HeatQuiz: An app framework for game-based learning in STEM education

1st Eva Jacobs
RWTH Aachen University
Aachen, Germany

2nd Oliver Garbrecht
RWTH Aachen University
Aachen, Germany

3rd Reinhold Kneer
Institute of Heat and Mass Transfer
RWTH Aachen University
Aachen, Germany
kneer@wsa.rwth-aachen.de

4th Wilko Rohlfs
Institute of Heat and Mass Transfer
RWTH Aachen University
Aachen, Germany
rohlfs@wsa.rwth-aachen.de

***Abstract*—The present paper aims to promote game-based learning using mobile apps in university-level education, specifically in the domains of science, technology, engineering, and mathematics (STEM). A survey among 102 respondents determined needs and preferences of STEM students when using learning apps: which learning strategies they prefer, what personal motivation drives them, which gamification elements appeal to them, and which usage scenarios they favor. An important result is that students prefer apps which promote transfer of learning to those which help structure or memorize content. This preference is in line with the skills expected from professionals in this field. Concrete design and content guidelines for learning apps are derived. Following these, the authors developed a framework which other lecturers may use to create their own app. Two universally applicable types of tasks in STEM education are supported: One allows to qualitatively draw any two-dimensional mathematical function and check its characteristics; The other allows to correct any mathematical expression as variables can also be processed. Using the framework, a mobile app for heat and mass transfer (HeatQuiz App) was generated. The app was evaluated with STEM students in an undergraduate class: The vast majority gave a positive rating and believed that the focus on transfer of learning is well implemented. This is reflected in the usage statistic: During one semester, 545 different students played a total of 27,350 games. As a measure of learning progress, the average score per game nearly tripled over the course of the class. While preparing for the exam, students pushed the app usage to a maximum of 10,000 games per week. This illustrates that the app was well-accepted as a learning tool and is an ideal complement for teaching.**

***Index Terms*—mobile game-based learning, gamification, interactive learning environments, applications in engineering education, undergraduate education, teaching / learning strategies**

I. Introduction

Teaching at engineering schools takes place in a field of controversy around digitalization. On the one hand, there are history-charged university libraries where scientific material – only a couple of decades old – lies well-hidden on microfilms. Even today, the content of many lectures is still published in textbooks, often even in paper form. On the other hand, research and publication of scientific findings shift more and more into the online world and lecturers use the possibilities of digitalization to improve their teaching. Today, “virtual learning spaces”, “online distance learning”, or “online exams” are state-of-the art. This development is reflected in the scientific interest in this topic over the last decades [1]. Digitalization is the key to adapt teaching to the fast-changing learning behavior of students. The smartphone represents the central access to a digitalized world for the present generation of students [2]. New learning systems are expected to be available on smartphones and to integrate into an existing landscape of apps. For lecturers, integrating smartphones into their academic teaching activities opens a whole range of possibilities for complementing traditional forms of teaching and even compensating for their deficits. Where the single relationship between lecturer and student is stressed, e.g. in large engineering schools with limited teaching resources, learning apps can augment teaching. They can support students on the path to self-regulated learning and help them pursue an efficient learning strategy [3].

On the design side, learning apps on mobile devices are a perfect tool to realize the gamification approach of digital game-based learning (DGBL). In an academic attempt to introduce a definition, Deterding et al. [4] refer to gamification as “the use of game design elements in non-game contexts”. Gamification allows to pursue new paths in the context of learning. The potential has been demonstrated in a wide range of pedagogically high-valued applications which have been successful for children’s learning over the last years [5]. Digital games have been used to promote spelling and reading and have improved domain-specific learning e.g. in physics, health, biology, mathematics, and computer science. Well-designed games are capable of improving the learning outcome by between 7% and 40% compared to traditional means of education [6].

The present paper focusses on DGBL in university-level science, technology, engineering, and mathematics (STEM) education. It introduces a DGBL-framework which allows to create mobile apps for STEM students and presents an app built with the framework. It aims to bridge the gap between theoretical knowledge and practical problem solving. These skills are challenging to teach but highly valued in the students’ prospective professional lives.

In a university course for production engineering, Silva et al. [7] used a digital game that aimed to simulate reality and succeeded in promoting the above-mentioned transfer of learning. As a positive side-effect, the authors noted that the drop-out rate of the course (which is a significant problem in engineering education) was reduced.

While the use of DGBL is well-established in engineering education (see e.g. [8] for an extensive overview), there is a significant lack of high-quality game-based mobile learning apps. This finding is rather surprising given the large number of apps available in different fields of education and/or different stages of education [9]. For university-grade engineering, most applications available either have limited gaming content, e.g. multiple-choice questions, or simply provide consolidated knowledge in the form of a mobile encyclopedia or a collection of mathematical equations.

However, one of the few pioneering mobile apps that combine gamification with engineering education is "Schnittkraftmeister", developed by the University of Graz [10]. Its German name translates as "Internal Force Master", giving a hint to the content which is based on the theoretical calculation of internal forces in solid structures. The game is available as app for all mobile platforms – its Android version alone has been downloaded more than 100,000 times. "Schnittkraftmeister" encourages users to compete with each other by incorporating a world-wide high-score list and by awarding virtual trophies.

In the present paper, learning apps for STEM students are being analyzed from a user-centered perspective. The following two research questions are addressed: *What are the demands that STEM students place on learning apps?* The preferences of the students are investigated and concrete design and content guidelines for learning apps are derived. Following these, the authors developed a framework (HQ Framework) which allows to create apps in STEM education. Using HQ Framework, a mobile app for heat and mass transfer (HQ App) was generated. This leads to the second research question: *Are the requirements met by HQ Framework and HQ App?*

II. Design of learning apps for STEM students

A survey was conducted to determine the demands STEM students place on learning apps. The study was split into two parts: The first part refers to learning apps in general, the second part to a particular application in the domain of STEM. The survey was placed on an internal website of the Engineering Department at the authors' institution. Therefore, the following characteristics of the participants are known: The respondents are undergraduate STEM students enrolled at RWTH Aachen University, thus qualified to study on university level. Their field of study is e.g. mechanical engineering or computational engineering science. Participants were surveyed anonymously. Personal data, such as age, gender or field of study, was not collected in order to guarantee anonymity even with a small number of respondents. Participants were assigned a unique user-ID, so multiple votes were impossible. The number of questions was kept to a minimum to achieve a low dropout rate. When designing and conducting the survey, particular attention was paid to validity, reliability and objectivity. Objectivity is inherent in this type of online survey. To ensure reliability and validity, the survey was carefully designed according to the current state of research (see [11] for an overview). In case of ambiguous recommendations, the option with the greatest advantage for the specific application was chosen. This approach led to a survey with closed-ended questions and direct, completely verbal, unipolar rating scales. There are a few multiple-choice questions, some dichotomous questions, and mainly rating scales with four possible answers. Filter questions were used instead of a middle category.

Among the 105 participants of the survey only 3 respondents have no use for learning apps at all. The vast majority is interested in using apps either to prepare for exams or to acquire knowledge beyond that. This clear outcome is emphasizing how well students are responding to innovative digital teaching. The following discussion is based on the answers of the remaining 102 participants, as a learning app should be designed for this target group.

