactive learning environments more frequently and for longer periods of time. Since then, there has
been abundant evidence that support this claim. Early findings also showed that the benefits of animated pedagogical agents increase with problem-solving complexity: “As students are faced with more complex problems, the positive effects of animated pedagogical agents on problem-solving are more pronounced. This finding suggests that agents may be particularly effective in helping students solve complex technical problems (as opposed to simple ‘toy’ problems).” [2]. However, the design and evaluation of pedagogical agents remains a highly complex and challenging task. Despite the great number of existing studies on pedagogical agents, a lot of questions remain: Do pedagogical agents always fulfil their promise and facilitate learner motivation and learning? Under what conditions are they most effective and how should they be designed? Heidig and Clarebout [4] reviewed 26 articles that focus on the effect of pedagogical agents on learner motivation and learning. They found that due to a lack of control groups, various studies did not investigate the first two fundamental questions because they focused rather on the third question of how to design pedagogical agents by comparing different agent groups. They propose a multi-level framework to conceptualize and situate future studies and argue in their conclusion that an experimental design with an additional control group would enable the provision of evidence on all three questions. Studies designed in this way may contribute to the discussion on whether pedagogical agents are effective, as well as to the development of empirically tested guidelines for practitioners under what conditions it is reasonable to implement an agent and how to design it.

In this article, we want to give a technically feasible solution for a better multimedia learning by means of a pedagogical agent. In the reported virtual laboratory (short: virtual lab), the pedagogical agent is a comic version of Albert Einstein who accompanies the learner from information input to numerous activating tasks with prepared tips that are available on request. All tasks throughout the virtual lab are classified with regard to relevant skills (or representations) in physics and are graduated due to Blooms taxonomy. A log file analysis records the detailed activities of the learner and reorganizes the collected data on a user-specific feedback page, indicating statistics of the unit like current progress and giving a competence chart to clarify personal strengths and weaknesses.

The structure of this article is the following: First of all, section 2 introduces the idea and goals behind the virtual labs from the project Open MINT Labs (OML). Afterwards, in section 3, the focus is put on didactics. We pick up the real and virtual experiment ‘Thermography’, respectively, that are both part of lab courses in physics at Trier University of Applied Sciences. Based on the present virtual lab, section 4 demonstrates our approach to an assisted learning by the use of a pedagogical agent whose concept and implementation is discussed further. Section 5 refers to the assessment of the student’s benefit. Finally, we conclude with a summary and an outlook. The latter shall address potential next steps to intensify communication and cooperation with the pedagogical agent and among the members of the learning group.

2. The project Open MINT Labs

The joint project OML is shared among Rhineland-Palatinate’s Universities of Applied Sciences Kaiserslautern, Koblenz and Trier [5]. Until 2020 OML is funded by the German Ministry of Education and Research (BMBF) within the so called ‘Qualitätspakt Lehre’ (translated: ‘Quality Pact Teaching’). It consolidates measures to improve academic teaching and learning in its various aspects. Central goal of OML is to develop and scientifically investigate virtual laboratories. This virtual offer gives students the flexibility to prepare experiments in the real laboratory independent of place, time or end device. Modern web technologies, like HTML 5 and CSS 3, are used and the labs are implemented into the widely spread learning management system OpenOLAT. From the so-called MINT-spectrum (corresponding to STEM in the English-speaking part) the project partners choose labs in physics, chemistry, biology and engineering. Altogether, OML addresses around 80% of Rhineland Palatinate’s places at Universities of Applied Sciences in natural sciences and engineering. To harness synergies with the traditional formats of teaching and learning (e.g. lecture, seminar, exercises, tutorial, laboratory, project work, thesis), the virtual labs are integrated in the teaching programme via a blended learning lab concept. In addition, the learning content is related with
authentic examples from application. Considered on a longer timescale, the hope is to increase the learning success and to strengthen the students’ competencies.

Conceptually, every virtual lab from the OML project is structured in a modular manner and consists of the following five self-explanatory chapters, namely: Orientation, Basic Information, Experiment, Application and Reflection. These lead the learner from the buildup of basics to the transfer of knowledge when answering questions from everyday life or in order to deal with authentic problems from research and industry. For a more detailed treatment of the didactical concept of the virtual labs from OML, the reader is referred to our publication in [6].

3. Concept of the pedagogical agent

This chapter attends to the concept and concrete implementation of the pedagogical agent. Here, the real experiment ‘Thermography’ serves as a model case to exemplify how its different objectives are met in the virtual version of the experiment. The latter is equipped with a pedagogical agent, that shall play the role of a mediator between the content and the individual student.

3.1. The experiment ‘Thermography’ in the real laboratory

On the one hand, the experiment ‘Thermography’ is part of two practical physics courses at Trier University of Applied Sciences. It is well known that practical courses play an important role in the quality of post-secondary education in natural and engineering sciences, particularly with regard to advanced and specialized skills [7].

