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DigiPhysLab: Digital Physics Laboratory Work for Distance Learning

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Abstract

Pursuing a broad range of learning objectives, effective physics laboratory courses need conducive-to-learning, motivating, and engaging experimental tasks. The Covid-19 pandemic has further increased the demand for quality experimental tasks which can also be used in online learning scenarios. The EU-funded DigiPhysLab-project meets this need by developing a set of 15 competence-centred experimental tasks which can be implemented by instructors effortlessly in their own lab courses, independent of whether they are held on-campus or in distance learning. For this, the project utilizes the broad availability of digital technologies like smartphones which allow an inexpensive data collection and analysis also outside a traditional laboratory. The developed tasks are characterized by a framework for design principles of experimental tasks derived from literature. In this conference proceedings, the general rationale and outline of the DigiPhysLab-project are described and exemplified by an experiment that is already developed, i.e., the Slamming Door experiment.

1. Introduction: The DigiPhysLab-project

Usually, physics teaching at undergraduate level has three different components: lectures introduce the physical concepts and theories, tutorials provide opportunities to deepen the knowledge of the lecture by solving physical problems, involving mostly various mathematical approaches, and in the laboratory courses students can conduct their own experiments which typically accompany the content of the lecture. During the Covid-19 pandemic, university learning and teaching needed to be implemented virtually in distance learning scenarios rather quickly (Klein et al., 2021). While lectures and tutorials could quite easily be realized for example as web conferences (Klein et al., 2021), transforming a lab course into a distance learning setting was much more difficult. Common challenges were for example related to the communication between instructors and students, the limited choice of equipment available at home, the production of supportive but also easily usable instructions, or students' grading (Hut et al., 2020). Several approaches for distance learning lab courses were tried out, with ambiguous success. Bauer et al. (2021) for example indicate that experiments conducted at home can support learning objectives with a reduced complexity while hybrid labs using simulations and virtually held group discussions with peers and instructors can deepen the knowledge about simulations but neglect the acquisition of elaborated experimental competencies.

Overall, these experiences and findings reveal that further work needs to be done to develop experimental tasks suitable for lab courses in distance learning scenarios. The DigiPhysLab-project (Developing digital physics laboratory work for distance learning, 2021 - 2023) follows this goal. In a cooperation between the Universities of Göttingen in Germany, Jyväskylä in Finland, and Zagreb in Croatia, and co-funded by the Erasmus+ programme of the European Union since March 2021, we are developing and evaluating 15 competence-centred experimental tasks which can be used in distance learning scenarios as well as in on-campus lab courses. We make use of the broad availability of digital technologies like smartphones or data analysis tools which enable hands-on data collection and analysis even outside the university laboratory. Additionally, we develop a framework for design principles of experimental tasks which allows a characterization of the developed tasks and can also function as a basis for the development of further new tasks.

In this contribution, we present the outline of the DigiPhysLab-project. In section 2, based on the current state of research, we argue why our project is relevant not only for teaching and learning under pandemic circumstances but follows a general approach to increase the effectiveness of physics lab courses at European universities beyond pandemic times. In section 3, we demonstrate the workflow of the DigiPhysLab-project with the example experiment Slamming Door, which has already been developed and evaluated in our project. Finally, in section 4, we give an outlook on the further progress of our project until its end in February 2023.

2. Motivation of the project based on the state of research about the effectiveness of lab courses

With lab courses as an integral part of physics studies, specific learning objectives are intended to be reached. As described in section 2.1, traditional lab courses do not reach the desired goals and the intended effectiveness, with multiple causes discussed in section 2.2. Since these observations emerged over the past decades, several approaches for improving lab have been tried which we outline in section 2.3. From this, we derive in section 2.4 the demand for further development which motivates the work of the DigiPhysLab-project.

2.1 Learning objectives and effectiveness of labs

In the past, a lot of effort has been put into identifying and listing the learning objectives of physics laboratory courses. Some of these approaches were more normative, others more empirical. Normative lists of learning objectives can be taken, for example, from the policy statement of the American Association for Physics Teachers (1997), which was updated in 2014 (American Association for Physics Teachers, 2014), or the study goals formulated by the Konferenz für Fachbereiche Physik in Germany (2010). On the other hand, empirical work has been done for example by Welzel et al. (1998; English version Sere et al., 1998), who conducted a Delphi survey among science teachers in schools and universities in six different European countries, as well as by Nagel et al. (2018), who let German lab instructors rate a list of learning objectives, in turn based on the findings of a survey among faculty at the University of Colorado Boulder (Zwickl et al., 2013). These references, which are just a selection of lists for known learning objectives, already portrays a huge variety of learning objectives for labs, for example linking theory to practice, acquiring experimental skills, developing collaborative learning skills, getting to know the ground-laying principles of experiments, or fostering students' interests and motivation.