A. Learning strategies and motivation

When developing learning apps, special attention should be paid to different learning strategies of the users. Learning strategies are behaviors and thoughts that learners activate in order to control the acquisition of knowledge [12]. These include cognitive strategies (elaboration, organization/structuring, knowledge utilization), meta-cognitive strategies (self-control/self-regulation), supportive motivational-emotional strategies, cooperative learning strategies and the systematic use of learning resources [12]. The present paper considers learning apps that convey mathematical and technical content, therefore the analysis focuses on cognitive and cooperative learning strategies as well as motivation. With regard to these three aspects, the survey determined the users' demands on learning apps. Results are discussed for each aspect and recommendations for learning app design are derived.

Cognitive learning strategies are divided into three intersecting groups, depending on the focus of information processing [12]: Elaboration strategies serve to integrate new information into existing knowledge, making it easier to retrieve and retain permanently. Repeating new information several times, for example, is a commonly practiced method. Organizational strategies serve to structure knowledge by working out the connections between information. Knowledge utilization strategies focus on thorough comprehension as a prerequisite of using knowledge. What has been learned should not only be reproduced but transferred and applied to new situations. Unfortunately, no prior knowledge on the theory of learning strategies can be assumed for undergraduates [13], which also applies to respondents of this survey. Therefore, the questions had to be kept simple and generally understandable. The question to investigate the most suitable learning strategy was: *What is the main purpose of a learning app?* The response options correspond to cognitive learning strategies: "structuring teaching content" corresponds to organizational strategies, "comprehending teaching content" refers to knowledge utilization strategies and "memorizing teaching content" is a fre-

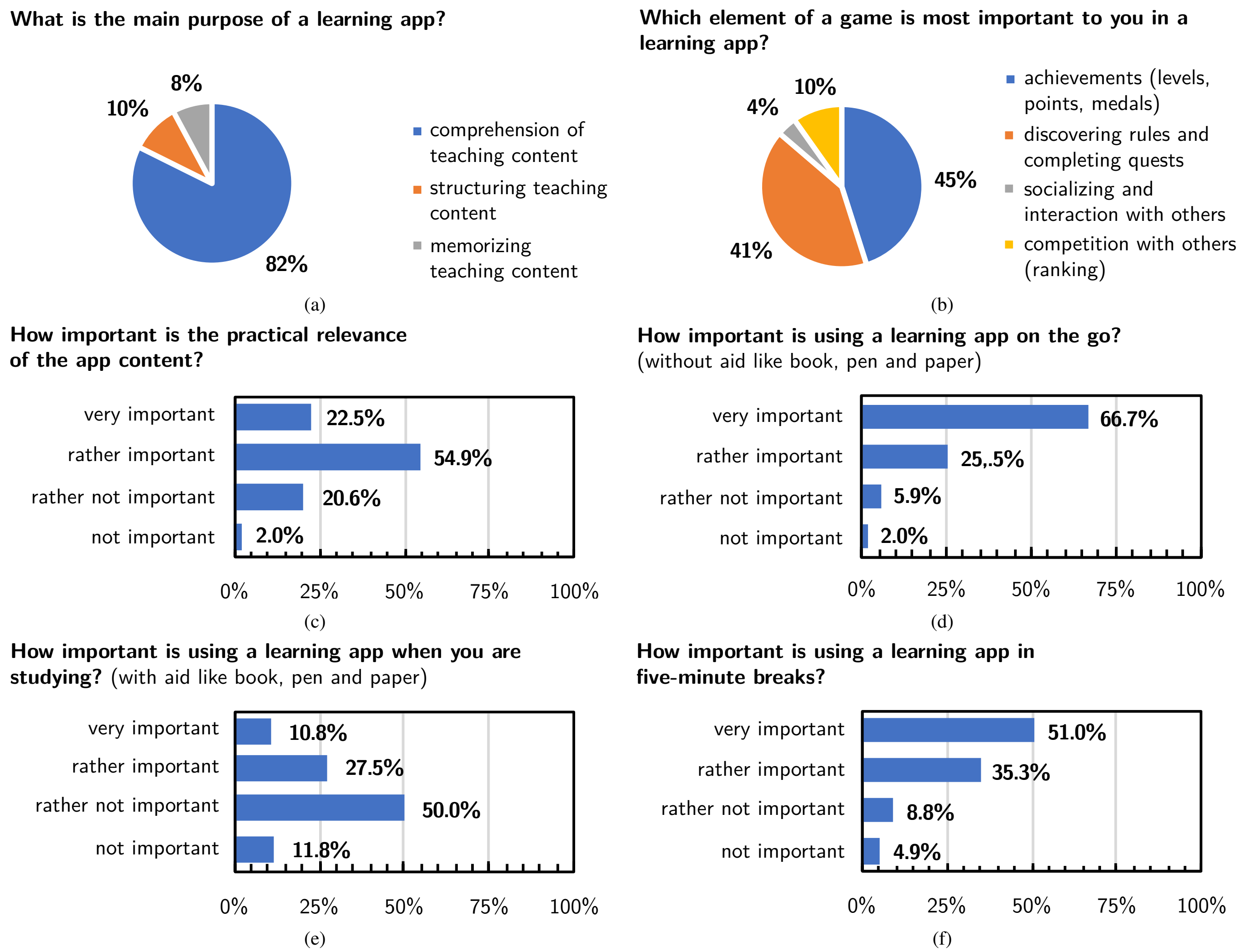

Fig. 1. Results of a survey on the general use of learning apps in university teaching among 105 undergraduate engineering students at RWTH Aachen University.

quently used elaboration strategy that is clearly separated from knowledge utilization strategies, even for laypersons. Results show that an overwhelming majority (82%) of students prefers a learning app that helps comprehending teaching content (see Figure 1(a)). Furthermore, students clearly demand practical relevance of the tasks, i.e. they value application of knowledge (see Figure 1(c)). In combination, this results in the need for an app that fosters transfer of learning. This is in line with the expectations placed on professionals in the domain of STEM. Professional engineers, for example, are often confronted with open-ended problems, i.e. the situation is insufficiently defined, assumptions complementing the constraints have to be made and there is more than one approach to the solution. Transfer of knowledge is the prerequisite to problem solving skills which are a key qualification to address open-ended problems [14]. In contrast, students are least interested in memorizing content, e.g. another flashcard app based on the Leitner-system.

Apart from cognitive learning strategies, academic learning is supported by student motivation. As Garcia and Pintrich [15] propose, students regulate their learning not only by cognitive strategies, but also by motivational strategies: Motivation influences which academic tasks students choose, the effort they make, and the perseverance they show [15]. This is particularly important in learning environments that allow learners to act on their own initiative, as it is the case with learning apps. Motivation is an inner state that causes, directs and maintains goal-oriented behavior [16]. Motivation can be induced by needs, goals and interests; Actions are then directed toward the desired state-of-being. Depending on the target state, motivation can be divided into intrinsic and extrinsic motivation: Intrinsically motivated actions are experienced positively, they are e.g. exciting, interesting or challenging. Consequently, the action itself is the target state, it serves as the motivating incentive [17]. In contrast, with extrinsic motivation, the target state is after the action [17]. Extrinsically motivated actions are carried out in order to achieve positive consequences, e.g. recognition, rewards or exceeding self-imposed standards. Suitable strategies to achieve extrinsic motivation are competitive situations, for example.

