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Game-based learning apps in engineering education: requirements, design and reception among students

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There is a lack of research on how game-based learning apps should be designed for engineering education. This paper addresses two research questions: What do engineering students expect from a learning app? Which educational approach and learning app design can meet these requirements? A survey revealed the particular demands of engineering students when using learning apps. They prefer apps that promote transfer of learning. They value a diversified game environment that leaves room for self-determined decisions. They want to use learning apps during five-minute breaks or on-the-go. Social interaction is only of minor importance. Concrete design and content guidelines are derived. Perceptual learning is an appropriate educational approach to meet the requirements. Two universally applicable task types for engineering education are discussed. A case study was conducted to investigate their use in practice. Following the guidelines, an app for heat-and-mass-transfer was generated and its impact on teaching was evaluated. Students considered that their requirements were met. This is reflected in the usage statistics: During one semester, 545 different students played a total of 27,350 games. As a measure of learning progress, the average score per game almost tripled. Apps that follow the guidelines have the potential to become well-accepted learning tools.

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1. Introduction

Today, engineering education takes place in a digitalised and increasingly mobile world. For the present generation of students, the smartphone is the central access to this world (Hinz, Maidl, and Puchan 2018). New learning systems are expected to be available on mobile devices and to integrate into an existing landscape of apps. In the context of this study, the authors consider learning apps to be applications primarily designed to support learning, optimised for small portable devices such as smartphones. For lecturers, integrating learning apps into their academic teaching activities opens up a whole range of possibilities to complement traditional forms of teaching and even compensate for their deficits. Where the face-to-face contact between lecturer and student is too short, e.g. in large engineering schools with limited teaching resources, learning apps can improve teaching. They can support students on the path to self-regulated learning, and help them pursue an effective learning strategy (see e.g. Zimmerman and Schunk 2001) with individual training and instant feedback. On the design side, gamification is a perfect approach to make learning apps

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engaging for students. In an academic attempt to introduce a definition, Deterding et al. (2011) refer to gamification as the use of game design elements in non-game contexts.

The present paper focuses on game-based learning apps in university-level engineering education. It aims to investigate the design of these apps from a scientific perspective. In recent research, Hartmann and Gommer (2021) investigated the motivational forms that engineering students exhibit when they engage in game-based learning. Their work is based on the self-determination theory (SDT), which provides a well-established theoretical framework for what motivates students to learn (for a recent review of research on SDT, see Ryan and Deci (2020)). In a postgraduate-level course in a civil engineering and management program, seven different games were introduced and the students' gameplay was evaluated through qualitative and quantitative data sampling. Hartmann and Gommer (2021) found that several different motivational forms can coexist in game-based learning for engineering students. This coexistence can be explained by the combined effects of game attractiveness, game learning, and game operativeness. Implications of this finding – which are relevant for the present work – are that the design of games in engineering education should incorporate multiple game mechanics. Furthermore, the teaching context of the game must be obvious to the students.

There are numerous examples of digital game-based learning (DGBL) being applied in engineering education, see e.g. Silva et al. (2017), Alanne (2015), Joiner et al. (2013), Darling et al. (2008, July 14–16), Coller and Scott (2009). In a recent systematic review, Udeozor et al. (2022) found that digital games are widely used for education across the engineering domain, especially in software engineering. There are also measurable benefits: Udeozor et al. (2022) reviewed 18 studies which measured the effectiveness of digital games in engineering education. In all of them, considerable evidence was found that students learned by playing the games. Some studies even found that students who played outperformed students who learned through conventional methods.

The same is true for mobile game-based learning, which is a subset of DGBL: Here, Gao, Li, and Sun (2020) recently analysed 30 publications. Their review paper shows that the mobile game-based approach consistently had a positive impact on learning performance in STEM education. However, while this review covers STEM education at all levels, the vast majority of the studies in literature (90 percent) were conducted in elementary and middle schools. There are few studies on mobile game-based learning in university-level STEM education and very few on engineering-related content (Gao, Li, and Sun 2020). This finding is rather surprising considering that DGBL is well-established in engineering education and given the large number of apps available in other educational domains (Zydney and Warner 2016).

One of the few pioneering learning apps that combine gamification with engineering education is 'Schnittkraftmeister', developed by the University of Graz (Ebner and Holzinger 2007). 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 an 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 publishing a worldwide high-score list and awarding virtual trophies.

Instead of promoting competition, the Physics Education Technology Project (PhET) at the University of Colorado in Boulder (Wieman, Adams, and Perkins 2008) is taking a different approach: It encourages engineering students to explore physics, chemistry, mathematics, earth science, and biology through interactive simulations. Each simulation is set up in a game-like environment without explanation, leaving students to discover the working mechanisms on their own. The growing number of simulation setups is available online in a platform-independent format. For the use on mobile devices, many of the simulations are implemented in html5. The overwhelming success of PhET's game-like simulations has been documented in numerous publications (see e.g. Wieman and Perkins 2006; Rutten, van Joolingen, and van der Veen 2012; Hensberry, Moore, and Perkins 2015).

Another smartphone app is 'Phyphox', which is designed for use in physics teaching (Staacks et al. 2018). It encourages students to perform and evaluate several physical experiments using their

smartphone – thus also following the exploratory approach. The app takes advantage of the wide range of built-in sensors in smartphones by measuring e.g. acceleration, brightness, pressure, or audio signals. The analysis of the raw measurement data can then be performed directly on the mobile device. The inherent mathematical requirements for this evaluation can be entirely removed (the lecturer provides the algorithm for evaluation) or tailored to a specific teaching situation (the students develop all or parts of the algorithm). 'Phyphox' has been integrated into different physics lectures at RWTH Aachen University. Despite being fully functional and having an elaborated design, its use in different teaching scenarios resulted in rather low acceptance by both, lecturers and students (Hütz et al. 2018). The authors therefore investigated the reasons for this. Their results indicate that – to be successful – the use of a learning app must be an active part of teaching.

These examples show that game-based learning apps in university-level engineering can be much more than e.g. multiple-choice questions, consolidated knowledge in the form of an encyclopaedia or a collection of mathematical equations. However, developing such an app requires certain skills, causes high expenses (Udeozor et al. 2022) and its success can only be judged after its first use. The obvious path of repurposing existing digital entertainment games for core engineering education would be challenging (Udeozor et al. 2022), as the teaching content at university level is complex and specific. This discloses a major challenge, as an app would need to be tailored to each subject. To reduce both the effort and the risk of failure, it makes sense to use frameworks and design guidelines for a particular user group. In educational areas related to engineering, this strategy has proven successful: For the teaching of computer programming, Malliarakis, Satratzemi, and Xinogalos (2016) have developed CMX, a framework for generating an educational massive multiplayer online role-playing game (MMORPG). The aim of CMX is to teach the programming language C to university students. In general, the framework provides three levels. In each level, tasks must be completed to achieve a common goal of all players. The first level aims to provide a theoretical background on the teaching material and uses multiple-choice questions to check whether the learning objective has been achieved. The second level lets students arrange tiles of programming code, and the final level requires students to write their own code. Here, an embedded compiler is used to evaluate the students' answers. Being a MMORPG, CMX provides the same game scenario to all students and allows interaction among the players (e.g. supporting, hindering, chatting). The content of a game must be defined by lecturers. For a case study involving 76 students at the University of Macedonia's Applied Informatics Department, Malliarakis, Satratzemi, and Xinogalos (2016) derived five separate games (each covering a different computer programming unit). The authors applied an evaluation framework consisting of an online questionnaire, student's interaction with the game, a pretest (the midterm exam), and a post-test (the final exam). From their results, they concluded that CMX had a likely impact on improving students' computer programming knowledge.

In summary, there is limited knowledge about how to design game-based learning apps in engineering, how to select content and how to leverage these apps. Udeozor et al. (2022) even see an absence of well-designed games relevant for engineering education and underline the risk that DGBL is therefore not going to be widely adopted. They call for more studies to explore best practices for educational games in engineering. Specifically for mobile game-based learning at university level, Gao, Li, and Sun (2020) also recommend further research to improve STEM education. Following these calls, the authors suggest developing guidelines for learning apps in engineering education based on the specific needs of engineering students. This includes identifying the students' needs, proposing an appropriate educational approach and recommending an engaging app design. The authors focus on the subset of mobile applications in this domain. The following two research questions are addressed:

- What do engineering students expect from a learning app?
- Which educational approach and which learning app design can meet these requirements?

2. Methodology

In this paper, learning apps for engineering students are analysed from a user-centred perspective. A survey was conducted to determine the requirements that engineering students place on learning apps. The study was devided into two parts: The first part refers to learning apps in general, the second part to a specific application in engineering. 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 engineering students enrolled at the authors' institution, thus qualified to study at university level. Their field of study is e.g. mechanical engineering or computational engineering science. The questions were tailored to the respondents' situation, as suggested by Thielsch, Lenzner, and Melles (2012). They were adapted to the participants' level of education (university studies) and their prior knowledge of the topics investigated (major in engineering, no background knowledge of learning strategies and motivation can be assumed). The response options were selected according to the participants' living conditions (full-time students in a German city with extensive public transport network). 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 survey was designed and conducted with particular attention 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 Menold and Bogner 2016 for an overview). In case of ambiguous recommendations, the option with the greatest benefit for the specific application was chosen. This approach resulted in a survey with closed-ended questions and direct, fully 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. The decision to use this survey design is discussed in Appendix 1.

2.1. Learning strategies

When designing learning apps, special attention should be paid to the different learning strategies of students. Learning strategies are behaviours and thoughts that learners activate to manage the acquisition of knowledge (Friedrich and Mandl 2006). These include cognitive strategies (elaboration, organisation/structuring, knowledge utilisation), meta-cognitive strategies (self-control/self-regulation), supportive motivational-emotional strategies, cooperative learning strategies and the systematic use of learning resources (Friedrich and Mandl 2006). The present paper focuses on cognitive and cooperative learning strategies as well as motivation. With regard to these three aspects, the survey revealed the users' expectations on learning apps. Results are discussed for each aspect and guidelines for learning app design are derived.

Cognitive learning strategies are divided into three intersecting groups, depending on the focus of information processing (Friedrich and Mandl 2006): 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 common method. The corresponding knowledge dimension in the revised Bloom's taxonomy (Krathwohl 2002) is factual knowledge. Organisational strategies serve to structure knowledge by working out the connections between information (Friedrich and Mandl 2006). In the revised Bloom's taxonomy, the corresponding knowledge dimension is conceptual knowledge. Knowledge utilisation strategies focus on thorough comprehension as a prerequisite for using knowledge. What has been learned should not only be reproduced but transferred and applied to new situations (Friedrich and Mandl 2006). The corresponding knowledge dimension is procedural knowledge.

Unfortunately, no prior knowledge on the theory of learning strategies can be assumed for undergraduate students (Mccabe 2010), which also applies to participants in 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 organisational strategies, 'comprehending teaching content' refers to knowledge utilisation strategies and 'memorizing teaching content' is a frequently used elaboration strategy that is clearly separated from knowledge utilisation strategies, even for laypersons.