The sheer abundance of goals already suggests that lab courses cannot easily reach all learning objectives as desired. Research has shown that there is a significant discrepancy between learning objectives and outcomes of physics lab courses which characterizes their ineffectiveness. Holmes et al. (2017) have shown that participating in a physics lab has no impact on the understanding of the physical content (measured by the success in the final exam), independent of the university, the lab instructor, the thematic field, or the exam task type (algebraic, calculus-based, or concept-based). As investigated by Teichmann et al. (2022), students do not internally follow expertise-like views and attitudes regarding lab work and experimental physics even though they have quite appropriate knowledge from the point of view of experts. Rehfeldt (2017) has shown that from students' perceptions physics lab courses mainly have medium quality as they do not support the acquisition of experimental, communicative, collaborative, or assessment competence appropriately and especially do not meet students' interests.

2.2 Causes for the ineffectiveness of lab courses

The ineffectiveness of traditional labs defined as the gap between the learning objectives and the actual achievements of labs is caused by various reasons. Some are instructional since traditional experimental tasks are quite cookbook-styled impeding students' engagement. Holmes and Wiemann (2018) state:

> "[A]ll the decision making […] is done for the students in advance. […] [S]tudents are told what value they should get for a particular measurement or given the equation to predict that value; they are told what data to collect and how to collect them […]. Although the students are going through the motions of physics experimentation, their brains are not engaged in the process […]. That mental effort is made by instructors beforehand when they design the experiment." (pp. 40f.)

This statement matches the findings by Haller (1999, p. 99), who measured the percentage of time for different students' activities in a typical (German) physics lab: While students spent much time manipulating the setup (37% of the time) and collecting data (35,7%), which are quite non-engaging actions, working with formulas (0,6%) or talking to peers and instructors (7,6%) play a minor role during a typical lab day even though these activities could be considered as meaningful for students' learning processes.

Further reasons for the ineffectiveness of labs are learner-related, for example facing the lack of motivating and interest-enhancing elements in labs (Rehfeldt, 2017), or content-related due to inherent difficulties like dealing with multiple representations during data collection and data analysis (Ainsworth, 2006; Scheid et al., 2019). Moreover, the Covid-19 pandemic had a huge impact on university teaching and learning especially in lab courses. For example, the shift to distance learning led to the less conducive-to-learning use of second-hand data (Klein et al., 2021) or to a shift from developing lab skills towards reinforcing physics concepts (Werth et al., 2021) which is generally spoken less beneficial for acquiring critical thinking skills and appropriate views about experimentation (Walsh et al., 2022).

2.3 Approaches for improving lab courses

Accompanying the research about the (in-)effectiveness of lab courses, several approaches were and are still followed to improve lab courses and to increase their outcome on students' learning. One approach tries to develop addressee-specific lab courses which meet the specific perspectives, desires, and prior knowledge of the students who participate in the lab course. Related work has been done for example by Theyßen (1999) and Klug (2017) for medicine students, by Neumann (2004) for physics students and by Andersen (2020) for teacher training students. Another approach aims to improve the students' preparation in advance of the lab day mainly by implementing multimedia elements in the instructions or newly developed learning environments (Zastrow, 2001; Nagel, 2009; Kreiten, 2012; Fricke, 2018). Furthermore, there are several competence-centred approaches based on the principle of cognitive apprenticeship (Bauer & Sacher, 2018; Bauer et al.,

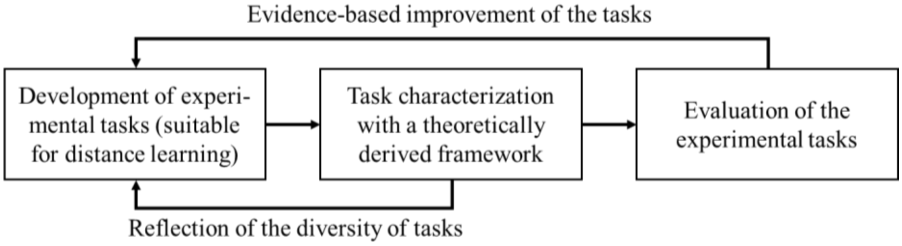

Fig. 1: Workflow of the DigiPhysLab-project.