The survey revealed what motivates STEM students at RWTH Aachen University. In order to keep the questions generally understandable, students were not asked about their motivation strategy, but about their target state. Based on the target state, appropriate content specifications for learning apps are derived. The following three possible target states were identified:

Target State A: Students study in order to pass the exam. The exam is attributed personal significance, e.g. because the students want to achieve a degree that allows them to pursue a career. The motivation of these students is extrinsically induced; Since it is committed to the exam, the students' interest is only temporary.

Target State B: Students have a topic-related interest. The topic is associated with positive feelings such as joy, stimulation or excitement. Since learning itself is the motivating incentive, this motivation is relatively permanent.

Target State C: Students study to apply their knowledge in practice. Here, a topic-related interest can be assumed, linked with medium-term personal goals. Thus, there is a combination of the above-mentioned motives. Interest in the theory is maintained as long as it leads to practically applicable insights.

In the survey, questions aimed at the three target states. Multiple answers were possible because target states are not exclusive. *A: Would you like to use learning apps to prepare for exams? B: Would you like to use learning apps to gain knowledge beyond the content of an exam? C: How important is the practical relevance of the app content?* While the first two questions are sufficiently answered by choosing "yes" or "no", a rating scale ranging from "very important" to "not important" was provided for the last one. Results show, that almost all students (99%) want to use learning apps to prepare for exams (Target state A). Additionally, the majority of the respondents (61%) is interested in using learning apps to gain knowledge beyond what is subject to the exam (Target state B). For most of the students (77%), practical relevance of the tasks is important or even very important (Target state C). By correlating these results, five different groups of students can be identified. Each group features a distinct combination of target states. Figure 2 provides an overview of the groups, their respective sizes and how their target states are overlapping or differing.

The largest group of **49 students** (48%) (dark yellow), lies at the intersection of all three target states. These students want to use learning apps not only for preparing for exams, but also for acquiring knowledge beyond that. The practical relevance of the tasks is important to them. This profile matches students who have their future profession in mind and want to prepare for it. These students strive to be competent and capable in performance-oriented situations. This extrinsic motivation can be activated by challenging tasks in a learning app. There has to be a quality standard that is perceived as mandatory and that can be missed, reached or exceeded, e.g. a detailed rating at the end of each task. With regard to content, a

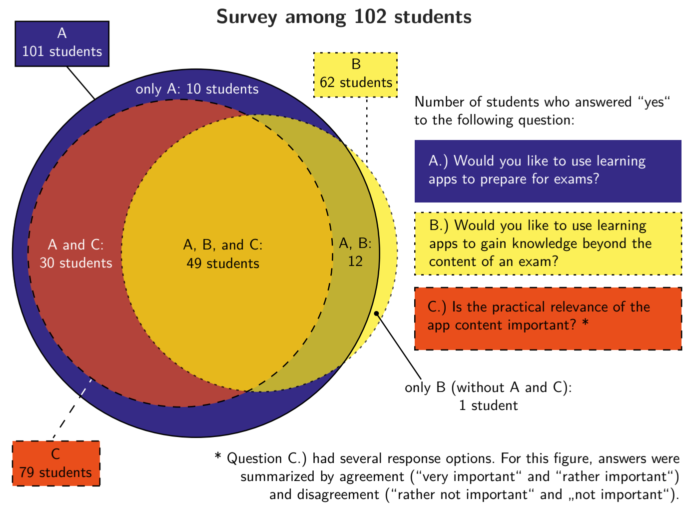

Fig. 2. Results of a survey about the motivation to use learning apps in university teaching among 102 undergraduate STEM students at RWTH Aachen University.

learning app should cover topics extensively and beyond exam-related questions, since this group of students shows intrinsic motivation as well. Here, an app has the potential to arouse curiosity. Students should be able to deepen their knowledge by choosing additional tasks based on their interests, e.g. special cases from practice. For this group, a large variety of tasks is sensible as long as the tasks are clearly linked to practice.

The second largest group of **30 students** (29%) (dark red) wants to use learning apps exclusively for exam preparation and considers the practical relevance of the tasks to be important as well. Obviously, these students are looking for a practical approach to exam questions. An explanation of what a technical solution is used for in real applications motivates them. Because their focus is on efficiently preparing for the exam, questions should be very similar to the exam and limited to exam-relevant content. This, however, contradicts the above-mentioned demands of the largest group. One way to satisfy both is to mark the exam-relevant tasks and allow students to select their preferred tasks.

The picture is different for the group of **12 students** (12%) (greenish color), to whom practical relevance is not important. These students enjoy theoretical tasks and want to acquire knowledge for the exam and beyond. Not only the exam, but also learning itself creates their motivation. This profile matches students who regard specialized knowledge as a personal value. They want to understand theory and how things interact. The survey did not differentiate whether students disapprove practice-related tasks, e.g. because they are more complex, or whether practical relevance is simply irrelevant to them. In the latter case, these students would also be satisfied with the configuration suggested above.

Overall, it can be stated that at least 78% of the students surveyed can be satisfied if the suggestions derived from the two largest groups are implemented. Given the number of participating students, this derivation of content specifications from personal motivation is considered to be universally valid for learning apps in STEM teaching.

In the following, design measures are derived that increase the motivating character of learning apps for STEM students. In general, motivation is a combination of personal motivation and the motivating character of the learning environment, which can be stimulating or inhibiting [12]. Within an app, the learning environment can be adapted to the user's preferences. This is an opportunity to create and maintain motivation and it can be taken through game-based learning. Which elements of a game particularly motivate STEM students was investigated in the survey. As discussed before, no background knowledge of motivational-emotional support strategies can be assumed among the respondents, but a certain experience with digital games can. A common categorization of player motivation [18] is the taxonomy of Bartle [19], where four aspects that typically motivate players are distinguished:

Achievements within the game context: Players set themselves game-related goals, and vigorously try to achieve them.

Exploration of the game: Players try to find out as much as they can about the virtual world. They explore rules and experiment with the possibilities of the game.

Socialising with others: Players use the communication possibilities of the game to chat and interact with their fellow players.

Victory over others: These players seek competition with their fellow players.[1]

Although many players enjoy several of these aspects, most players have a primary interest [19]. Based on the above-mentioned taxonomy, the survey asked: *Which element of a game is most important to you in a learning app?*

The results are presented in Figure 1(b): Clearly, the vast majority of users is either in the group of Achievers (45%) or in the group of Explorers (41%), two groups that Bartle [19] considers to be focused on the experience of the game environment. Achievers act according to the rules of the game environment in order to succeed and earn rewards for their achievements. Rewards can be points, levels or medals, which Achievers proudly display in their status. Explorers want to interact with the game environment. Their curiosity drives them to solve puzzles and discover universally valid rules. They are proud of their knowledge and strive to gather more. This can be achieved through special quests and ever new puzzles.