2.2. Motivating character of learning app content

In addition to cognitive learning strategies, motivation supports students' learning. As Garcia and Pintrich (1994) suggest, students regulate their learning not only through cognitive strategies, but also through motivational strategies: Motivation influences students' choice of tasks, the effort they make, and the perseverance they show. Motivation is an inner state that causes, directs and maintains goal-oriented behaviour (Bandura 2006). It can be induced by needs, goals and interests; Actions are then directed towards 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 (Schiefele and Streblow 2006; Ryan and Deci 2000). In contrast, with extrinsic motivation, the target state is after the action (Schiefele and Streblow 2006). Extrinsically motivated actions are carried out to achieve positive consequences, e.g. recognition, rewards or exceeding self-imposed standards.

Motivation is particularly important in learning environments that allow learners to act on their own initiative, as it is the case with learning apps. The simple distinction between intrinsic and extrinsic motivation is not sufficient here. With regard to the relevance of autonomous action, extrinsic motivation is considered in a more comprehensive way. Following self-determination theory's (SDT) taxonomy of motivation, extrinsic motivation is divided into subtypes of autonomous and non-autonomous forms (Ryan and Deci 2020). Motivation categories differ in their degree of internalisation. The higher the degree of internalisation, the more self-determined and positive motivation is perceived. While intrinsic motivation is based on enjoyment (i.e. completely internalised), autonomous extrinsic motivation is based on a sense of value (i.e. people view the activities as worthwhile, even if not enjoyable). In contrast, non-autonomous extrinsic motivation is mainly induced by external rewards, sanctions or evaluations and generally leads to lower performance (Ryan and Deci 2020).

The survey was designed to reveal what motivates engineering students. Based on the results, the authors develop guidelines to support internalised motivation of engineering students. While it might not be possible to spark intrinsic motivation in all students, it is realistic to support the autonomous parts of their extrinsic motivation and thereby improve their learning. The authors see a direct link between the degree of internalisation and the persistence of motivation over time. Non-autonomous extrinsic motivation persists – at best – only as long as external pressure is maintained. In contrast, learners' perseverance increases with the degree of internalisation.

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 motivation of these students is extrinsically induced; Since it is committed to the exam, the students' interest is only temporary. This is either due to autonomous extrinsic motivation – the exam is attributed personal

significance, e.g. because the students want to earn a degree that will enable them to succeed in their careers – or this is due to non-autonomous external regulation.

Target state B: Students have a topic-related interest. Here, motivation is highly volitional and autonomous. Either because the topic is associated with positive feelings like joy, stimulation or excitement or because the topic is attributed personal value. Since this motivation is highly internalised, it is relatively permanent.

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

In the survey, questions were 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', the last question has a rating scale ranging from 'very important' to 'not important'.

2.3. Motivating character of learning app design

In general, motivation is a combination of personal motivation (as discussed in the section above) and the motivational characteristics of the learning environment, which can be stimulating or inhibiting (Friedrich and Mandl 2006). 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. In the survey, it was investigated which elements of a game particularly motivate engineering students. As discussed before, participants cannot be assumed to have any background knowledge of supportive motivational-emotional strategies, but some experience with digital games can. A common categorisation of player motivation (see Alsawaier 2018) is the taxonomy of Bartle (1996), which distinguishes four aspects that typically motivate players:

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 the rules and experiment with the possibilities of the game.

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

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

Although many players enjoy several of these aspects, most players have a primary interest (Bartle 1996). Based on the above-mentioned taxonomy, the survey asked:

- Which element of a game is most important to you in a learning app?

2.4. Usage scenarios

A well-designed learning app can complement the existing teaching. The desired effect is that students spend more time learning effectively. The crucial question is when and where students would

actually use a learning app. The survey investigates these circumstances. The authors found that three conditions substantially influence the concept of tasks within an app:

- How much time the students have to solve a task
- Whether aids are available, e.g. textbooks, formularies, pen and paper
- Whether an app has to run on mobile devices

In order to help students visualise these conditions, the survey asked them to rate typical learning situations. Therefore, the authors identified three usage scenarios which, in sum, cover all plausible situations of app usage.

Scenario a: At a desk. This can be during class if the learning app is integrated in the teaching, as Hütz et al. (2018) recommend. This can also be during independent exam preparation, alone or in study groups. Students are in a working environment where 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 use a learning app on-the-go, e.g. on public transport. One difference to Scenario a is that there are no aids available. In the given situation, it would be extremely impractical to consult textbooks and calculate on paper. This scenario requires the app to run on a mobile device. 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 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. 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 due to the lack of a suitable learning tool. In Scenario c (five-minute break), students invest time that they previously used for other purposes. In the survey, students could indicate more than one scenario at a time.

3. Results

Out of the 105 participants of the survey, only 3 respondents have no use for learning apps at all. The following results are based on the answers of the remaining 102 participants, as learning apps should be designed for this target group.

Concerning learning strategies, 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 the application of knowledge (see Figure 1(c)).

Concerning content, almost all students (99%) want to use learning apps to prepare for exams (Target state A). Additionally, the majority (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

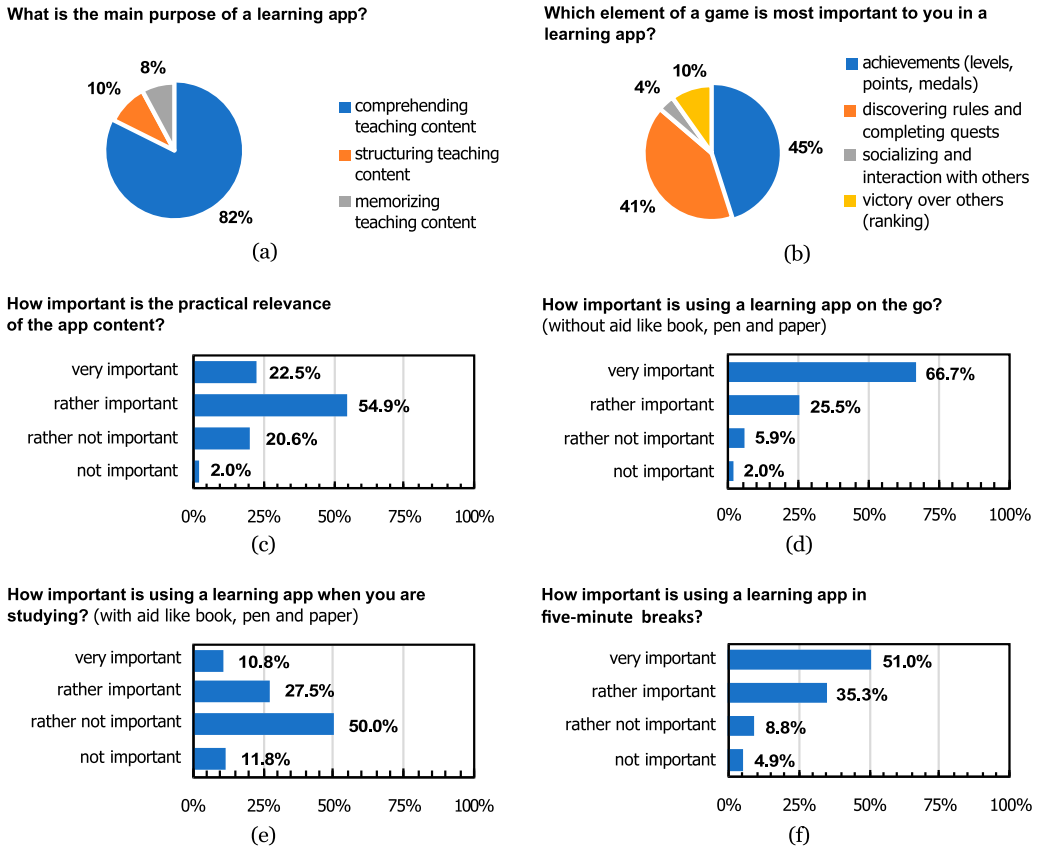


Figure 1. Results of a survey on the general use of learning apps in university teaching among 105 undergraduate engineering students at the authors' institution. (a) Most students value apps that foster thorough comprehension and (c) practically relevant tasks. (b) They prefer to interact with the game environment in contrast to social interaction and (d) want to use learning apps on-the-go or (f) in five-minute breaks (see also Jacobs et al. (2021)).

relevance of the tasks is important or even very important (Target state C). By examining the correlation between these results, five different groups of students can be identified. Each group is characterised by a distinctive 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 to prepare for exams, but also to acquire knowledge beyond that. The practical relevance of the tasks is important to them. The second largest group of 30 students (29%) (dark red) wants to use learning apps exclusively for exam preparation and considers practical relevance of the tasks to be important as well. The picture is different for the group of 12 students (12%) (greenish colour), to whom practical relevance is not important. Very few students report only one single target state: Merely 10 students (10%) (dark blue) exhibit purely extrinsic motivation as described by Target state A. To them, learning apps exclusively serve as a way to prepare for the exam. Beyond that, neither theoretical nor practical knowledge seems to be important to this group. One single student (1%) exclusively names Target state B, which corresponds to a purely intrinsic motivation. This student wants to use learning apps without reference to the exam (although participating in the exam). The practical relevance of the tasks is not important to this person.

Concerning learning app design, the distribution of player motivation is shown in Figure 1(b): Clearly, the vast majority of students is either in the group of Achievers (45%) or in the group of

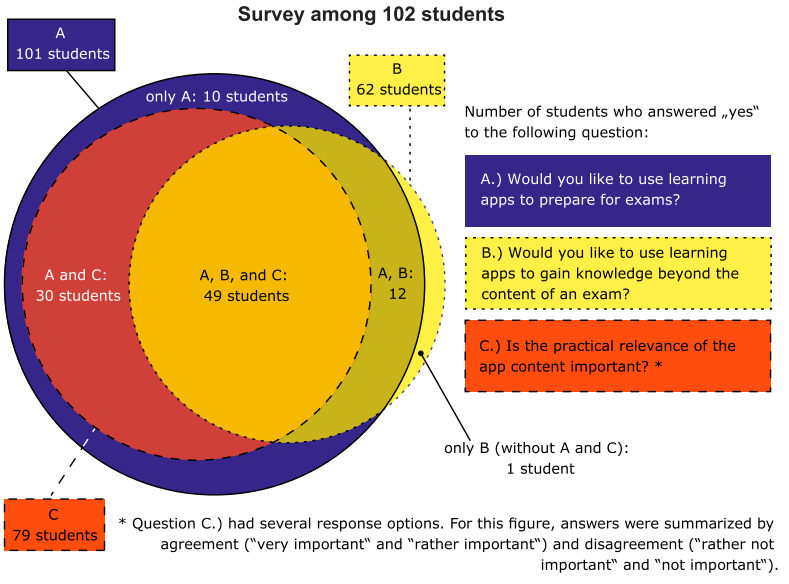


Figure 2. Results of a survey that aimed to find out what motivates university-level engineering students to use learning apps. Survey among 102 undergraduate engineering students at the authors' institution. By examining the correlation between the questions A, B and C, five different groups of students can be identified (see also Jacobs et al. (2021)).

Explorers (41%), two groups that Bartle (1996) considers to be focussed on the experience of the game environment. Students 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 engineering students (4%), making the group of 'Socializers' the smallest among potential app users.