2020) or hypotheses- and phenomenon-initiated open inquiry (Holmes & Wieman, 2018; Etkina, 2015; Kontro et al., 2018; Teichmann et al., 2022).

A rather new approach that arose with the broad emergence of new digital technologies is the use of digital tools like smartphones, tablets, augmented and virtual reality environments, computers with interactive screen experiments, or artificial simulations for data collection and analysis. Experimenting with mobile devices (e.g., video analysis) can reduce the extraneous cognitive load and therefore support the conceptual understanding since information is coherently represented in space and time, dynamically linked, and usable by the learner in one's own pace and order (Becker et al., 2020). Otherwise, digital technologies like smartphones can increase students' motivation and interest due to the use of an everyday object linking physics to everyday life (Hochberg, 2016) or with virtual reality environments due to the principles of engagement and immersion known from game design (Pirker, 2017). Therefore, digital technologies allow inexpensive, conducive to understanding, and motivating data collection and analysis which provide new opportunities for competence-centred, effective physics lab courses.

2.4 Necessity for further development and research

The approaches already pursued reveal that the use of digital technologies can be seen as a promising opportunity to innovate physics lab courses as they are not only conducive to understanding, motivating, and engaging, but also rather inexpensive and broadly available. Thus, they can be utilized for effective, fruitful labs under pandemic circumstances and beyond for contemporary physics education flexible in terms of space and time. To support instructors all around Europe to implement corresponding experimental tasks in their lab courses successfully, carefully tested experimental tasks of high quality need to be developed. The DigiPhysLab-project follows exactly this goal with a specific workflow described in section 3.

3. Workflow and initial findings of the project

The DigiPhysLab-project develops new experimental tasks, characterizes them with a theoretically derived framework, and evaluates them. The findings enable an evidence-based improvement of the tasks and the use of the framework secures a diversity of the tasks to be developed. In the following subsections, we describe each step of this specific workflow (cf. Fig. 1) in general and exemplify all steps based on the already developed experiment Slamming Door.

3.1 Experimental tasks – the experiment Slamming Door as an illustrative example

As the focus of the DigiPhysLab-project is the development of high-quality, digital experimental tasks which can be used for distance learning as well as for on-campus learning scenarios, we understand our work not (only) as generating new experimental ideas conductible for example with a smartphone, but also as the development of out-written task instructions for students and instructors who should be able to implement our tasks easily in their studies or lab courses. Therefore, our tasks are conceptualized as standalone experimental tasks that are independent of a specific lab concept. The set of our 15 tasks to be developed addresses a broad range of typical topics from introductory physics lectures which are commonly attended by physics bachelor and physics teacher training students in their first four semesters. Our tasks typically enable a data collection and/or data analysis using digital technologies like smartphones or computers with data analysis software. These technologies allow a contemporary and precise collection and analysis of greater data sets even without using specific measurement devices like in traditional labs. Besides that, our experimental tasks require mainly household items or objects borrowable from physics faculties to facilitate the conduction of our experiments also in distance learning scenarios at the students' homes.

One of the experimental tasks already developed is the experiment Slamming Door. The idea is based on Klein et al. (2017). In this experimental task, the students should replicate a part of the study described in this paper by investigating (for their specific door) which frictional model(s) describe(s) the effects of the slamming door most simply but precisely. As described by Klein et al. (2017), one can expect a nested model containing dry friction $D{\sim}\omega^0$, Stokes friction $S{\sim}\omega^1$ and/or Newtonian friction $N{\sim}\omega^2$. Solving the differential equation

$$a + b\omega + c\omega^2 = -I\dot{\omega} \qquad \{1\}$$

for the frictional torque with parameters a, b, and c leads to the general solution

$$\omega_{DSN}(t) = \frac{2\omega_0 c + b - \gamma\tan\left(\frac{\gamma t}{2I}\right)}{2c\left[1 + \frac{(2\omega_0 c + b)\tan\left(\frac{\gamma t}{2I}\right)}{\gamma}\right]} - \frac{b}{2c} \qquad \{2\}$$