In the first scenario, the experiment ‘Thermography’ is one out of five experiments that form a self-contained practical course for Bachelor students in electrical engineering, medicine technique and medicine informatics. Thematically, however, it is linked to the lecture ‘Spezielle Themen der Physik’ (translated: ‘Special Topics of Physics’). In the second scenario, the experiment ‘Thermography’ is – together with the experiments coupled pendulum, electrical fields, Helmholtz coils and optical diffraction – performed by students of the Master level within ‘Physik M’ (translated: ‘Physics Master’). They learn more about mathematical methods in classical and modern Physics, e.g. Lagrange formalism, wave function description in electrodynamics or quantum mechanics and statistics in thermodynamics. In this context, several teaching and learning formats (lectures, exercises and practical courses) are used and combined with virtual elements. In the real lab, the experiment ‘Thermography’ addresses the following objectives:

- Usage of a professional thermography system (‘VarioCAM hr’, InfraTEC GmbH)
- Interpretation of thermal pictures from a human hand
- Qualitative comparison of the transmission and reflection of a plastic film with a rescue foil
- Investigation of the optical properties of glass for different wavelengths (visible, infrared)
- Quantifying the emission coefficients of Leslie’s dice (black, white, polished, matt)
- Measuring the distance dependence of radiation from a light source (with Moll’s detector)
- Characterization of the angle distribution of radiation from a light bulb
- Experimental confirmation of Stefan Boltzmann’s law of radiation by “heating” a light bulb

Students are encouraged to answer these scientific questions by performing the real experiment in the lab. In addition, the measured data has to be prepared and analysed in a lab journal with respect to scientific standards.

3.2. The virtual laboratory ‘Thermography’

On the other hand, the virtual lab shall help students to prepare the experiment in the real lab. Thus, particular attendance is paid to the presentation of a theory that is tailored to understand the experiment. Furthermore, the experiment is made transparent to the learner before entering the real lab. In accord with the overall structure (compare section 2), the virtual lab ‘Thermography’ consists of five chapters, we will elucidate in the following.
When opening the virtual lab, its structure is presented to the student, who can decide whether to go ahead in a chronological way or to select single chapters of the learning unit – depending on the individual pre-knowledge with the topic. Beginning with chapter Orientation, it tries to motivate the student for the content and to give the necessary information, so that she or he can organize the own learning process more efficiently. The first video experiment intentionally leaves the learner with a surprising observation that demands further explanation: Why does the shown human hand become ‘invisible’ when hold behind a beaker glass? With the help of a list of buzzwords the learner can check the overall pre-knowledge. Afterwards, learning requirements are listed, learning goals are defined, and the time to invest for the virtual lab is estimated. The next chapter, Basic Theory, provides the theoretical background. Thus, the preparation with the virtual lab frees the student from the theoretical load when performing the experiment in the real lab, meaning that the cognitive capacity can focus more on practical aspects or handling routines. According to the above mentioned objectives of the real experiment (compare subsection 3.1), the theory is subdivided into ‘Emission, Transmission, Reflection’, ‘Stefan Boltzmann’s law of radiation’, ‘Planck’s law of radiation’, ‘Wien’s law’ and ‘Leslie’s dice’. In order to stimulate the learner’s activity, it is essential to incorporate tasks. For example, one task is to read out the given transmission spectrum for glass at a given wavelength or to calculate the frequency of the maximum of the solar spectrum. By answering these tasks, the learner is able to resolve the astonishing observation in the introducing video of chapter Orientation (see above). All in all, we recommend a mixture of different types of tasks (e.g. cloze, assignment, calculation) to keep it interesting to the learner. We will continue discussing this interaction level in the next subsection, which deals with the implementation of the pedagogical agent. Chapter Experiment visualizes the set-up, thus, allowing the student to familiarize with the experimental design, some measurement routines (procedural knowledge) or how to analyse the measured data. Nevertheless, the virtual experiment cannot (and should not) substitute the hands-on experience gained when working with the real apparatus. In the virtual lab ‘Thermography’ the learner’s task is, in a first step, to confirm the temperature dependence of Stefan Boltzmann’s law of radiation, and, in a second step, to determine the emissions coefficient $\varepsilon$ of a metal plate by analysing a given set of fictitious raw data. The next task shows an infrared video of a rotating Leslie’s dice which has been filled with hot water. Here, the learner is prompted to assign the thermal information on the heated surfaces to the correct surface material that fixes the emission coefficient. In another infrared video the effect of lacquer on a ceramic cup has to be interpreted as well as the locally different heat conduction (at the pot handle, the edge, for the dipped silver, the black coloured and the white plastic spoon-handle, respectively). Chapter Application, shall further deepen the learning content by giving exercises to practice calculation routines and the transfer to related problems. In order to sensitize the learner to the temperature measurement with an infrared camera, she or he is expected to correctly read out the infrared picture from a dog, whose physiology imposes some restrictions on this technique. Finally, chapter Reflection aims at ensuring the learning success. It offers a printable compilation of the most important laws and some questions to trigger once more the student’s reflection on the topic. Finally, a video demonstrates that it is possible to hold a glowing piece of isolation wall from the space shuttle – when touched at its corners where thermal radiation predominantly takes place. The virtual lab is completed by the imprint and an e-mail contact form in case of technical or other problems. As the user data is collected ‘by the pedagogical agent’ to provide a statistical analysis (see subsection 3.3), a data privacy statement has to be attached, too.