With regard to usage scenarios, the majority of participating students stated that they wanted to use apps while being on-the-go. Two thirds even describe this use case 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 considers using learning apps in an at-a-desk scenario (Figure 1(e)).

4. Discussion of the results

The vast majority of participants in the survey (97%) is interested in using apps either to prepare for exams or to acquire knowledge beyond that. This clear result underlines how well students respond to innovative digital teaching.

4.1. Discussion on learning strategies

Concerning learning strategies, students are least interested in memorising content with a learning app, e.g. another flashcard app based on the Leitner-system. Engineering students emphasise thorough comprehension of teaching content. At the same time, they value application of knowledge. Taken together, this results in the need for an app that promotes transfer of learning.

Transfer is what education is fundamentally about: acquiring knowledge to be used outside of the classroom (Day and Goldstone 2012). According to the traditional view, transfer means using previously known, structured symbolic representations to understand and make inferences about

new, structurally similar cases (Day and Goldstone 2012). The process begins with recognition of structural commonalities, followed by mapping between the representations, and ends with drawing analogical inferences, thus generating new potential knowledge (Day and Goldstone 2012). The underlying assumption is that knowledge is a stable mental entity and that the structure of a situation can be understood and processed independently of the particular objects and features involved (Day and Goldstone 2012).

The traditional view is a rather static view of the transfer process and unapt to explain several empirical findings (see Day and Goldstone 2012, for examples). To highlight one influential example, Schwartz and Martin (2004) demonstrated that it is possible to prepare students for future learning and transfer: At the beginning of their instruction, some students were asked to invent their own solution to a given problem. Although they produced imperfect solutions, this approach significantly increased these students' ability to learn the conventional solution in a subsequent training and to transfer this learning to a new problem. According to the traditional view, these students' knowledge remained the same because they did not receive any new information. This view is unable to explain why the student's learning ability increased.

The present paper takes a more flexible, dynamic view of the transfer process. It includes the following three important differences to the traditional view: First, it is assumed that existing representations can be altered. Day and Goldstone (2012) review several examples where prior knowledge is transformed or modified to make it applicable to a new problem. At the same time, a new problem is reinterpreted to enable mapping. Second, prior knowledge can be used implicitly, even without conscious awareness. It serves as an interpretive lens for understanding new content rather than being the direct focus of cognition itself (Day and Goldstone 2012). Thus, the process of analogical reasoning is considered less deliberate than in the traditional view. Third, knowledge and structure are regarded as linked, and a mental model is an integrated representation of both. Mental models serve to explain the learning process in a broad range of academic disciplines, for example in mechanical reasoning tasks, or comprehending text passages (see Day and Goldstone 2012 for discussion). A mental model provides an analogous description of a situation, allowing individuals to reason about relationships within a system and about consequences of different possible actions (Day and Goldstone 2012). The representations in the mental model do not have to be realistic, they may be only analogically or metaphorically similar to the situation. The essential aspect is that the mental model facilitates logical reasoning (Day and Goldstone 2012). Reasoning about complex situations is facilitated through simplified representations. Reasoning about abstract problems is performed through concrete representations, e.g. understanding concepts related to electrical currents using mental models of flowing water (see Day and Goldstone 2012).

Based on this view of the transfer process, an educational approach that supports engineering students in transfer of learning is derived in the following. The starting point is a feature of mental models, namely that representations are often perceptually and spatially concrete. The reason is that cognition relies on perceptual processes, as Day and Goldstone (2012) assume. They regard mental models as linking both perceptual and meaningful conceptual content. As an example, a subjectively strong perceptual component to mathematical reasoning is routinely reported (Day and Goldstone 2012): Particularly experts seem to handle equations in a way that makes them tangible. For instance, students may learn to equivalently transform an equation, that is, 'moving' a term from one side of the equation to the other. There is evidence that experienced students conceive of this operation as actual spatial movement (Day and Goldstone 2012).

Perception is inherently an interpretive process, in which existing knowledge structures guide and constrain the organisation of new information (Day and Goldstone 2012). Perceptual processes provide a critical foundation for both knowledge representation and knowledge use. They tend to be very fast, occur without conscious deliberation, and rely largely on pattern matching with existing

representations (Day and Goldstone 2012). This parallels the implicit use of prior knowledge during transfer (see above, second difference to the traditional view).

Perceptual representations are important in comprehension and reasoning, and in transfer of learning as well (see Day and Goldstone 2012 for examples in literature). In an experiment, Day and Goldstone (2012) demonstrated the important role of perceptual processing in transfer of knowledge. Transfer occurred between problems that seem unrelated on the surface, but are represented by similar mental models. In a study involving a training task and a subsequent transfer task, they concluded that the overtly perceptual and spatial nature of the training task was critical for transfer to occur. Similarly, Kellman, Massey, and Son (2010) demonstrated that perceptual learning can successfully support transfer of learning. For their studies, they used tasks in mathematics, an abstract discipline that is fundamental in engineering. Results indicate that perceptual learning supports selecting and extracting information fluently, discovering important relations, and mapping structure across representations. These perceptual learning effects applied even to complex tasks that involve symbolic processing. Perceptual learning resulted in major and lasting advances in learning, as their studies showed no decrement in performance in delayed posttests (Kellman, Massey, and Son 2010).

Thus, perceptual learning is particularly well suited to promote transfer of learning in engineering. It is an appropriate educational approach to meet engineering students' requirements.

4.2. Discussion on learning app content

Concerning learning app content, the largest group of students demands practical relevance of the tasks and wants to use apps not only to prepare for exams, but also to acquire knowledge beyond that. This profile matches students who want to prepare for their future profession. The authors conclude that these students strive to be competent and capable in performance-oriented situations, thus show their basic psychological need for competence (as discussed in SDT by Ryan and Deci 2020). This autonomous extrinsic motivation can be activated by challenging tasks in a learning app. Learners perceive tasks as challenging if they are adapted to their current learning level. The tasks should therefore cover the entire spectrum from easy to difficult. There has to be a quality standard that the user commits to, and that can be missed, reached or exceeded (Schiefele and Streblow 2006), e.g. a detailed feedback and rating at the end of each task which reflects its difficulty. This rating, however, should be purely informative and the student should be free to decide whether to share the result with anyone (see SDT by Ryan and Deci 2020). The authors propose that a 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 related to practice.

The second largest group also demands practical relevance of the tasks, but wants to use learning apps exclusively for exam preparation. The authors suppose that these students are looking for a practical approach to exam questions. An explanation of what a technical solution is used for in real applications can motivate them. Questions should be similar to the exam and limited to exam-relevant content. However, this contradicts the above-mentioned requirements of the largest group. One way to satisfy both is to provide meaningful choices, which supports autonomous forms of motivation and thus enhances students' engagement (Ryan and Deci 2020). In this context, an app must allow students to select their preferred type of task: first, tasks that specifically and exclusively prepare for the exam and second, tasks that cover topics extensively and beyond exam-relevant questions.

To a small group of students, practical relevance is not very important. These students want to gain knowledge for the exam and beyond and seem to enjoy theoretical tasks. The authors assume that they are motivated not only by the exam, but also by learning itself. This profile

matches students who regard specialised 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.

To sum up the investigation on learning app content, it can be stated that at least 78% of the students surveyed can be satisfied if the guidelines 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 engineering education.

4.3. Discussion on learning app design

A motivating game environment has to provide structure while at the same time supporting autonomy to facilitate greater internalisation and performance. In this context, providing structure has to be clearly distinguished from exercising control: Control puts pressure on students to accomplish results. Structure means setting clear expectations, establishing consistent rules and guidelines, and providing information and feedback to encourage engagement (Ryan and Deci 2020). A learning environment that provides structure rather than control has been demonstrated to promote transfer of learning, both during initial learning and at the time of transfer (Day and Goldstone 2012). Instructions that emphasise competence (mastery goals) are beneficial, as opposed to instructions that impose control (performance goals) (Day and Goldstone 2012).

As shown above, the vast majority of students is either in the group of Achievers or Explorers, thus focuses on the experience of the game environment – as opposed to focussing on fellow players. The game environment must therefore leave enough space for discovery and exploration.

Achievers act according to the rules of the game environment in order to succeed and earn rewards for their achievements (Bartle 1996). It is important to clarify that Bartle (1996) means self-imposed goals. The goal is chosen by the player, which is in line with SDT. Any form of control, whether through evaluations or externally imposed rewards and sanctions, paradoxically leads to lower performance (Ryan and Deci 2020). 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 (Bartle 1996). This can be achieved through special quests and ever new puzzles. Finding universally valid rules is part of the learning process and should be rewarded. With regard to motivation, measures that focus on supporting learning processes rather than learning outcomes are favourable (Ryan and Deci 2020). In engineering sciences, such universally valid rules can be, for example, physical laws and the conditions under which they apply. Having discovered these principles is a learning progress, because students can use them to solve similar tasks. This is transfer of learning.

Results show that there is a lack of resonance for social interaction through a learning app among the target group. Engineering students only show minor interest in interaction with their fellow players – neither in collaborating with them, nor in defeating them. For example, implementing group work or a chat function would not add any value for most users. This also implies that cooperative learning strategies are only of minor importance in a learning app for engineering students.

4.4. Discussion on usage scenarios

Usage Scenario b (on-the-go) and c (five-minute break) were found to be the most relevant. This is in line with Alanne (2015), who found that ubiquitous gaming is perceived attractive from the perspective of student motivation. These results impose specific constraints for learning app design and

content: Tasks have to be solvable in limited time, an app must be optimised for mobile devices and all relevant help has to be included. Long and complex calculations cannot be practiced effectively, not least because students may be distracted in their preferred usage scenarios. Selecting suitable content is crucial.

4.5. Implementing the guidelines in learning apps for engineering education

The question arises, how to translate these challenging guidelines into practice. The most demanding constraint is to create tasks that, on the one hand, promote transfer of learning and, on the other hand, can be solved in just five minutes. As discussed above, the perceptual learning approach is pursued in this paper.

Kellman, Massey, and Son (2010) list three general properties common to perceptual learning interventions. First, task requiring transactions with structure: A perceptual learning task focuses on commonalities and variations in structure as its primary learning content. Learners are expected to extract structure from representations or displays. Success in the task depends on whether learners attend to, discriminate, classify, or map the structure. Second, numerous classification trials with varied instances: Perceptual learning involves many short trials in which learners make classifications and receive feedback. The learning objective is to discover invariant properties. To decouple relevant from irrelevant properties, a sufficient number of trials and variations in learning instances is required. Third, minimal emphasis on explicit instruction: The primary task in a perceptual learning intervention does not involve verbal or written explanations of facts, concepts, or procedures.

Considering these general properties, the authors of the present paper propose a concrete solution for perceptual learning tasks in engineering: Tasks that work with mathematical graphs and equations. The strategy is to refrain from asking for facts or numbers and instead work with variables and qualitative graphs. This helps students to stay focussed on solving the problem and not get bogged down in calculations. Formulating or drawing the solution without actually performing a calculation is feasible in five minutes, thus in line with the guidelines derived above.