for the angular velocity ω with $\gamma = \sqrt{4ac - b^2}$. By setting various combinations of a, b, c equal to zero, seven possible nested models can be derived. Students can now attach a smartphone to the face of their door and measure the angular velocity directly with the gyroscope sensor or indirectly over the centripetal acceleration with the acceleration sensor of their smartphone. For this, the application phyphox (Staacks et al., 2018) can be utilized. Example data can be seen in Fig. 2 where the orange box marks the section where the door is closing after an initial impact at around the time $t = 2\text{s}$. By fitting the seven theoretically possible models and taking account of the two "fitting criteria" (high R² and realistic order of magnitude of the fit parameters; Klein et al., 2017), students can identify which model describes the friction of their door best. The analysis of the example data with the help of the applications Origin (or SciDaVis) using initial guesses and intervals for the fit parameters based on the findings of the paper can be seen in Tab. 1. One can recognize that the combination of dry friction D and Newtonian friction N has the highest R² while adding Stokes friction S to the model does not improve the explanatory quality of the model as the R² remains the same and the related fit parameter b is set as nearly zero. This is in accordance with the original paper which assumes that the door hinges cause the dry friction, and the Newtonian friction is generated by the air drag at the door face.

For this experimental task, we developed instructions for students and instructors. The students' version consists of four parts:

1. Introduction and preparational tasks (1 page) that should be distributed to the students before the lab work.
2. The actual experimental task (1 page) consisting of a small motivation, a list of experimental materials and addressed experimental skills, the task itself, and information regarding the assessment. The task itself is quite roughly sketched, so the students have the chance for open inquiry. The document should first be distributed to the students when the lab work starts.
3. Instructions (3 pages) for how to use the applications phyphox and SciDAVis in case the students are not familiar with them.
4. Key questions (1/2 page) that guide the students through their work. The questions are just a scaffold for the experimental process as they do not provide any suggestions for the experiment but initiate a reflection on one's own approach.

The instructors' version provides some further tips and tricks as well as to-be-expected results for each phase of the experimental process. Additionally, this document provides some suggestions regarding the assessment and potential modifications of the task. Both versions can be found on our project website (https://www.jyu.fi/digiphyslab).

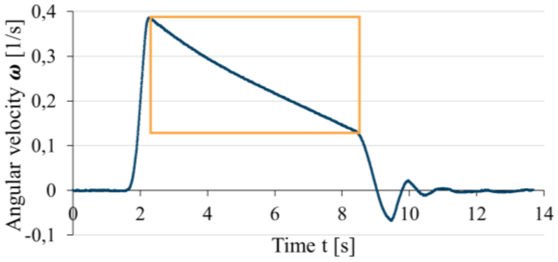

Fig. 2: Angular velocity of the slamming door over the time. The part marked with the yellow box describes the actual movement of the door after it was slammed until the door interferes with the door frame.

3.2 Framework for design principles

To keep track of the characteristics of our developed tasks, provide a certain diversity, and to provide an overview of our tasks for potential users, we develop a theoretical framework for design principles of experimental tasks. It allows a characterization of the developed tasks and can also function as a basis for designing new tasks (in our project and beyond for all lab instructors). The framework is derived from a literature review and the reflection of existing lab courses at our home universities. It integrates literature from several perspectives, for example, the to-be-acquired experimental (Millar, 2009; Welzel et al., 1998) and digital competencies (Thoms et al., 2021) or the use of digital technologies in physics labs (Chen et al., 2012; Trinh-Ba, 2016). The initial version of the framework (see an extract in Fig. 3) consists of five dimensions which are specified by several categories:

1. The dimension general outline/circumstances gives an overview of what the experimental tasks look like, e.g., providing information about the topic, the target group, or the necessary equipment for the experiment.
2. The dimension learning objectives provides different kinds of learning goals which can be linked to the experimental task, e.g., linking theory to practice, acquiring experimental skills, or digital competency.

	a (D)	Δa	b (S)	Δb	c (N)	Δc	ω_0	$\Delta\omega_0$	R²
D	0,03988	8,23E-05	:=0	-	:=0	-	0,36779	2,91E-04	0,99352
S	:=0	-	0,16282	2,43E-04	:=0	-	0,38839	2,49E-04	0,99696
N	:=0	-	:=0	-	0,61788	0,00294	0,40702	9,42E-04	0,97326
DS	0,01581	1,94E-04	0,09892	7,93E-04	:=0	-	0,38085	1,41E-04	0,9994
DN	0,0273	7,63E-05	:=0	-	0,20251	0,00119	0,38246	1,14E-04	0,99966
SN	:=0	-	0,16282	2,43E-04	2,17E-17	≈0	0,38839	2,49E-04	0,99696
DSN	0,0273	7,63E-05	1,92E-25	≈0	0,20252	0,0012	0,38246	1,14E-04	0,99966

Tab. 1: Fit parameters for the seven different frictional models describing the rotary motion of the slamming door. The DN-model (dry & Newtonian friction) is most precisely (highest R²) while adding Stokes friction (S) to the DSN-model does not improve the explanatory quality of the model.