3.3. Implementation of the pedagogical agent into the virtual laboratory ‘Thermography’

Although the virtual lab is based on the experiment in the real lab, the transformation into the virtual format is not a straightforward ‘mirroring’. In the real lab multiple interactions take place that influence the learning process: (i.) the interaction with the apparatus, (ii.) the interaction with the
supervising tutor, and (iii.) the exchange with fellow students. In general, the quantity, quality and modality (self-reflective or socially) of these interactions differ considerably between the real and the virtual lab environment. For the virtual lab the goal is to refine the information level by stimulating interactions that are the essence of learning (germane load). In principal, a well-designed computer simulation (e.g. to study the effects of different parameter settings on the result) allows to mimic an interaction of type (i.). By far more challenging is the realization of a pedagogical agent that – according to interaction type (ii.) – plays the role of the supervising tutor (meaning a person with authority and professional knowledge, who mediates between the content and student). In contrast, the direct social exchange of type (iii.) is typically not possible for an asynchronous learning in the virtual environment. Interestingly, the evaluation of the Bachelor group stresses the wish to communicate with their fellow students during the visit of the virtual lab. A preliminary survey among students indeed confirms that there is a desire for assistance in the virtual lab – being more emphasized by Bachelor students (yes: 17/33, no: 9/33, don’t know: 7/33) as compared to Master students (yes: 8/20, no: 7/20, don’t know: 5/20). Moreover, according to the preliminary survey, most students prefer a comic like representation of the pedagogical agent instead of a photo of a real person – with only slight differences between Bachelor (yes: 24/33, no: 3/33, don’t know: 6/33) and Master students (yes: 13/18, no: 1/18, don’t know: 4/18). Furthermore, the predominant majority of students want a visual representation of the pedagogical agent. Around one quarter of students say that the pedagogical agent should be able to speak. Note, the intention of this survey is to obtain a rough confirmation of the students’ need and wishes instead of finding out all details of an ‘ideal’ pedagogical agent (e.g. investigation of group specific bias). Apart from that, we suggest a pedagogical agent that can, with respect to its design and functionality, be personalized by the individual user. Hence, the user decides if the pedagogical agent shall speak or not. Further steps to optimize the pedagogical agent will be reviewed later in the outlook.

With regard to the students’ evaluation we chose a pedagogical agent that is designed as a (voiceless) comic version of Einstein (see figure 1, right). The pedagogical agent is placed on the right margin of the webpage and equipped with some useful control elements: There is an input box and buttons to request more information, to navigate from one task to the other or to switch to the personal feedback page (compare section 4). Besides, there is also the option to fade out the pedagogical agent.

Beyond the pure learning content (information level), the virtual lab is enriched by tasks (interaction level) that – being the main idea of our pragmatic approach – are exclusively mediated and triggered.

\[\text{Figure 1.} \text{ Left: The orange coloured frame highlights the task with the entry field. Middle: The learner is asked to assess her or his self-confidence with the given answer. Right: Appearance of the pedagogical agent and control bar for navigation (left/right arrow), information (i-symbol), tip (Tipp), and cross-symbol to remove the pedagogical agent.}\]
by the pedagogical agent. In other words, one can say that the pedagogical agent is realized as a second ‘learning layer’ imposed over the content-addressed virtual lab. This second layer is made visible by highlighting the activating tasks throughout the virtual lab (see figure 1, left). After having submitted the solution to ‘Einstein’, the student is requested to assess her or his self-confidence with the given answer on a five stage Likert scale, before the correctness is displayed by the pedagogical agent (see figure 1, middle). Independent if the answer is correct or wrong, the pedagogical agent makes available several prepared tips for the solution. Altogether, with the implementation of the pedagogical agent, a new quality is added to the virtual lab. In line with the publication by Bendel [8], the pedagogical agent can introduce, (explain), present, (demonstrate), help, (communicate), give feedback, (remark), navigate, evaluate and (personalize), whereupon the functions written in brackets are not yet on hand.