By investigating mathematics education at middle and high school level, Kellman, Massey, and Son (2010) demonstrated that this approach can lead to important learning gains, especially to transfer of learning. Their perceptual learning tasks required mapping across multiple representations of a linear function, e.g. generating a correct graph from an equation or vice versa. This involves recognising patterns and extracting structural attributes (e.g. knowing where to find the slope in an equation). The tasks were interactive and short, asking for classification but not for numerical answers. The study group performed better on a transfer task than the control group on a task they had previously practiced. Kellman, Massey, and Son (2010) found evidence of remote transfer of learning. Learning was transferred to contexts that look different but share the same underlying structure. Recognizing and processing of structural invariants across variable contexts was improved. Students classified novel tasks fluently and more accurately, which indicates generative use of structure.

Perceptual learning changes the way a learner views a problem or representation. Recognizing implicit patterns does not need to be accompanied by explicit facts, concepts, or procedures. Perceptual learning itself does not need to involve explicit knowledge (Kellman, Massey, and Son 2010). Kellman, Massey, and Son (2010) found evidence supporting this, by investigating algebraic transformation tasks that required structural comparison between equations. Although students did not practice solving equations during perceptual learning tasks, they were able to solve equations much more accurately and fluently in the posttest. This, again, demonstrates generative use of structure. Students recognised implicit patterns without explicitly performing calculations. A considerable benefit was that these improvements persisted over a delay, unlike facts and procedures, which tend to be rapidly forgotten. Patterns and structures that emerge during perceptual learning, e.g. how to ride a bicycle, seem to persist significantly longer in memory (Kellman, Massey, and Son 2010).

Perceptual learning techniques have the potential to address crucial dimensions of learning which are often neglected in traditional teaching (Kellman, Massey, and Son 2010), although they are highly valued in engineering students' prospective professional lives. In their professional life, engineers are often confronted with open-ended problems, i.e. the situation is insufficiently defined and there is more than one approach to the solution. The method of solution is key: Engineers have to identify and formulate the problem (see Mourtos, Okamoto, and Rhee 2004). For instance, they have to decide on an appropriate theory, select an approach to calculate the unknown quantities, determine constraints, and make reasonable assumptions. All of these steps require decisions rather than calculations, although equations are involved. In a subsequent step, the solution can be implemented. Oftentimes, engineers do not perform calculations themselves, but set up a computer to do so. It is therefore important to assess whether calculation results are plausible. This check often involves interpreting graphs. Consequently, the authors see applications of their proposed task type at the beginning and the end of the problem solving process. Equations with variables and qualitative graphs can be used when formulating the problem and evaluating the solution.

Graphs and equations are extremely versatile in engineering education. This opens up a broad range of possible applications in educational tasks. Here, perceptual learning can beneficially complement traditional teaching and promote transfer of learning. Digital technology such as learning apps allows for numerous trials and sufficient variation in short periods of time, which can accelerate perceptual learning (Kellman, Massey, and Son 2010).

In order to evaluate their approach under real-life conditions, the authors developed a compatible app framework (HeatQuiz Framework). It provides two game engines to easily implement tasks that comply with the guidelines derived above.

- description by graphs: The HeatQuiz Framework's first game engine allows users to qualitatively draw any two-dimensional mathematical function and to check its characteristics. The curve could represent any spatial or temporal behaviour of a physical entity.
- description by equations: The HeatQuiz Framework's second game engine allows users to correct any mathematical expression as variables can be processed. It is possible to check whether an equation has been set up correctly without the user having to solve it.

Other lecturers may use HeatQuiz Framework to create their own mobile learning app. The authors consider a detailed description of the technical implementation to be too extensive, but they are happy to provide the software to anyone interested. For a comprehensive case study, the framework was used to generate an app for heat and mass transfer (HeatQuiz App). Case studies are an appropriate method for investigating e.g. the motivational aspects of educational games in engineering (Hartmann and Gommer 2021). At the authors' institution, HeatQuiz App was provided to an undergraduate engineering course. The app and its impact on teaching were evaluated by the students.

5. Case study: a learning app for undergraduate engineering education

In the case study, HeatQuiz App was integrated into the teaching concept. The authors consider it important to critically reflect on the app usage in face-to-face discussions with their students. HeatQuiz App incorporates the educational approach and the guidelines derived above to meet the specific expectations of engineering students. At the same time, the app facilitates learning based on six empirically-supported strategies (Mccabe 2010) which are generally accepted as being influential to learning (see Winne 2017 for discussion). First, presenting study material in different ways is beneficial to the learning success (dual coding). Second, studying from static material is better than from animated media (animation overload). Third, study material with high-interest but less-relevant details leads to poorer learning outcomes (extraneous details). Fourth, testing the learned material

yields better results than restudying (testing effect). Fifth, spreading study sessions over time is more beneficial than cramming the study material (spacing effect). Sixth, self-structuring the study material and generating a personal representation leads to improved memorisation (generation effect).

In addition to lectures, HeatQuiz App provides a different, perception-based approach to study material, thus contributes to dual coding. The app refrains from animation overload as its design copies a whiteboard where users solve tasks within a sketch. To avoid extraneous details, tasks in HeatQuiz App are reduced to the essential information. Following the perceptual learning approach, explicit instruction is kept to a minimum (see Section 4.5). Tasks are self-explanatory, there is no text except for some variables (familiarity with a standard nomenclature is required). Relevant details are presented in an integrated form, which is in line with the cognitive load theory (Chandler and Sweller 1991; Sweller 1988). Tasks are designed to be solved on a smartphone without any additional help (help is provided within the app if needed). Students benefit from the testing effect as they try to apply their knowledge of heat transfer. As discussed in Section 4.5, perceptual learning requires numerous classification trials and feedback for students to discover invariant properties. In HeatQuiz App, short exercises allow for quick success. Every task can be completed within a few minutes, as required by the guidelines. If students frequently use the app during short breaks, they benefit from the spacing effect. All of these measures are intended to reduce the cognitive load so that students have the mental capacity for schema acquisition (Sweller 1988). Students should use their mental capacity to understand commonalities and variations in structure, which is the primary learning content in a perceptual learning task (see Section 4.5).

The question arises as to how concrete or abstract the tasks should be in order to facilitate transfer of learning. Here, recommendations in literature are contradictory (see Day and Goldstone 2012, for discussion). On the one hand, concreteness supports comprehension, but it can lead to overly specific mental representations that inhibit transfer. On the other hand, abstraction emphasises structure, but it can impair accurate mental representations at all. As a solution, comparing multiple cases seems beneficial for transfer. Again, recommendations are divided on whether these cases should be similar or dissimilar (see Day and Goldstone 2012, for discussion). On the one hand, comparing similar cases facilitates the mapping process, but produces very specific knowledge. On the other hand, comparing dissimilar cases should lead to the best generalisation, but the mapping process is prone to error. In HeatQuiz App, the authors try to strike a balance between both concreteness and abstraction and leverage the advantages of similar and dissimilar cases. They rate the difficulty of a task by how dissimilar it is to other tasks, i.e. how difficult transfer of learning is. Traditional criteria such as required prior knowledge or the extent of the task also play a role.

An educational game invites users to spend part of their leisure time with educational content. Strategically used gaming effects motivate and challenge users, which encourages continuous self-study. In HeatQuiz App, users receive points for each problem solved, but the distribution of points is adapted to the difficulty of the task. They can track their personal learning progress graphically, with their score plotted over time. Users can compare themselves with others in a high score list. Either they can see their ranking against all players or against a specific group they can relate to, such as their peers. For the high score list, the app creates an anonymous user ID, but transferring personal data is strictly avoided.

HeatQuiz App covers relevant fundamentals for a variety of technical applications. The app helps to understand physical phenomena in the fields of heat conduction, radiation, convection and mass transfer and offers a total of about 300 tasks. Half of the tasks use the first game engine – description by graphs – and the other half use the second – description by equations. Users apply the formulas they have learned and visualise the underlying physical processes. As a result, they develop a sense of the principles and mechanisms of heat transfer, e.g. energy or mass flows.

5.1. First game engine: description by graphs

The first game engine allows users to draw the course of any two-dimensional curve, representing the spatial or temporal behaviour of a physical entity. Following the perceptual learning approach, only a qualitative course is asked for, numerical values are not. Users have to specify where they expect extrema and inflection points and their positions relative to each other. The procedure of constructing a curve can be practised to learn why the curve looks the way it does. Entering the curve is easy, as it is constructed section by section from predefined options. The sections emphasise the structure of the curve by dividing the problem into meaningful units. These structural insights promote transfer of learning as shown by Kellman, Massey, and Son (2010) and required by the guidelines. At the beginning, the end, and wherever the curve cannot be differentiated, the transition has to be entered, resulting in a complete description of the curve. This method is easy to use, even on small displays, as required by the guidelines. Following the perceptual learning approach, users receive individual and detailed feedback. When the game engine checks the solution, correct and incorrect sections are rated separately. Wrong answers are highlighted first, then the correct solution is displayed. The game engine also shows the score this user achieved last time. Following SDT, points are awarded for each correct section of the curve to reward learning progress, even if the curve as a whole is not fully correct yet. Tasks with many options for each section are usually more difficult. By providing more or fewer options, it is easy to adjust the level of difficulty, as required by the guidelines.

There are two different input screens, one for steady curves and one for potentially unsteady curves. For differentiable curves, the answer is given step-by-step along a decision tree with increasing precision (see Figure 3). First, the rough tendency of the curve is selected (e.g. rising, constant or falling), followed by the exact course (e.g. exponentially rising). This multi-level selection system ensures clarity, even with a large number of options. To enter non-differentiable curves, users select the curve progression in the immediate proximity of a given point. Here, spatial distances are considered infinitesimally small. A maximum of four points is sufficient: One point in front and one behind the (potential) discontinuity determine the gradient. If the curve is unsteady, two points at the point of discontinuity determine the step (see Figure 7). In the steady but non-differentiable case, one point at the location of the kink is sufficient and in the differentiable case, no further point is needed. The user draws the correct solution by moving the points. A solution is considered to be correct if the relative position of the points is correct.

In HeatQuiz App, two different physical phenomena are implemented using HeatQuiz Framework's first game engine: drawing temperature profiles to visualise heat transfer and concentration profiles to describe mass transfer. The two phenomena are superficially different, but looking at the underlying Equations (1) and (2), it becomes apparent that they share the same structure. In the lectures, the first topic covered is heat transfer because it is perceptually more concrete than mass transfer. Perceptual learning, with its emphasis on structure, can open up access to the relatively

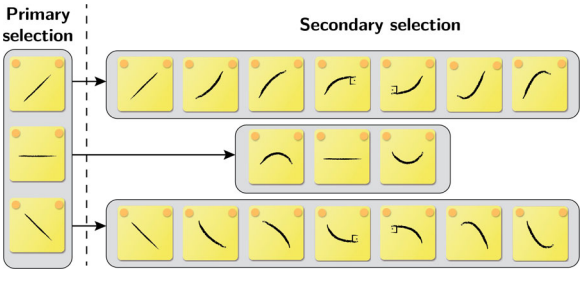


Figure 3. Pop-up menu of the HeatQuiz App used in the case study: selection of the correct gradient and curvature along a decision tree

abstract topic of mass transfer (see below for examples). Mass transfer tasks are very dissimilar to heat transfer tasks, so they are rated as difficult, because transfer of learning is difficult (see above). The degree of difficulty also increases when phenomena interact or overlap. HeatQuiz App takes this into account.