3. The dimension task design focuses on the characteristics of the actual task, e.g., the degree of open inquiry, the recommended organizational form, or the logical function of the activity.
4. The dimension focused experimental activities consists of a list of potential activities students run through during the experimental process.
5. The dimension delivery/implementation contains aspects of how lab instructors could integrate the task in their lab course, e.g., by addressing the delivery of the instructions, the (logical) integration in the lab course, or the students' assessment.

Each category comes with a vocabulary list that can be used to characterize the experimental tasks with a more standardized wording. Fig. 3 shows the characterization for the Slamming Door experiment. The final framework will be published separately soon.

3.3 Evaluation of the tasks

Besides the development of our experimental tasks and their characterization with the help of the framework, we also pilot and evaluate our tasks. Through this, we can revise and improve the task documents as well as secure that our tasks can be implemented in the university teaching. Some of these tasks are piloted on-campus to allow a precise observation of the students' interaction with the task documents and their experimental process. Other tasks are piloted in distance learning settings to evaluate the usability of our experimental tasks also in the intended learning environment. Each task is evaluated at least once, some tasks will also be tested in a small- (<5 students) or medium-scale (~10-15 students) evaluation in our three contributing universities. For the evaluation we use, depending on the group size and the status of the pilots, a self-developed questionnaire and/or guideline-structured group interviews. Both evaluation instruments will be published after an already planned revision.

The experiment Slamming door described above has so far been piloted with 14 teacher training students in their second to third master semester at the University of Göttingen as part of a school practical lab course (Didaktikpraktikum). The students were divided into groups of two to three (5 groups in total) and got an obligatory task (reading the paper and installing the software) as well as an optional task (familiarizing with phyphox & SciDAVis) in advance.