Players in the other two categories "Socializing with others" and "Victory over others" are primarily interested in their fellow players. Merely 10% feel that victory over fellow players is an important element of a learning app. Surprisingly, social interaction through the app is important only to a minority of the STEM students (4%), making the group of "Socializers" the smallest among potential app users. This indicates that there is a lack of resonance for cooperative learning strategies among the target group. It would be possible to enable group work or implement a chat function in an app, for example, but this would represent no added value for most respondents. Consequently, the priority to implement these features is low.

B. Usage scenarios

A successful learning app must complement the existing teaching offer. The desired effect is that students spend more time learning effectively. The crucial question is, how and where students would actually use a learning app. The survey investigates these circumstances. Three conditions were identified, each also influencing the concept of tasks within an app: How much time the students have to solve a task, whether aids are available (e.g. textbooks, pen and paper) and whether the students can concentrate on the tasks. Three usage scenarios have been identified and rated by STEM students. In order to make them easier to visualize, the survey asked for typical situations:

Scenario a: At a desk. This may be during class if the learning app is integrated in the teaching as Hütz et al. [20] recommend. This may also be during independent exam preparation, alone or in study groups. Students are in a working environment in which they concentrate on the subject. They sit at a table and have everything they need for learning, such as textbooks, formularies, calculator, pen and paper. There is no time limit for the tasks. The corresponding survey question was: *How important is using a learning app when you are studying (at a desk with aid like book, pen and paper)?*

Scenario b: On the go. Students learn with an app on the go, e.g. while using public transport. One difference to Scenario a is that no aids are available. In the given situation, it would be extremely impractical to consult textbooks and calculate on paper. Most likely, a smartphone app will be better accepted than one for a tablet. In this scenario, there is a lot of distraction in the learning situation so that learners cannot fully concentrate. The corresponding survey question was: *How important is using a learning app on the go (without aid like book, pen and paper)?*

Scenario c: Five-minute break. The main characteristic of this scenario is the limited time for the tasks. Short breaks are scheduled between courses or occur spontaneously in everyday life. The word "break" suggests a form of recreation or leisure. Consequently, fun of learning is in focus. As in Scenario b, distraction caused by the environment must be expected. The corresponding survey question was: *How important is using a learning app in five-minute breaks?*

Scenario a (at a desk) describes a classic learning situation where an app is used in addition to existing learning tools. In the other two scenarios, the app unlocks additional time for learning. In Scenario b (on the go), students spend time learning that previously was inaccessible because a suitable learning tool was missing. In Scenario c (five-minute break), students invest time that they previously used for other pur-

[1] The categories as defined by Bartle [19] have been adapted to learning apps, i.e. the last category "killers" (players that enjoy killing the characters of other players) was changed to a less negatively connoted wording. In the survey, this reduces a bias towards socially desirable answers. Furthermore, it seems inappropriate to allow the elimination of other players in an educational game.

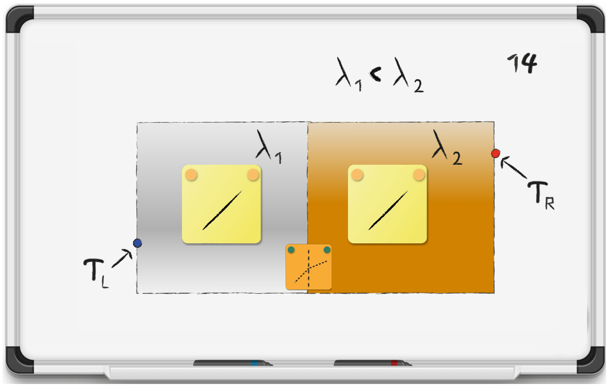

Fig. 3. Example from HQ App concerning heat conduction in solids

poses. In the survey, students could indicate more than one scenario at a time.

The majority of participating students stated that they wanted to use the app while being on the go. Two thirds describe this use case even as “very important” (see Figure 1(d)). More than half of the students said that it was “very important” to use the app in five-minute breaks (Figure 1(f)). Consistently, only a minority of the students considers using a learning app in an at-a-desk-scenario (Figure 1(e)). These results have significant implications on the app content and its implementation: Tasks have to be solvable in limited time and all relevant help has to be included within the app. However, in STEM subjects, it seems difficult to include the entire exam-related content in a learning app. Exams require long and complex calculations and these cannot be practiced effectively under the conditions of Scenario b and c.

In summary, a learning app for STEM students should focus on profound comprehension and transfer of learning. Thus, new approaches are in demand. Concerning content, an app should cover topics extensively, but allow students to choose between exam-relevant tasks and questions beyond. Selecting suitable content is crucial, as STEM students want to solve tasks in limited time without needing additional help. Concerning app design, emphasis should be placed on a diversified game environment with manifold rewarding elements.

III. HQ Framework and HQ App

From the requirement specifications discussed above, the authors developed HeatQuiz (HQ). HQ is both – a powerful framework for mobile learning apps with focus on STEM and an app which addresses heat and mass transfer. HQ Framework is perfectly suited to pose a variety of questions, both theoretical and application-oriented ones.

Two universally applicable types of tasks in STEM education are supported: One allows to qualitatively draw any two-dimensional mathematical function and check its characteristics. The curve could represent any spatial or temporal behavior of a physical entity. The other allows to correct any mathematical expression as variables can also be processed. It is possible to check whether an equation has been set up correctly without actually solving it.

In contrast to flashcard apps which simply help memorizing facts, HQ Framework focuses on transfer of learning. With HQ Framework, questions that require profound comprehension of theoretical background can easily be generated. When embedded into a modern teaching concept, these apps can be beneficial for students, as shown in the following.

Using HQ Framework, HQ App was built to support university teaching in the undergraduate heat and mass transfer course at RWTH Aachen University [21]. HQ App covers relevant basics for a variety of technical applications. It helps to understand physical phenomena in the fields of heat conduction, radiation, convection and mass transfer. As it is free-of-charge and available worldwide, everyone interested can benefit. For effective use, basic understanding of physics and mathematics on a university-level is required, prior knowledge of heat and mass transfer is an advantage. At RWTH Aachen university, HQ App is part of the teaching concept.