5.1.1. Example: heat conduction in solids

A short glance on the physics behind heat conduction: In general, heat is conducted from higher to lower temperatures. A metal rod heated at one end conducts heat to the colder end. The whole problem of steady-state heat conduction is described by Fourier's law:

$$\dot{Q}(x) = -kA\frac{\partial T}{\partial x} \tag{1}$$

with heat flow $\dot{Q}$, cross-sectional area A (perpendicular to the considered heat flow), thermal conductivity k and temperature gradient $\partial T/\partial x$. Heat flow and temperature profile are interdependent. A temperature profile is a perceptually concrete representation of a heat flow. Therefore, these profiles are well suited for teaching and learning the basics of heat transport. Only users who visualise Fourier's law in a physically correct way can derive correct temperature profiles. This requires transfer of learning, as suggested in the guidelines. In parallel, users develop an understanding of energy balances, which contributes to profound comprehension. For instance, it enables engineers to assess ad hoc whether a corresponding problem is solvable. Depending on the application, the variables in Fourier's law may vary. For example, heat flow $\dot{Q}$ can be caused by a heat source or sink, area A varies in pipe walls or spheres, and thermal conductivity k varies with temperature-dependent thermal conductivity or in multi-layer walls of different materials. In many cases, boundary conditions for the heat conduction problem are caused by other heat transfer mechanisms, like convective heat transfer or radiation. This leads to the variety of problems engineers are confronted with and also to the variety of practice-oriented tasks, as required by the guidelines. HeatQuiz App provides tasks at different levels of difficulty, allowing students to choose their current learning level (see guidelines for discussion).

Below, the solution path to the correct temperature profile is explained. Particularly simple examples from HeatQuiz App clarify the underlying principle. In all of the following examples, heat transfer occurs in only one direction and there is only one variable at a time.

Example 1 – plain wall: It is assumed that the two sides of a wall have different temperatures. Heat flow $\dot{Q}$, cross-sectional area A and thermal conductivity k remain constant. This results in a constant temperature gradient $\partial T/\partial x$ and the temperature curve is a straight line (see Figure 4(a)).

Example 2 – multilayer wall made of different materials (see Figure 4(b)): The two external surfaces of a wall have different temperatures: Heat flow $\dot{Q}$ and cross-sectional area A are constant, but the thermal conductivity of the materials is different. In each material, the temperature curve is a straight line, but with different gradients, respectively. At the interface, the function is constant but non-differentiable, it has a kink. This can be verified by an energy balance at the interface.

Example 3 – wall with an adiabatic side (no heat exchange with the environment) and a heat source on the other side: Cross-sectional area A and thermal conductivity k are constant. Heat flow $\dot{Q}$ is location-dependent – zero on the adiabatic side and positive on the other side. Due to the homogeneous, volumetric heat source, the temperature curve starts perpendicular to the adiabatic side and then falls exponentially (see Figure 4(c)).

Example 4 – pipe wall: The inside and outside of a pipe have different temperatures. Heat flow $\dot{Q}$ and heat conductivity k are constant, but the cross-sectional area A depends on the radial position. From the inside to the outside, cross-sectional area A increases, resulting in an exponential decrease of the temperature (see Figure 4(d)).

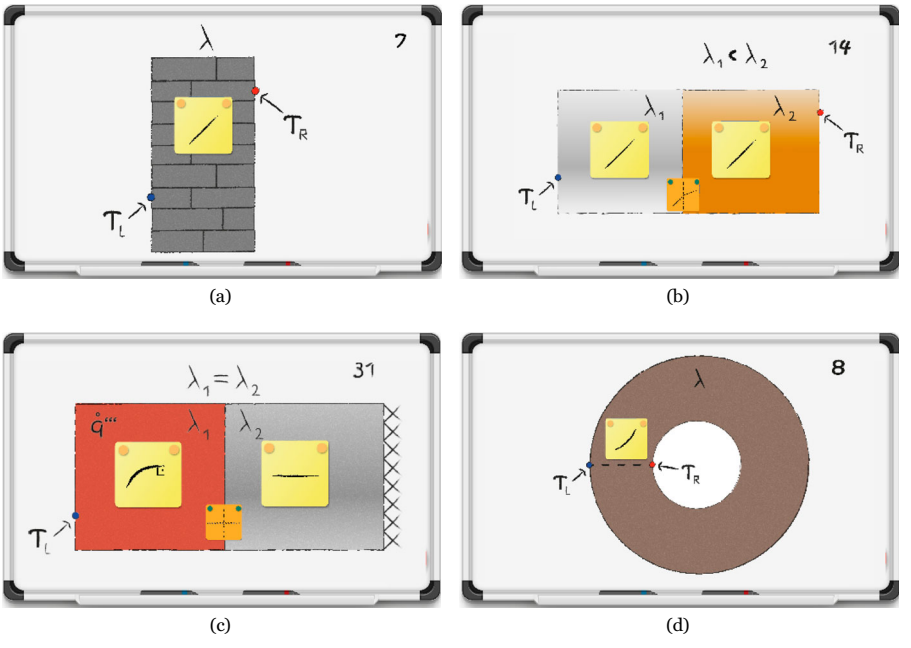


Figure 4. Examples of simple tasks in HeatQuiz App concerning heat conduction in solids, showing how perceptual learning through 'description by graphs' is implemented.

In the examples above, it becomes apparent how the components of Equation (1) affect the resulting curve, how they lead to a straight line, a kink or exponential decrease. Perceptual learning promotes visualising the influence of each individual component, which provides the structural insights necessary for transfer of learning.

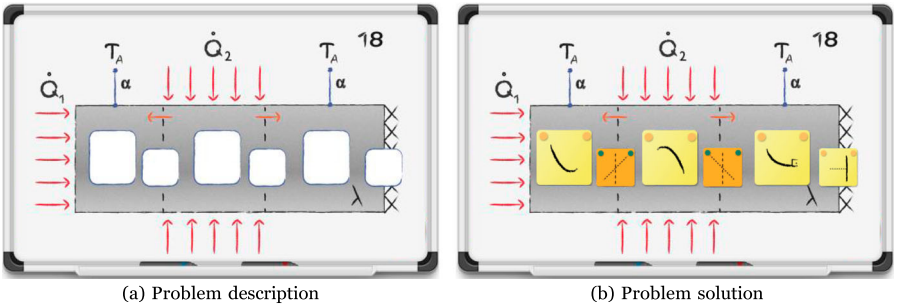
In real applications, combinations of these basic tasks occur, as shown in the following example. However, the approach to solving the problem remains the same. Figure 5(a) shows a complex task with different boundary conditions alongside a metal rod. The rod is divided into three sections by dashed lines. The entire problem is described without text. On the left side, a constant heat flow $\dot{Q}_1$ is imposed, the right side is adiabatic. On the two outer sections, heat is transferred to the environment, while the middle area is heated with a constant heat source $\dot{Q}_2$. The small red arrows inside the metal rod indicate that $\dot{Q}_2$ is the larger energy source and therefore heat flows from the middle to both sides. The solution is shown in Figure 5(b).

5.1.2. Example: mass transfer

The same way that temperature profiles describe heat transport, concentration profiles describe mass transport. Since molar flow and concentration profile are interdependent, mass transfer can be taught using concentration curves. Similar to the above, the solution requires transfer of learning. When deriving temperature profiles, the continuity of energy can be used as additional information, in the case of concentration profiles it is the conservation of mass. Diffusive mass transport is expressed by the mass diffusion equation, Fick's law:

$$\dot{J}(x) = -DA\frac{\partial c}{\partial x} \tag{2}$$

with molar flow $\dot{J}$ in the direction of diffusion x, diffusion coefficient D, cross-sectional area A (perpendicular to the direction of diffusion), concentration c. As with the Fourier law discussed above, the variables in Fick's law vary depending on the application. In contrast to most temperature



(a) Problem description (b) Problem solution

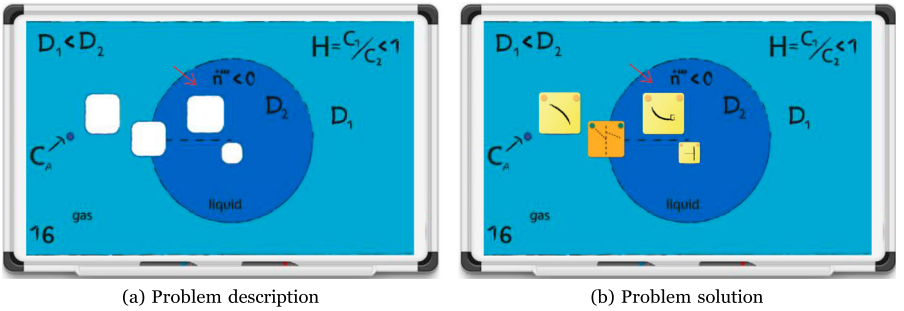
Figure 5. Example of a more complex problem in HeatQuiz App, representing the real application of a metal rod with different boundary conditions, showing how the game engine 'description by graphs' permits to draw the course of any two-dimensional curve. (a) Problem description (b) Problem solution.

curves in heat transfer, most concentration curves are non-differentiable, because a step occurs at the interface of two different media.

In the following task (see Figure 6(a)), the concentration profile of a substance is to be derived. The substance diffuses from a gas into a liquid, which is indicated by a red arrow. All relevant information is given as coefficients or constants: a volumetric sink $\dot{n}'''$ in the liquid, the solubility constant H, and the ratio of the diffusion coefficients D_1 and D_2 in gas and liquid. The input screen shows a zoomed view of the location of discontinuity (see Figure 7). Since the input is only qualitative, one point at the discontinuity is given and three other points can be moved vertically. The solution is shown in Figure 6(b). Evaluation is similar to tasks with temperature profiles.

5.2. Second game engine: description by equations

Each scientific or technical field has its own mathematical formulas and variables. Following the perceptual learning approach, the second game engine checks mathematical expressions without the user having to solve them. It permits to ask for equations, e.g. mathematical approaches, formulas and calculation methods. The 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 recognised as correct if it can be transformed into the given solution, e.g. by addition, multiplication, or commutation. Expressions in brackets are expanded. Thus, correct solutions can be detected, no matter how the user writes them down. The game engine highlights correct and incorrect parts of the user's solution separately, making it easy to locate errors. In engineering, equations are modular in structure. The terms of an equation are often meaningful units and correspond to a field of knowledge (see e.g.



(a) Problem description (b) Problem solution

Figure 6. Exemplary question illustrating the use of the game engine 'description by graphs' for a different physical mechanism (mass transfer): Diffusion of a gas into a liquid with a step change in concentration at the interface. (a) Problem description (b) Problem solution.

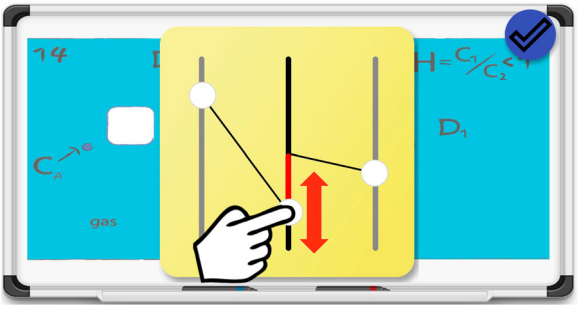


Figure 7. Input screen of the HeatQuiz App used in the case study: slider to define a step in the curve and the corresponding gradients.