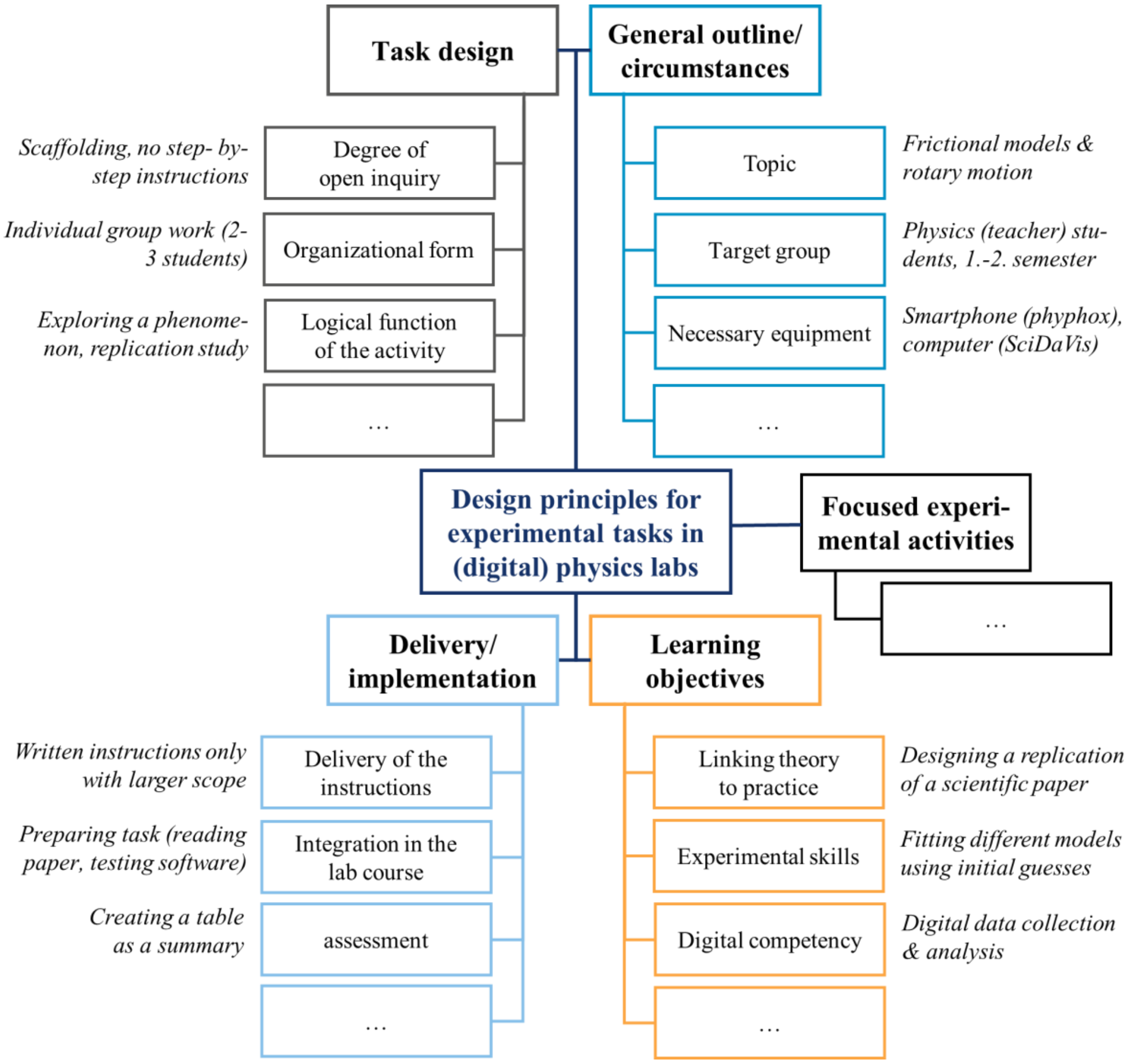

Fig. 3: Framework of design principles for experimental tasks in (digital) physics labs and it's use for task characterization exemplified for the experiment Slamming door.

During the lab day of two hours, the students conducted the experiments mainly self-sufficiently while three instructors were available in case of any questions or difficulties. The observations and final students' documentation revealed that students had obstacles with an appropriate data analysis and the use of given criteria for choosing a suitable frictional model. Therefore, the task complexity was sufficient even for master students whereby many obstacles would not have occurred if students had read the paper and the task instructions more carefully.

In the group interviews conducted directly after the lab work, students evaluated positively that the experiment was interesting, the use of smartphones motivating, and thereby the phenomenon easily accessible. They perceived the instructions as clearly written and understandable with a good structure and layout. Some students mentioned that the use of the smartphones and the data analysis tool SciDAVis reduced their reservations regarding the use of digital technologies in the future, also during their upcoming work as physics teachers. While some students liked the given freedom of choice and the opportunity to formulate one's own hypothesis, other students would have preferred even less guidance or conversely a debug list to finish the work more smoothly and quickly. Negatively evaluated was the tasks' focus on data analysis which was described as too long and too tough and that the digital data collection and analysis would increase the extent and complexity of the experiment more than the advocated manual data collection and analysis.

Here, students revealed several misconceptions which explain the ambivalent perception of experimental tasks: On the one hand, students did not recognize the data analysis as part of the experimental process which would already end with the data collection from the students' point of view. On the other hand, students refused the fact that the desired decision for a precise frictional model could hardly be done without big and precise data sets which are only provided and can only be handled with digital technologies. These misconceptions were addressed during a reflection session after the lab session.

3.4 Task revision

Based on our observations and evaluation data, we modified all documents for our experimental tasks available on the project website. In particular, the instructors' version benefits from the pilot runs as we can provide specific suggestions and advice on how to deal with or even avoid obstacles that might occur during the implementation of our tasks in university teaching. The pilot runs also led to improved instructions for students: For example, typing errors were eliminated, some expressions in the task description and learning objectives were specified, and the already mentioned guiding questions were added.

4. Summary and outlook

To conclude, the DigiPhysLab-project follows the aim to develop and evaluate competence-centred, digital experimental tasks which can be conducted in distance learning and on-campus learning settings and which are mapped to a framework for design principles of experimental tasks for a precise task characterization. In the following steps of the project, we will finalize and evaluate the framework, develop further experimental tasks for other subject areas like magnetism or optics, characterize them with the help of the framework, and evaluate them with our evaluation instruments (partially to be improved) in our three home universities. All documents (task instructions for students and instructors, framework, overview of the tasks based on the framework, guide to use tasks and framework, …) will be published as open educational resources in four languages (English, German, Finnish, and Croatian) on our project website (https://www.jyu.fi/digiphyslab) until the end of our project. By this, we hope that our work can support instructors at universities (and schools) all around Europe to provide high-quality experimental tasks using modern digital technologies for the learning processes of their students.

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