In general, engineers have to understand the theoretical background and apply it to a real system. Oftentimes, they do not actually perform calculations but set up a computer to do so. It is therefore most important to form the right equations and assess whether calculation results are plausible. In order to achieve this educational goal, HQ App follows a unique approach: It deliberately refrains from asking for facts or numbers but works with variables and qualitative graphs instead. This helps users to stay focused on solving the problem and not get bogged down in calculations. Users apply the formulas they have learned and visualize the underlying physical processes. As a result, they develop a sense for the principles and mechanisms of heat transfer. The HQ App offers different game modes with a total of about 300 tasks. As stated before, students want to use the app being on the go or having a five-minute break. This results in a number of challenges: limited time, limited space on small displays and no tools (like books, pen and paper) available. The HQ App addresses these challenges: The app design copies a whiteboard where the current task is sketched out and the user solves it within the sketch (see Figure 3). Tasks are self-explanatory, there is no text except for some variables (a standard nomenclature is presupposed). Tasks are designed to be solved on a smartphone without any additional help, as help is provided within the app if needed. Short exercises allow quick success. Every task can be solved within a few minutes, without calculations. The game invites users to spend part of their free time with educational content. Strategically used gaming effects motivate and challenge the users. This encourages continuous self-study. User can track their personal learning progress graphically, the achieved number of points is plotted over time. Users can compare themselves with others in a list of high scores. Either they see their rank in comparison to all players or to a specific group they can relate to, e.g. their peers.

The first game engine allows to derive mathematical curves, representing spatial or temporal behavior of a physical entity. Only a qualitative course is queried, numerical values are not. Users have to specify where they expect extrema and inflection points and their positions relative to each other. Entering the curve is easy as it is constructed section by section from predefined options. At the beginning, the end, and at all points where the curve cannot be differentiated, the transition needs to be entered, resulting in a complete description of the curve. This method is easy to use, even on small displays, and has proven to be effective. When the game engine checks the solution, correct and incorrect sections can be rated separately. The difficulty of the tasks can be adjusted, as tasks with many options for each section are usually more difficult.

In HQ App, two different types of tasks are implemented using HQ Framework's first game engine: drawing temperature profiles to visualize heat transfer and concentration profiles to describe mass transfer.

Every scientific or technical field has its own mathematical formulas and variables. The second game engine can do far more than just match input and solution: It handles variables and masters mathematical operations to evaluate the input. An input is recognized as correct if it can be transformed into the given solution, e.g. by addition, multiplication, or commutation. Expressions in brackets are extended. Thus, correct solutions are detected, no matter how the user writes them down. The game engine individually marks correct and incorrect parts of the users' solution. Users receive points for the correct terms and can easily localize possible errors. The input is particularly user-friendly because of the flexible keyboard. If required, the keyboard can be customized and even look different for each individual task. Keys can be assigned any symbols, special characters, indices and mathematical operators. The number of keys can be chosen as needed. This is advantageous if the number of possible answers is to be limited in order to simplify the task. Moreover, on smartphone displays a minimal keyboard is more convenient.

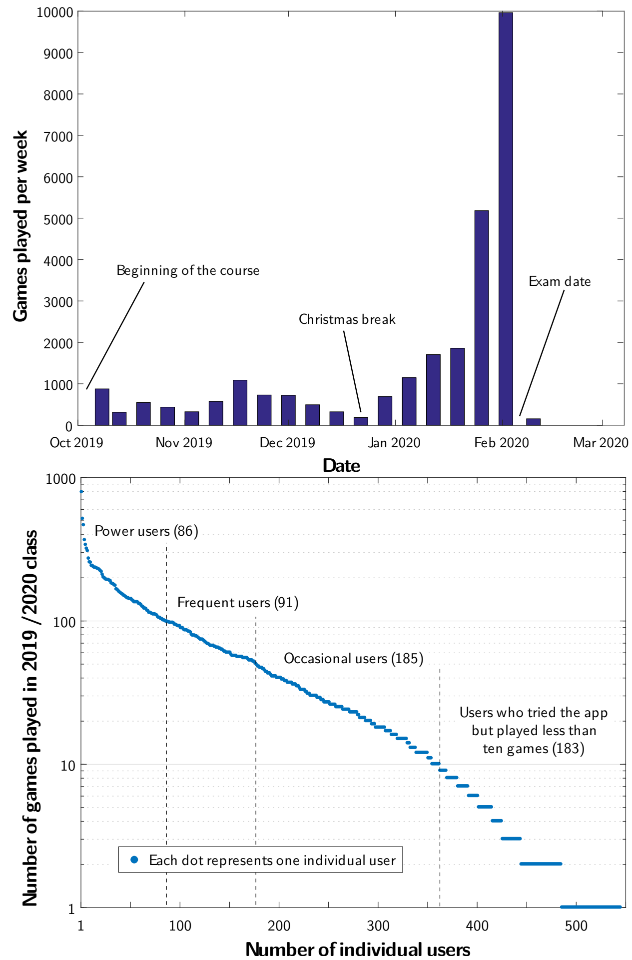

Fig. 4. Statistic on the HQ App usage during the 2019/2020 class of "Heat and Mass transfer I" at RWTH Aachen University showing when the game was played (top) and by whom it was played (bottom).

IV. Evaluation of HQ App

A. Usage Statistics

The Bachelor course "Heat and Mass transfer I" at RWTH Aachen University takes place in the winter semester between October and February. Using HQ App in this particular course has complemented teaching very well. It facilitated a novel, more modern approach to teaching, e.g. by incorporating the app in lectures and tutorials (see below). Over the entire class, the app was subject to the office hours where students asked for support when having comprehension questions that arose from a certain task. From the feedback, it is also understood that certain tasks of HQ App sparked discussions within the student's learning groups, and thus supported the students in developing the problem-solving competence that is required for engineers. In the 2019/2020 course, HQ App was introduced at the very beginning and the student's interest in the app has been tracked over the course of the semester. Figure 4 shows the number of games that students of this particular class have played per week. Using this data, four different phases of use were identified:

Trial phase: After its introduction in October 2019, roughly 1,000 games were played in the very first week. Students tried out the new app, but – without having had any background on heat and mass transfer – found it difficult to solve the tasks. However, at this early point in the semester, students became aware of HQ App and it remained installed on the smartphones in the following teaching phase.

Teaching phase: Between October and the end of December, HQ App has been part of the active teaching. In lectures and tutorials it was used occasionally to provide and present example tasks. In one tutorial, lecturer and students played the game together while discussing their approach to the task solution. The idea of this teaching approach was to overcome the student-teacher relationship that is common in large classes and generate a sense of interactive cooperation – which is expected to inspire students to independently solve problems. The direct feedback from the students was very positive. Consequently, the number of played games rose to slightly above 1,000 per week before it dropped toward the Christmas break. Unsurprisingly, the students' learning activity over the holidays was on a rather low level.

Learning phase: With the re-start of the class in January 2020, game usage started picking up again and approached

2,000 games during the third week of January. In this phase, students had sufficient knowledge on heat and mass transfer to benefit from the app. The increasing number of played games shows that the app is supporting students in their self-studying. **Exam phase:** In preparation for the final exam on February 8th, students pushed the app usage to a maximum of 10,000 games per week. This heavy use shows that HQ App has indeed been accepted as a learning tool. Its use as a tool to finalize studies on heat and mass transfer and prepare for the final exam is in line with the results of the student survey discussed above in Section II.