Equation (3), where heat flux consists of the emission, reflection and transmission term). In this case, highlighting the incorrect term as a whole (rather than just the erroneous variable) means highlighting the deficient field of knowledge. This emphasises the structure of the equation, as recommended for perceptual learning. Following SDT, points can be assigned to each correct part of the solution to reward learning progress, even if the expression as a whole is not fully correct yet. The input is particularly user-friendly thanks to a flexible keyboard. If required, this keyboard can be customised and even look different for each task. Keys can be assigned any symbols, special characters, indices and mathematical operators. The number of keys can be chosen as needed. This is useful to limit the number of possible answers and thereby simplify the task. This makes it easy to provide a task with different levels of difficulty, as recommended in the guidelines. Moreover, the game engine meets the guidelines for usage scenarios: A minimal keyboard fits onto a smartphone display.

5.2.1. Example: thermal radiation

One aspect of radiation covered by HeatQuiz App is surface brightness, which is a mathematical concept valid for highly simplified radiation properties. This concept is applicable for diffuse radiating bodies. Surface brightness describes the total outgoing radiant heat flux of a surface

$$\dot{Q} = \dot{Q}_\epsilon + \dot{Q}_\rho + \dot{Q}_\tau \tag{3}$$

composed of emission $\dot{Q}_\epsilon$, reflexion $\dot{Q}_\rho$ and transmission $\dot{Q}_\tau$. However, it is irrelevant which of these three mechanisms produces the radiant flow. Multiple reflections on other surfaces are taken into account by reciprocal references.

A short glance on the physical background: Thermal radiation is the transport of heat by electromagnetic waves. Stefan-Boltzmann's law specifies the radiant power $\dot{Q}_\epsilon$ emitted by an idealised body of area A and absolute temperature T:

$$\dot{Q}_\epsilon = A\epsilon\sigma T^4 \tag{4}$$

with emissivity ε for grey radiators and Stefan-Boltzmann constant σ.

Figure 8(a) shows a simple example in HeatQuiz App. The main screen has three areas: The task as a sketch (left), an input line like on a scientific calculator (above), and a keyboard (right) that has been customised to the question. The sketch shows two parallel walls, one is considered a black body ($\epsilon = 1$) and the other a grey body ($\epsilon < 1$). In this task, the surface brightness of the red dashed surface is asked for. The student has to understand what components the heat flow consists of, express each as a formula and derive the final equation. This is one of an engineer's core competences. Each component has to be expressed by an individual mathematical term, derived from Stefan-Boltzmann's law. Here, the components are the surface's own emission and the reflected part of the other wall's surface brightness. On the solution screen (see Figure 8(b)), the user's solution (top) is compared with the correct solution (bottom). Due to the modular structure of the solution,

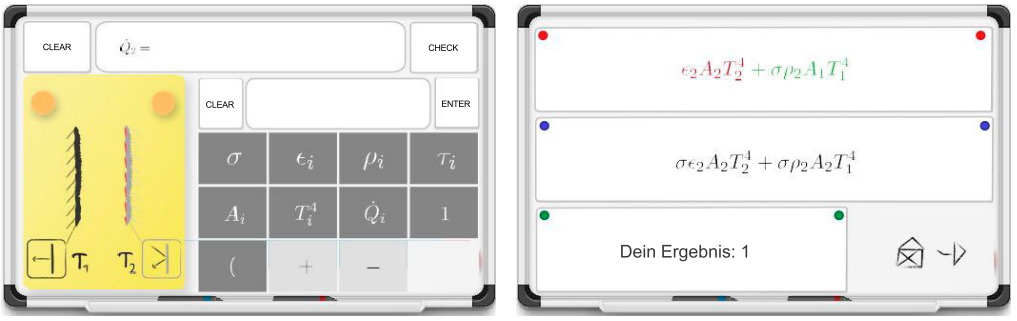


Figure 8. Game mode 'Surface brightness' in HeatQuiz App, illustrating perceptual learning through 'description by equations': (a) Input window with two input lines and customised keyboard. (b) Solution screen showing the solution entered by the user (top) and the correct solution (bottom). The first term is missing a σ (red) and – as $A_1 = A_2$ – the second is correct (green).

applying the guideline is especially useful here: It makes sense to award points not only for the correct expression as a whole, but also for single correct terms. If the first term is correct, the student has understood emission; if the second term is correct, the student has understood reflection. As the equation is composed of modular components, the task requires structural insight. Transfer of learning, as required by the guidelines, is supported by perceptual learning.

5.3. Evaluation by engineering students

The objective of the case study was to assess perceptual learning as educational approach for a learning app in university-level engineering education. The following evaluation by students shows to what extent the two task types meet the requirements derived from the survey above.

5.3.1. Usage statistics

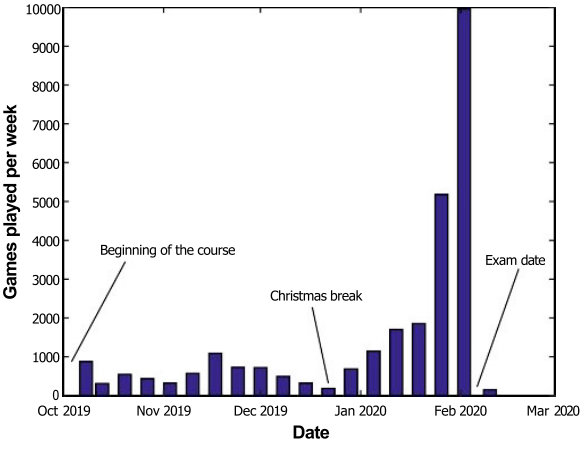
HeatQuiz App was evaluated by undergraduate engineering students. During the 2019/2020 semester, the app was embedded into the Heat and Mass Transfer course at the authors' institution. In this course, the use of HeatQuiz App has complemented the teaching very well. It facilitated a novel, more modern approach to teaching, e.g. by being incorporated into lectures and tutorials (see below).

Throughout this semester, tasks from the app were discussed in the office hours where students asked for help with comprehension questions. From their questions and according to student feedback, it is concluded that certain tasks in HeatQuiz App sparked discussions within the study groups, helping students to develop the problem-solving skills that engineers need.

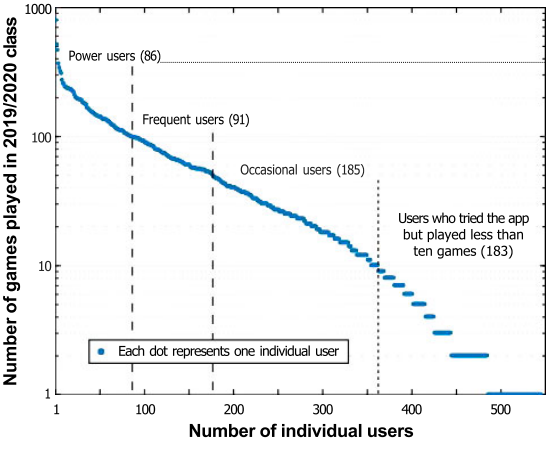
The way lecturers present the app strongly influences how students perceive feedback from the app: either as pressure (thus having a controlling significance) or as incentive (thus having an informational significance). It is therefore crucial to integrate the app into a teaching concept (see Ryan and Deci 2020). Failing to do so can lead to low acceptance of the app (Hütz et al. 2018).

In 2019/2020, the course took place in the winter semester between October and February. HeatQuiz App was introduced at the very beginning, and the students' interest in the app was tracked throughout the semester. Figure 9(a) shows the number of games that students of this particular class have played per week. Based on this data, four different phases of use were identified:

(1) **Trial phase:** After its introduction in October 2019, roughly 1000 games were played in the very first week. Students became aware of HeatQuiz App and it remained installed on their smartphones in the following teaching period. At this early point in the semester, students had no background in heat and mass transfer. This allowed them to explore the app and try to solve



(a)



(b)

Figure 9. Case study: Statistic on the use of HeatQuiz App during the 2019/2020 class of 'Heat and Mass transfer I' at the authors' institution, showing (a) when the game was played and (b) by whom it was played (see also Jacobs et al. (2021)).

the exercises on their own. This approach can prepare students for future learning and also for transfer of learning, as Schwartz and Martin (2004) demonstrated (see also Section 4). In particular, tasks on temperature profiles (description by graphs) seem to lend themselves to this approach as they use images and relate to common knowledge.

(2) **Teaching phase:** Between October and the end of December, HeatQuiz App was 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 solved the task together while discussing their approach to the solution. The idea was to overcome the student-teacher relationship that is common in large classes and create a sense of interactive collaboration that encourages students to solve problems on their own. The direct feedback from the students was very positive. Consequently, the number of played games rose to slightly above 1000 per week, then it dropped towards the Christmas break. Unsurprisingly, the students' learning activity over the holidays was at a rather low level.

(3) **Learning phase:** With the resumption of the class in January 2020, game usage started picking up again and approached 2000 games during the third week of January. By this stage, students

had sufficient knowledge of heat and mass transfer to benefit from the app. The increasing number of played games shows that the app supports students in their self-regulated learning.

(4) **Exam phase:** While preparing for the final exam on February 8th, students pushed the app usage to a maximum of 10,000 games per week. This high usage shows that HeatQuiz App has indeed been accepted as a learning tool. Its use to finalise studies on heat and mass transfer and prepare for the final exam is in line with the guidelines discussed above.

The following evaluation shows how the number of played games is distributed across the students. As each user has a unique ID (which is rendered anonymously), gaming activity per ID was tracked on the server side of the app (see Figure 9(b)). Here, each dot represents one 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 HeatQuiz App. About a third (183 users) have tried the app but played fewer than ten games. 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 frequent users (91 users) and so-called power users (86 users). In the latter group, each user played more than 100 games. One enthusiastic student even accumulated a total of 791 games.

As a measure of the learning progress, the average score per game is shown over time in Figure 10. Each point represents the weekly average, and the dashed line is the thirty-day moving average. At the beginning of the class, the students' average score is 12 points per game. This value rises steadily throughout the course, almost tripling to 33 points per game. Interestingly, three distinct outlier points can be associated with particular evens: First, the introduction of the app in the very first week, when games were played in the lecture hall. Second, the Christmas break, which has already been noticed in the number of games played. Third, the days leading up to the exam, when students are at the maximum of their individual preparation.