4. Assessment of the students’ benefit
To quantify the students’ benefit we performed an evaluation for both, the Bachelor students and the Master students (for definition of both groups see subsection 3.1).

First of all, we evaluated if the students would like to communicate with their fellow students about the learning content during the processing of the virtual lab. The evaluation yields some differences between Bachelor and Master students. From the Bachelor students’ point of view (yes: 27/33, no: 4/33, don’t know: 2/33) the communication with fellow students is much more important than it is for the interviewed Master students (yes: 9/18, no: 8/18, don’t know: 1/18). Strikingly, a very similar trend results from the question to the students’ demand on a detailed feedback. As Master students (yes: 8/20, no: 9/20, don’t know: 3/20) are assumed to be the more advanced learners as compared to Bachelor students (yes: 24/33, no: 7/33, don’t know: 2/33), they may feel self-confident enough to learn independently.

In order to give the student an additional benefit when learning with the pedagogical agent, a log file analysis records the detailed activities of the learner during the visit of the virtual lab, and reorganizes the collected data on a user-specific feedback page. It indicates statistics of the (unit like) current progress as well as the number of correct/wrong/not answered tasks and the number of used/not used tips. Moreover, the learner’s self-assessment is compared with the objective correctness of the different tasks. Among the five types of tasks (see table 1), namely input, choice, show, video and service, self-assessment is only possible for the first and second type. Depending on the difference between both quantities (self-assessment minus objective correctness), it tells the reflecting learner if the self-estimation is realistic, or if there is an over- or underestimation, respectively.

Finally, the feedback page provides a chart of competencies to identify personal strengths and weaknesses. To achieve this, we create a simplified competence model by answering the question: What is the typical wealth of expression a physicist has? A physicist can express oneself either by conducting an experiment, by drawing a figure, by using written or spoken text or by working with symbols in an equation. In other words, there are four representations: experiment (non-symbolic), figure (pictorial), text (lingual), and equation (mathematical). In contrast to literature [9], we add the experiment as a fourth class representation to capture practical lab skills.

| Table 1. Defining types of tasks as used in the virtual laboratories. |
|---------------------------------------------------------------|
| types | subtypes (examples) |
|-------|---------------------|
| input | text (e.g. crossword puzzle) or number (e.g. calculation) |
| choice | single choice, multiple choice, assignment, cloze |
| show | tip, hint, assistance, graded solution |
| video | motivation, information, experiment |
| service | navigation, print, links, display tools, handling, data export |
Combining these representations with Bloom’s taxonomy [10] – to distinguish levels of complexity – we end up in the displayed scheme of figure 2. Hence, it is required to classify all tasks throughout the virtual lab with regard to relevant skills in physics and to graduate them due to Bloom’s taxonomy. To give an example, in general it is easier to reuse (first level) an experimental set-up or to reproduce (first level) an equation as compared to the ability to design (third level) a novel set-up or to derive (third level) an equation (see figure 2). Such a classification has advantages for both groups: On the one hand, the author or teacher of the virtual lab can rely on a didactically substantiated scheme that is easily adaptable to other labs. On the other hand, the learner is able to understand the information from the competence chart without any deeper knowledge of didactics.

Figure 3 arranges the different representations with the corresponding level of complexity following from the presented simplified competence model. For instance, the virtual lab ‘Thermography’ includes 36 tasks (Orientation: 5, Basic Theory: 18, Experiment: 5, Application: 6, Reflection: 2) that span the lab-specific green or light shaded area. Obviously, many tasks request the learner to calculate with equations or to read figures. The competencies acquired by the individual learner are shown as blue or dark shaded area – being directly comparable to the reference area.

Figure 2. Scheme of the simplified competence model. The four representations (experiment, figure, text and equation) are weighted pursuant Bloom’s taxonomy to measure physical skills.
5. Summary and outlook
In summary, we demonstrate the concrete realization of a pedagogical agent embedded in a virtual physics lab, that itself is part of a comprehensive blended learning lab concept. We claim that the pedagogical agent does not only assist but foster a more successful multimedia learning – mainly because of motivational reasons, and the possibilities to guide the learner’s attention for a more goal-oriented learning process. In this context, we give a pragmatic solution for a multi-feedback that triggers the learner’s reflection. A feedback page is utilized providing self-assessment and logs that are used to monitor and track the learners’ individual performance. Furthermore, the comparison of the learner’s individual performance with average results of fellow students may be helpful or even motivating when linked with competitive elements like a high score. Another idea – already feasible from the log file – is the reconstruction of the personalized learning path, if so completed with recommendations to optimize the own learning strategy. We further plan to generate a supervisor’s page with specific statistics. In the future, investigations with control groups will be performed to substantiate how the pedagogical agent affects the learning.

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