Below, it is evaluated how this high number of played games is distributed across the students. As every user has an individual ID (which is rendered anonymously), gaming activity per ID was tracked on the server side of the app (see Figure 4). Here, each dot represents one individual user and shows the total number of games that this particular user played during the 2019/2020 class. In total, 545 different users played 27,350 games in HQ App. About a third (183 users) have tried the app but played less than ten games. It is assumed, that this user group installed HQ App during the trial phase (see above), and either disliked the concept or became frustrated and never returned. In future classes, in order to retain this user group, emphasis is going to be placed on how the app is introduced to the students. A second third of the users (185 users) have played occasionally, i.e. between ten and 50 games during the class. The last third is evenly split between users who frequently use the app (91 users) and so-called power users (86 users). In the latter group, every user played more than 100 games. One enthusiastic student even accumulated a total of 791 games. Overall, this user statistic is very satisfying, showing that two thirds of the users develop a habit of playing HQ App. In the evaluated class, this self-studying tool proved to be very successful, as shown in Figure 5. Here, as a measure of the learning progress, the average score per game is shown as a function of time. Each dot represents the weekly average, and the dashed line is the thirty-day moving average. At the beginning of the class, the student's average score is 12 points per game. Over the course of the semester, this value steadily rises and – with 31 points per game – reaches 2.75 times that score. Three distinct outlier points can be associated to particular evens: First, the introduction of the app in the very first week, where games have been played in the auditorium. Second, the Christmas break, which has already been noticed in the number of games played. Third, the days ahead of the exam, where students are at the maximum of their individual preparation, which is reflected in a weekly average of 33 points per game.

In order to further improve HQ App and also reduce the number of users who "drop out", an extensive survey on the app and its usage has been conducted toward the end of the class.

B. Survey

In the first part of the survey (Section II), general requirements for learning apps in STEM education were discussed.

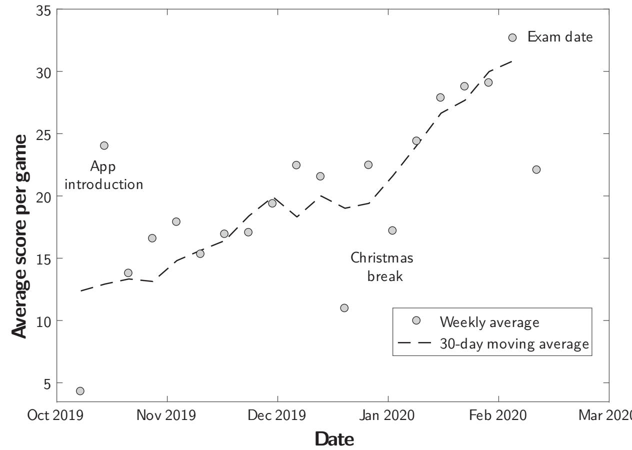

Fig. 5. The average score per game used as a measure of the students' learning progress as a function of time. Over the course of the class, the score nearly triples, illustrating the success of the HQ App.

In the second part, STEM students were asked to share their experiences with HQ App. The results show to what extend the app meets their expectations. The survey design allows to correlate the answers obtained in the first part with those in the second part. This survey has been conducted in the winter semester 2020. It has been initiated three weeks ahead of the exam and was stopped at the exam day. It can be assumed that – in this period – most of the participants had been confronted with the study matter and the app. This increases the probability to get well-founded feedback. Out of 102 participants who generally want to use learning apps, 74 have actually tried out HQ App.

The vast majority of users (89%) gives HQ App a positive assessment (Figure 6(a)). As this good rating is independent of the player type, the game elements incorporated appeal to all users. All respondents (100%) see the potential of the app, as they want HQ App to be further refined. The following, more detailed questions will clarify to what extent there is room for improvement in the concept.

The vast majority of the students (84%) prefers learning apps that foster thorough understanding, which is exactly the focus of HQ App. A total of 70% believe that this focus is well implemented in the app, i.e. it conveys technical comprehension in the field of heat and mass transfer (see Figure 6(b)).

According to the first part of the survey, 99% of the students want to use learning apps when preparing for exams. It can be considered a success that almost all respondents (92%) actually do use HQ App for this purpose (see Figure 6(c)), 37% even on more than half of their learning sessions. This is a very good feedback because the app only covers part of the exam-relevant content, so students have to do additional preparation without the app. Long and complex calculations, for example, would contradict the concept of the app, because the two preferred usage scenarios require short tasks. Nevertheless, students spend a lot of time learning with HQ App. These results show that the concept of game-based