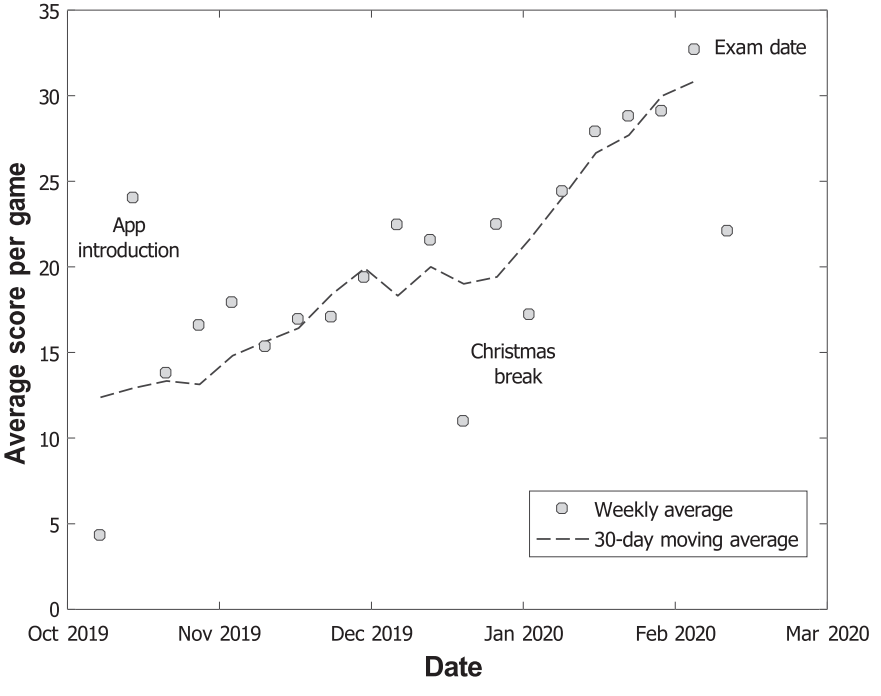


Figure 10. Case study: As a measure of the students' learning progress, the average score per game is shown over time. Throughout the course, the average score almost triples, illustrating the success of the HeatQuiz App (see also Jacobs et al. (2021)).

5.3.2. Survey on HeatQuiz App

From the first part of the survey, general guidelines for learning apps in engineering education were derived. In the second part of the survey, engineering students were asked to share their experiences with HeatQuiz App. The results show the extend to which the app meets their expectations. The survey design allows the answers from the first part to be correlated with those from the second. This survey was conducted in the winter semester 2019/2020. It was initiated three weeks before the exam and stopped on 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 receive well-founded feedback. Out of 102 participants who generally want to use learning apps, 74 actually tried out HeatQuiz App. The user profile of this subgroup equals that of all respondents[2], where most students prefer learning apps that convey comprehension, and the most represented player types are Achievers and Explorers (see Figure 1(a ,b)).

The vast majority of users (89%) gives HeatQuiz App a positive assessment (Figure 11). 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 HeatQuiz App to be further refined. In order to ensure that users give their unbiased opinion, the overall satisfaction is deliberately gathered at the beginning of the (HeatQuiz-specific) survey. Certain aspects might only become salient through the survey questions and influence the user's overall verdict (Thielsch, Lenzner, and Melles 2012). 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 comprehension. A total of 70% states that this focus is well implemented in the app, i.e. it improves the comprehension of heat and mass transfer (see Figure 12(a)).

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 HeatQuiz App for this purpose (see Figure 12(b)), 37% even in more than half of their learning sessions. This is a very good feedback because HeatQuiz 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 HeatQuiz App. These results show that the educational approach is well-accepted by the students.

Concerning practical relevance, the app content falls short of the users' expectations. Practical relevance is important to the students (see Figure 1(c)), but only half of the students (49%) describe the HeatQuiz tasks as rather practice-oriented (Figure 12(c)). At the same time, more than two thirds of the students (70%) consider the difficulty of the tasks as 'just right' (Figure 12(d)). However, these two characteristics of the tasks are interrelated: In heat and mass transfer, practice-oriented tasks are often more complex, e.g. because multiple heat transfer mechanisms have to be considered.

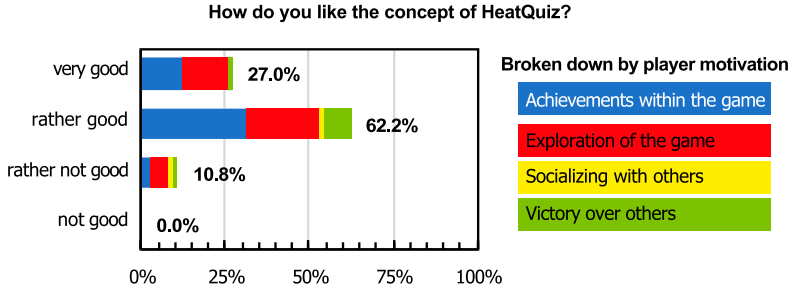


Figure 11. Evaluation of the HeatQuiz App concept used in the case study (broken down by player motivation), showing that the good rating is independent of the player motivation.

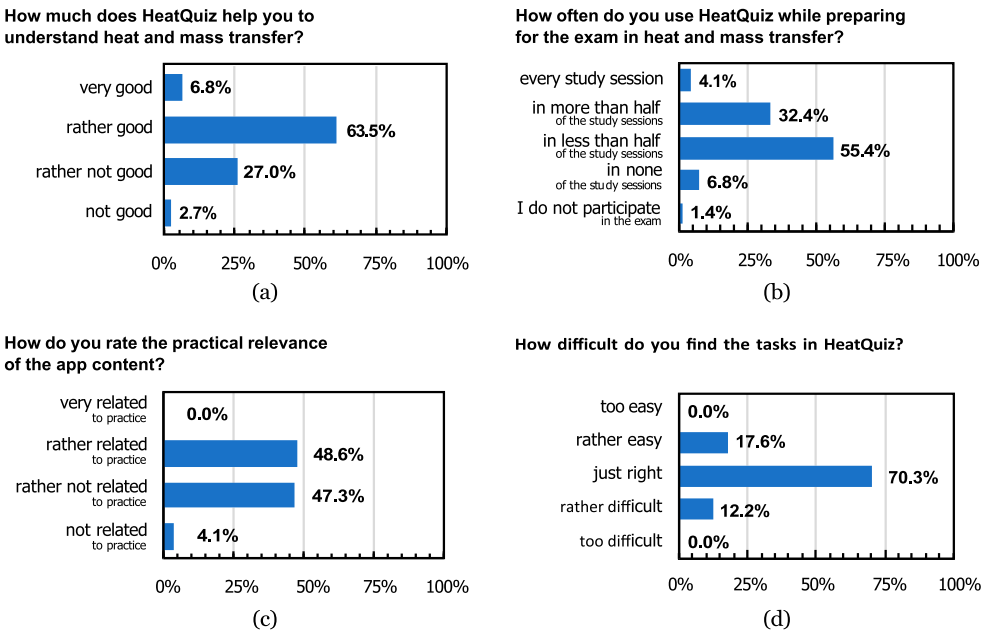


Figure 12. Result of the students' evaluation of the HeatQuiz App used in the case study: (a) A majority of students states that the app fosters comprehension and (d) the difficulty of the tasks is just right. (b) Most students use the app in less than half of their individual study sessions for exam preparation. (c) The app falls short of users' expectations concerning practical relevance (see also Jacobs et al. (2021)).

Consequently, a fragile balance has to be found: Practice-oriented tasks increase motivation, but very difficult tasks destroy it. Adjustments must be made thoughtfully.

The two most relevant usage scenarios define the conditions under which HeatQuiz App has to work: on-the-go and in five-minute breaks. Particularly interesting is the assessment of students to whom the respective usage scenario is important. It is assumed that these users have tried out the app in their preferred situation and formed an opinion, so their answers represent a sound judgement.

Learning on-the-go is the most important usage scenario, as 67 out of 74 HeatQuiz users (90.5%) consider it very important or rather important. Accordingly, aids like books or pen and paper are a hindrance to them. About a third of this subgroup, 28%, never needs any aid for the tasks of HeatQuiz App. According to these users, the tasks fit perfectly into this important learning situation (Figure 13(b)). Another 54% of the subgroup state that more than half of the tasks are suitable for learning on-the-go. There is a need for improvement, especially because of the great interest in learning on-the-go.

The second usage scenario is the five-minute break. For 64 out of 74 HeatQuiz users (87%) this learning situation is very important or rather important, so the tasks have to be solvable quickly. Of this user group, 39% complete all tasks in less than five minutes (Figure 13(c)), so the tasks are well-suited to their preferred learning situation. For a further 52%, this applies to at least more than half of the tasks. Here, HeatQuiz App is already on the right track.

Overall, the user groups of both scenarios overlap to a large extent: Students who want to learn on-the-go, also want to learn in five-minute breaks. 81% of the HeatQuiz users rate both usage scenarios as very important or rather important. This preference should be reflected in the actual use of HeatQuiz App: two significant usage peaks should be detectable. However, at least the on-the-go scenario seems to be underrepresented (Figure 13(a)). 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 above interpretation: Some students would like to use HeatQuiz

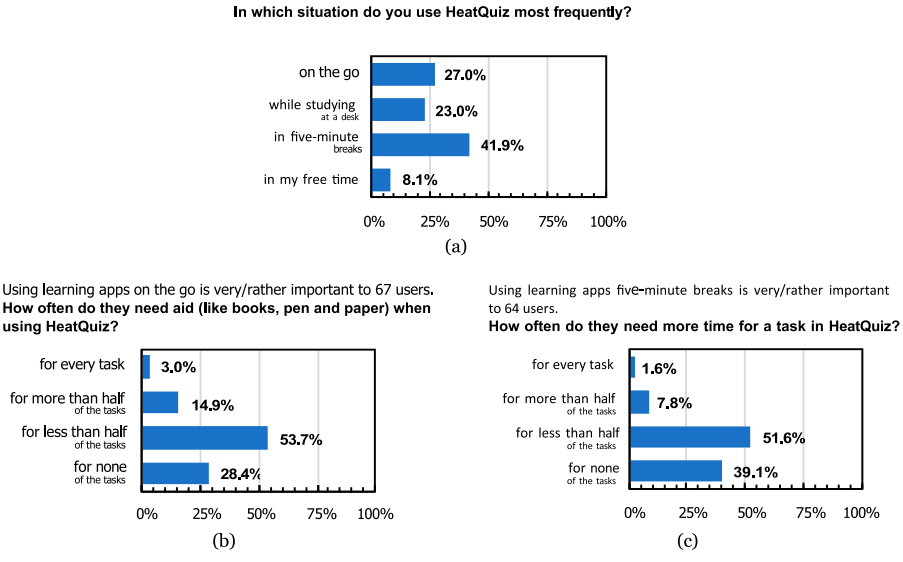


Figure 13. Result of the survey on HeatQuiz App: (a) Students use it mainly on-the-go and in five-minute breaks. (b) Evaluation of users, to whom the respective usage scenario is important: Subgroup of students who wanted to use learning apps on-the-go – could they comfortably use the HeatQuiz App? (c) Subgroup of students who wanted to use learning apps in five-minute breaks – did they manage to complete a task in time? (see also Jacobs et al. (2021)).

App on-the-go, but in this usage scenario it falls short of their requirements. For this reason, students deviate from their preferred usage scenario and use HeatQuiz App at a desk. The problem may be related to the need for textbooks, formularies and other aids when solving the tasks. In short breaks, e.g. between two lectures, using HeatQuiz App appears to be more feasible, probably because students have a table and their documents available. The duration of the tasks seems appropriate.

6. Conclusion

The present work investigated how mobile learning apps can enrich teaching in engineering education at university level. The authors aimed to identify the students' needs, propose an appropriate educational approach and recommend an engaging app design. The following two research questions were addressed: What do engineering students expect from a learning app? Which educational approach and which learning app design can meet these requirements?