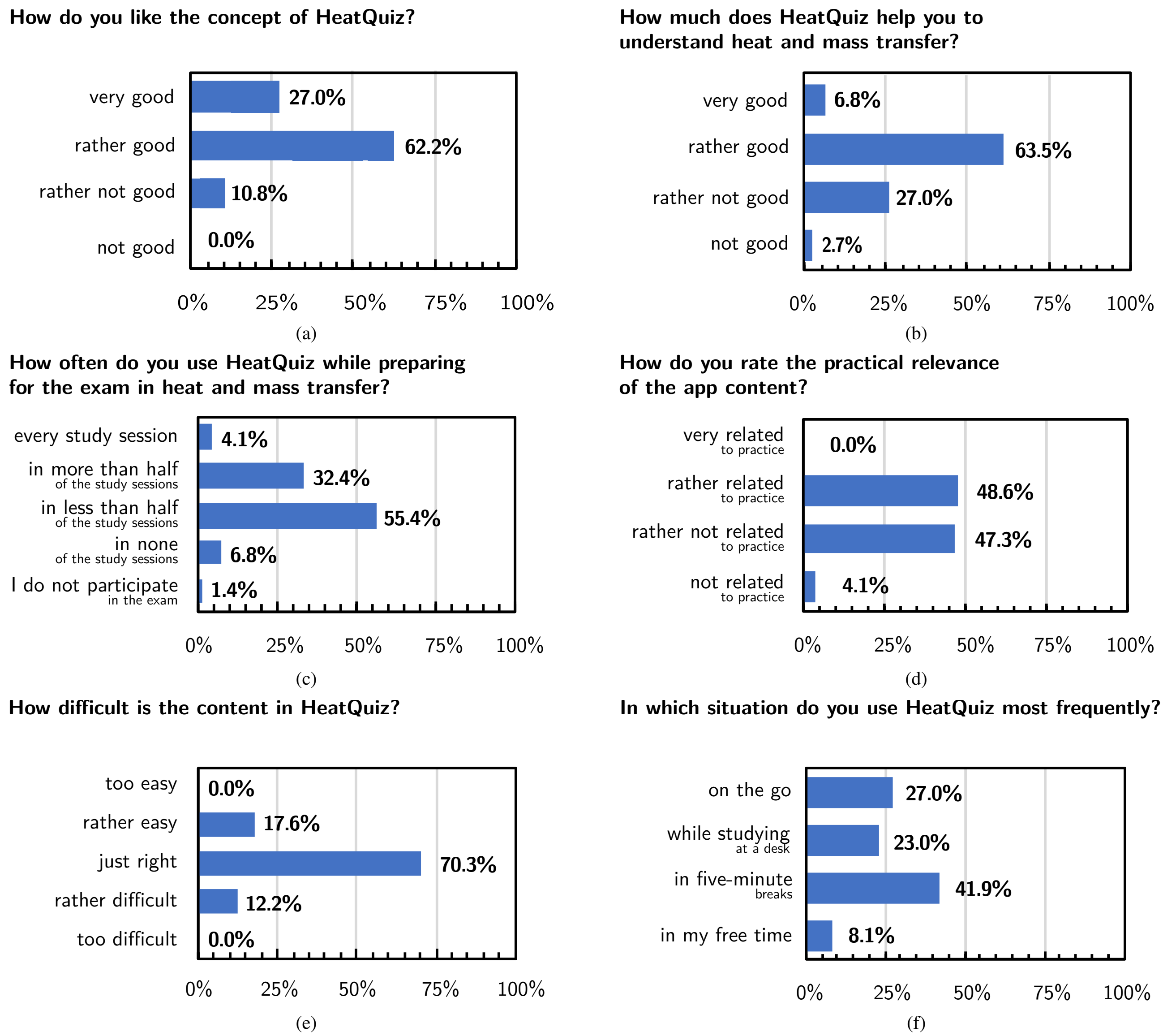

Fig. 6. Result of the students' evaluation of the HQ App from the 2020 survey.

learning is well-accepted by the students.

Concerning practical relevance, the app content falls short of the users' expectations. The first part of the survey shows the importance of practical relevance, but only half of the students (49%) describe the HQ tasks as rather practice-oriented (Figure 6(d)). At the same time, more than two thirds of the students (70%) consider the difficulty of the tasks as "just right" (Figure 6(e)). However, these two characteristics of the tasks are associated with each other: In heat and mass transfer, practice-oriented tasks are often more complex, e.g. because multiple heat transfer mechanisms have to be considered. Consequently, a fragile balance has to be found: Practice-oriented tasks increase motivation but very difficult tasks destroy it.

Overall, the user groups of both scenarios overlap widely: Students who want to learn on the go, also want to learn in five-minute breaks. 81% of the HQ users rate both usage scenarios as very important or rather important. This preference should be reflected in the actual use of HQ App: two significant usage peaks should be detectable. However, at least the on-the-go scenario seems to be underrepresented (Figure 6(f)). In contrast, the at-a-desk scenario appears to be overrepresented, also compared to the initially determined preferences of all participants (Figure 1(e)). This confirms the interpretation stated above: Some students would like to use HQ App on the go, but under these circumstances it falls short of their demands. For this reason, students deviate from their preferred usage scenario to using HQ App at a desk. The problem might be related to the need for textbooks, formularies and other aids when solving the tasks. In short breaks, e.g. between two courses, using HQ App appears to be more feasible, probably because students have a table and their documents available. The duration of the tasks seems appropriate.

V. Discussion

In the present work, it has been demonstrated that mobile apps can enrich teaching in university-level STEM education. A survey has been conducted to determine the needs and preferences of this specific target group: Which learning strategies STEM students prefer, what personal motivation drives them, which gamification elements appeal to them, and which usage scenarios they favor. Design and content guidelines for learning apps in STEM education have been derived. An analysis of the results provides information on the appropriate design of a learning app for STEM students.

An important result is that STEM students prefer learning apps that enhance profound comprehension and transfer of learning to those which help structure or memorize content. This preference is in line with the skills expected from professionals in this field. Transfer of learning is essential and there is a need for innovative tools to promote this ability. Moreover, results showed that cooperative learning strategies, such as social interaction through the app, are only of minor importance to STEM students.

Almost all STEM students want to use learning apps to prepare for exams and nearly two thirds are interested in gaining knowledge beyond that. Practical relevance is important to most of the students, partly as practical approach to exam questions and partly as preparation for their future profession. Concerning their personal motivation, results indicate two main categories: short-term motivation with focus on the exam and long-term motivation induced by a topic-related interest. Thus, tasks should be selectable and clearly labeled: first, tasks that specifically and exclusively prepare for the exam and second, tasks that cover topics extensively and beyond exam-relevant questions. There needs to be a detailed feedback that shows if a student missed, met, or exceeded the quality standard of a task. The tasks should cover the entire spectrum from simple to challenging and the rating should reflect the task difficulty. At least 78% of all students can be satisfied if these suggestions are implemented in a learning app.

Another source of motivation are gamification elements in a learning app. A DGBL app particularly for STEM students should include rewarding elements and leave enough space for discovery and exploration. Results show that STEM students clearly prefer the experience of the game environment over social interaction through the app: They only have minor interest in their fellow players - neither in collaborating with them, nor in defeating them. Instead, a learning app should offer two incentives, which might also reflect the above-mentioned categories of motivation: First, the app should emphasize on achievements within the game context, i.e. rewards such as points, levels or medals which users can proudly present in their status. Second, the app should provide a game environment that users can explore to satisfy their curiosity. When solving puzzles, users should discover universally valid rules that apply to other tasks. Special rewards should be assigned for every discovery.

Moreover, the preferred usage scenarios create specific constraints for app design: More than two-thirds of the STEM students want to use apps on the go and more than half of them in five-minute breaks. This implies that tasks have to be solvable in limited time and with limited space on small displays. Long and complex calculations cannot be practiced effectively, also because students are potentially distracted in these situations. All relevant help has to be included within the app, as no tools (such as books, pen and paper) are available. Selection of suitable content is crucial but feasible, as demonstrated with HQ App.

Following the design and content guidelines above, the authors developed a framework with the focus on transfer of learning. The authors wish to promote this approach, therefore other lecturers may use HQ Framework to create their own app. Two universally applicable types of tasks in STEM education are supported: One allows to qualitatively draw any two-dimensional mathematical function and check its characteristics. The curve could represent any spatial or temporal behavior of a physical entity. The other allows to correct any mathematical expression as variables can also be processed. It is possible to check whether an equation has been set up correctly without actually solving it.

These types of tasks help students to stay focused on understanding the problem and finding the right approach to the solution. HQ Framework deliberately refrains from asking for numerical solutions since performing a calculation usually contributes little to comprehension and is often fraught with carelessness errors. Because of these characteristics, the framework would – for example – be perfectly suited to built a learning app for automatic control classes. The first game engine would allow to draw functional diagrams, where the decision tree would offer a selection of different types of control loop elements. By using the second game engine, Laplace transformation could be incorporated in this app.

For heat and mass transfer, the authors developed HQ App by using HQ Framework. The app benefits from the playful approach to complex topics and the advantages of a mobile application, i.e. availability at all times, individual training and instant feedback. HQ App is part of the teaching concept for undergraduate STEM students at the authors' institution. It has been incorporated in lectures and tutorials and is well-accepted as a learning tool among students, as results show. HQ App considers the special design and content guidelines for STEM students derived above. They perfectly fit into the STEM students' preferred usage scenarios: Tasks are solvable on a smartphone within a few minutes, without calculations or any additional help. Game based learning motivates students and encourages continuous self-study.

HQ App has been evaluated with STEM students in an undergraduate class: The vast majority gave a positive rating and believed that the focus on transfer of learning is well implemented. Considering practical relevance, there is room for improvement: Only half of the students describe the tasks as rather practice-oriented. As discussed above, in heat and mass transfer, practical relevance is linked to the difficulty of the tasks, which is "just right" for two thirds of the students. Adjustments must be made thoughtfully.

HQ App offers different game modes with a total of about 300 tasks. During one semester, 545 different students used the app. In the survey, almost all students wanted to prepare for exams with learning apps and stated they actually did with HQ App. This is reflected in the usage statistic: While preparing for the exam, students pushed the app usage to a maximum of 10,000 games per week. As a measure of learning progress, the average score per game nearly tripled over the course of the class. Nevertheless, about a third of the students installed the app at the beginning of the class but tried less than ten games. Most likely, students quit the app due to a lack of basic knowledge. Basically, there are two main starting points for improvement: simplifying the tasks and providing more help within HQ App. However, taking into consideration the users' goals discussed above, tasks and content should be adapted to the exam. This has priority over revising the tasks. So extending the help-function within HQ App is the way of choice for further refinement. Particularly useful would be context-related help for individual tasks and user-related help, that is adapted to the users' behavior. Based on incorrectly answered questions, a smart function can offer help on related topics [22]. Improvements of the help function will also have a positive effect on the duration of the tasks and the usability of HQ App on the go. In the future, the authors' objective is to teach most of the course content in heat and mass transfer with game-based learning. Additional content will be included in HQ App, such as dimensionless numbers. Currently, the authors are designing a third game engine to query energy balances, one of the most important topics in any course related to thermodynamics. Energy balances lead to the governing system of equations for a given problem. For students, the difficulty is to determine whether to set up a global or a local energy balance and how to derive the differential equation. As this can be taught without actually solving the equations, the third game engine will consistently follow the transfer of learning approach.

ACKNOWLEDGEMENTS

We would like to thank all students and colleagues who supported the project as well as the German "Stifterverband" and RWTH Aachen University for financial support.

REFERENCES

[1] O. Zawacki-Richter and C. Latchem, "Exploring four decades of research in computers & education," *Computers & Education*, vol. 122, pp. 136 – 152, 2018.

[2] O. Hinz, A. Maidl, and J. Puchan, "QuizApp zur Prüfungsvorbereitung – Vorbereitung von Prüfungssituationen mit Gaming-Effekten," in *Digitale Führungskräfteentwicklung: Konzepte, Impulse und Trainingsformate aus der Praxis*, M. A. Ciesielski and T. Schutz, Eds. Berlin, Heidelberg: Springer Gabler, 2018, pp. 51–67.

[3] B. Zimmerman and D. Schunk, *Self-Regulated Learning and Academic Achievement: Theoretical Perspectives*. Taylor & Francis, 2001.

[4] S. Deterding, R. Khaled, L. Nacke, and D. Dixon, "Gamification: Toward a definition," in *Proceedings of CHI 2011 Workshop Gamification: Using Game Design Elements in Non-Game Contexts*, 2011, pp. 6–9.

[5] M. Pivec, O. Dziabenko, and I. Schinnerl-Beikircher, "Aspects of game based learning," in *3rd International Conference on Knowledge Management, Graz, Austria*, 2003, pp. 216–225.

[6] R. Van Eck, "Digital game-based learning: Still restless, after all these years," *Educause Review*, vol. 50, pp. 12–28, 2015.

[7] E. D. Silva, M. Macedo, C. Teixeira, E. Lanzer, and Á. P. Graziani, "Game-based learning: Analysis of students' motivation, performance, and drop out in a production engineering course," in *Advances in Human Factors, Business Management, Training and Education*, J. I. Kantola, T. Barath, S. Nazir, and T. Andre, Eds., vol. 498. Springer, Cham, 2017, pp. 933–945.

[8] K. Alanne, "An overview of game-based learning in building services engineering education," *European Journal of Engineering Education*, vol. 41, 2015.

[9] J. M. Zydney and Z. Warner, "Mobile apps for science learning: Review of research," *Computers & Education*, vol. 94, pp. 1 – 17, 2016.

[10] M. Ebner and A. Holzinger, "Successful implementation of user-centered game based learning in higher education: An example from civil engineering," *Computers & Education*, vol. 49, pp. 873–890, 2007.

[11] N. Menold and K. Bogner, "Design of rating scales in questionnaires," in *GESIS Survey Guidelines*. GESIS – Leibniz Institute for the Social Sciences, Mannheim, Germany, 2016.

[12] H. F. Friedrich and H. Mandl, "Lernstrategien: Zur Strukturierung des Forschungsfeldes," in *Handbuch Lernstrategien*, H. Mandl and H. F. Friedrich, Eds. Hogrefe Verlag, 2006, pp. 1–26.

[13] J. Mccabe, "Metacognitive awareness of learning strategies in undergraduates," *Memory & cognition*, vol. 39, pp. 462–76, 2010.

[14] N. Mourtos, N. Okamoto, and J. Rhee, "Defining, teaching, and assessing problem solving skills," in *7th UICEE Annual Conference on Engineering Education*, 2004, pp. 1–5.

[15] T. Garcia and P. R. Pintrich, "Regulating motivation and cognition in the classroom: The role of self-schemas and self-regulatory strategies," in *Self-regulation of Learning and Performance: Issues and Educational Applications*, D. Schunk and B. Zimmerman, Eds. Hillsdale, NJ: Lawrence Erlbaum Associates, 1994, pp. 433–452.

[16] A. Bandura, "Going global with social cognitive theory: From prospect to paydirt. In S. I. Donaldson, D. E. Berger & K. Pezdek (Eds.)," *The rise of applied psychology: New frontiers and rewarding careers*, pp. 53–79, 2006.

[17] U. Schiefele and L. Streblow, "Motivation Aktivieren," in *Handbuch Lernstrategien*, H. Mandl and H. F. Friedrich, Eds. Hogrefe Verlag, 2006, pp. 232–247.

[18] R. Alsawaier, "The effect of gamification on motivation and engagement," *The International Journal of Information and Learning Technology*, vol. 35, no. 1, pp. 56–79, 2018.

[19] R. Bartle. (1996) Hearts, clubs, diamonds, spades: Players who suit MUDs. [Online]. Available: https://mud.co.uk/richard/hcds.htm

[20] S. Hütz, S. Staacks, C. Stampfer, and H. Heinke, "Gelingensbedingungen von Innovationen in der Hochschullehre am Beispiel des Einsatzes der App phyphox," *PhyDid B - Didaktik der Physik - Beiträge zur DPG-Frühjahrstagung*, vol. 1, 2018.

[21] W. Rohlfs, S. Welten, M. Rietz, E. Sabelberg, C. Ehrenpreis, L. Cammiade, P. N. Figueiredo, and R. Kneer, "HeatQuiz: Game-Based Learning In Heat And Mass Transfer," in *HEFAT 2019 : 14th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*, 2019, pp. 791–796.

[22] C. Troussas, A. Krouska, and C. Sgouropoulou, "Collaboration and fuzzy-modeled personalization for mobile game-based learning in higher education," *Computers & Education*, vol. 144, p. 103698, 2019.