A survey was conducted to understand the preferences of the specific target group: which learning strategies engineering students prefer, what personal motivation drives them, which gamification elements appeal to them, and which usage scenario they favour. Based on the results, the authors developed guidelines for learning apps in engineering education:

- Engineering students value thorough comprehention of teaching content and its application in practice. Apps that promote transfer of learning were found to be well suited for this purpose.
- Engineering students want to use apps not only to prepare for exams, but also to acquire knowledge beyond that. The authors analysed what forms of motivation underlie these goals. Based on SDT, they proposed guidelines for maintaining and promoting intrinsic motivation as well as autonomous forms of extrinsic motivation, while addressing common pitfalls.
- Concerning learning app design, engineering students focus on the game environment rather than on fellow players. The game environment should encourage discovery and exploration and leave room for self-determined decisions. Social interaction within the game is only of minor importance.

- Engineering students want to use learning apps during five-minute breaks or on-the-go. These usage scenarios impose constraints for learning app design and content: Tasks must be solvable in limited time, an app must be optimised for mobile devices and all relevant help must be included. Long and complex calculations cannot be practiced effectively.

Implementing these guidelines results in demanding constraints: Tasks must promote transfer of learning and, at the same time, be solvable within only five minutes. The authors consider perceptual learning to be a suitable educational approach. Perceptual learning can beneficially complement traditional teaching, because it changes the way learners view a problem. Perceptual learning supports transfer of learning. It can lead to important learning gains, i.e. transfer of learning to contexts that look different but share the same underlying structure. This includes recognising implicit patterns in mathematical tasks without explicitly performing calculations.

Considering the potential of perceptual learning, the authors derived an appropriate app design for engineering students. They suggested a concrete task type that works with mathematical graphs and equations. The strategy is to refrain from asking for facts or numbers, and work with variables and qualitative graphs instead. Formulating the solution to a given task or drawing the corresponding graph without actually performing a calculation is feasible in five minutes. A broad range of applications in educational tasks is possible, as graphs and equations are extremely versatile in engineering education. Especially the beginning and end of a problem-solving process can be practiced effectively by formulating a problem or evaluating a solution. This is particularly beneficial for engineers because they often face open-ended problems in their professional lives.

In order to assess the educational approach and the guidelines under real-life conditions, the authors wanted to evaluate a corresponding app among the user group. Repurposing an existing digital entertainment game was impossible because teaching content at university level is complex and specific. Since developing a learning app requires skills, time and money, the effort is worthwhile if it can be reused for different subjects. The authors decided to develop an app framework (HeatQuiz Framework) which is tailored to the needs and preferences of engineering students. On this basis, various apps can be created, all of which comply with the educational approach and the guidelines.

For an extensive case study, the framework was used to generate an app for heat and mass transfer (HeatQuiz App). Illustrative examples of perceptual learning tasks and implementation of the guidelines were discussed in this paper. The app was provided to an undergraduate engineering course and its usage was tracked over one semester. A survey among student users evaluated HeatQuiz App and shows to what extent the tasks meet their expectations. The vast majority of students gave a positive assessment.

Other lecturers may use HeatQuiz Framework to create their own mobile learning app. To illustrate the versatility of the framework, the game engines would, for example, be perfectly suited to create a learning app for automatic control classes. The first game engine would permit to draw functional diagrams, with the decision tree providing a selection of control loop elements. Using the second game engine, Laplace transformation could be incorporated in this app.

6.1. Limitations

As is the case with most studies, the present work has some limitations. The present study is based on observations during one single academic year. To increase the validity of the study, it would be worthwhile to repeat it for several consecutive years.

In the case study, the authors integrated HeatQuiz App into a teaching concept for the reasons discussed above. Consequently, the students' performance within the app was influenced by the ongoing lessons. Therefore, it is impossible to determine what proportion of the students' learning success was based solely on using the app. It would be interesting to link the students' exam grades

to their use of HeatQuiz App. However, the privacy policy of the authors' institution prohibits this linking, as app users must remain anonymous.

6.2. Future work

Overall, the usage statistics is very satisfactory, showing that two thirds of the users develop a habit of playing HeatQuiz App. In the class evaluated, this self-studying tool proved to be very successful, as the average score per game almost tripled. However, especially if a learning app is well accepted, it should be taken into account that the uncritical use of game-based learning apps also carries risks. In general, the use of technology always has side effects, e.g. the change of people's social behaviour (Winner 2004). The risk that technical solutions – once established – are no longer critically questioned is what Winner (2004) refers to as technological somnambulism. A learning app can change the learning behaviour of students. As a side effect, it also has the potential to influence, for example, the social interaction of learning groups. Responsibility for the consequences arising from the use of technology begins with its conception (Winner 2004): Only features implemented by the developer can be used later on. The authors (as developers of HeatQuiz App) try to meet their responsibility by integrating their app into a teaching concept (see Section 5, case study). If necessary, negative side effects can thus be detected and the implementation of the guidelines in the app can be adjusted. Future work should address this aspect.

In the future, the authors aim to build on the case study and support most of the teaching in heat and mass transfer with game-based learning. In future classes, the app will be introduced differently at the beginning of the semester: Guiding students in the trial phase should be given higher priority than in the previous approach inspired by Schwartz and Martin (2004), as this could be a way to reduce the dropout rate.

There is another starting point for improvement: extending the help-function within HeatQuiz App. Particularly useful would be contextual help for each task, and user-related help that adapts to the user's behaviour. Based on incorrectly answered questions, a smart function can offer help on related topics (see e.g. Troussas, Krouska, and Sgouropoulou 2019). Improving the help function will also have a positive impact on the task duration and thus on the usability of HeatQuiz App on-the-go.

To further refine the knowledge on mobile game-based learning in engineering education, the existing HeatQuiz Framework will be used as a platform for research in other subjects in STEM education. In addition to the above-mentioned application in automatic control classes, the authors see, for example, applications in thermodynamics to ask for energy balances. Energy balances lead to the set of governing equations for a given problem. For students, the difficulty is to decide whether to set up a global or a local energy balance and how to derive the differential equation. As this requires transfer of learning and can be taught without actually solving the equations, the perceptual learning approach will be consistently followed.

Another interesting application of HeatQuiz Framework is realising the Learner-Designer Approach to Serious Games (LDASG), as described by Paciarotti, Bertozzi, and Sillaots (2021): Here, engineering students are not only players, but also take on the role of game designers and develop an educational game for their fellow students. This instructional approach has two objectives: First, students structure and learn the teaching content to develop their own game. Second, they deepen their knowledge by reviewing and playing the games of their fellow students. Referring to the cognitive load theory (discussed above), Paciarotti, Bertozzi, and Sillaots (2021) emphasise the need to avoid overloading students with too much complexity in the game design process. HeatQuiz Framework is a perfect tool for this, as it reduces the process of game design to the pedagogically valuable conceptual work. On the one hand, the game engines offer a manageable amount of predefined game elements and task types, so that students can focus on the content of their game. On the other hand, the game engines provide sufficient possibilities for the student designers to create numerous tasks of varying complexity. Thus, HeatQuiz Framework permits to teach the above-mentioned engineering courses using the LDASG.

Notes

1. The categories as defined by Bartle (1996) were adapted to learning apps, i.e. the last category 'killers' (players who 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.
2. Concerning learning strategy and player type, the distribution differs by a maximum of 2%. Main purpose of a learning app: comprehension of teaching content (84%), structuring teaching content (10%), memorising teaching content (7%). Most important element of a game: achievements (levels, points, medals) (46%), discovering rules and completing quests (41%), socialising and interaction with others (3%), victory over others (ranking) (11%).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Alanne, K.. 2015. "An Overview of Game-Based Learning in Building Services Engineering Education." *European Journal of Engineering Education* 41: 204–219. doi:10.1080/03043797.2015.1056097.

Alsawaier, R.. 2018. "The Effect of Gamification on Motivation and Engagement." *The International Journal of Information and Learning Technology* 35 (1): 56–79. doi:10.1108/IJILT-02-2017-0009.

Bandura, A.. 2006. "Going Global with Social Cognitive Theory: From Prospect to Paydirt." In *The Rise of Applied Psychology: New Frontiers and Rewarding Careers*, edited by S. I. Donaldson , D. E. Berger, and K. Pezdek, 53–79.

Bartle, R.. 1996. *Hearts, Clubs, Diamonds, Spades: Players Who Suit MUDs*, https://mud.co.uk/richard/hcds.htm.

Bogner, K., and U. Landrock. 2015. "Antworttendenzen in Standardisierten Umfragen." In *GESIS Survey Guidelines*. Mannheim, Germany: GESIS – Leibniz Institute for the Social Sciences. doi:10.15465/gesis-sg_016

Chandler, P., and J. Sweller. 1991. "Cognitive Load Theory and the Format of Instruction." *Cognition and Instruction* 8 (4): 293–332. doi:10.1207/s1532690xci0804_2.

Coller, B., and M. Scott. 2009. "Effectiveness of Using a Video Game to Teach a Course in Mechanical Engineering." *Computers & Education* 53 (3): 900–912. doi:10.1016/j.compedu.2009.05.012.

Darling, J., B. Drew, R. Joiner, I. Iacovides, and C. Gavin. 2008, July 14–16. "Game-Based Learning in Engineering Education." In *EE2008: International Conference on Innovation, Good Practice and Research in Engineering Education*.

Day, S., and R. Goldstone. 2012. "The Import of Knowledge Export: Connecting Findings and Theories of Transfer of Learning." *Educational Psychologist* 47 (3): 153–176. doi:10.1080/00461520.2012.696438.

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

Ebner, M., and A. Holzinger. 2007. "Successful Implementation of User-Centered Game Based Learning in Higher Education: An Example From Civil Engineering." *Computers & Education* 49 (3): 873–890. doi:10.1016/j.compedu.2005.11.026.

Friedrich, H. F., and H. Mandl. 2006. "Lernstrategien: Zur Strukturierung des Forschungfsfeldes." In *Handbuch Lernstrategien*, edited by H. Mandl and H. F. Friedrich, 1–26. Hogrefe Verlag.

Gao, F., L. Li, and Y. Sun. 2020. "A Systematic Review of Mobile Game-Based Learning in Stem Education." *Educational Technology Research and Development* 68 (4): 1791–1827. doi:10.1007/s11423-020-09787-0.

Garcia, T., and P. R. Pintrich. 1994. "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*, edited by D. Schunk and B. Zimmerman, 433–452. Hillsdale, NJ: Lawrence Erlbaum Associates.

Hartmann, A., and L. Gommer. 2021. "To Play or Not to Play: On the Motivational Effects of Games in Engineering Education." *European Journal of Engineering Education* 46 (3): 319–343. doi:10.1080/03043797.2019.1690430.

Hensberry, K., E. Moore, and K. Perkins. 2015. "Effective Student Learning of Fractions with an Interactive Simulation." *Journal of Computers in Mathematics and Science Teaching* 34 (3): 273–298.

Hinz, O., A. Maidl, and J. Puchan. 2018. "QuizApp zur Prüfungsvorbereitung – Vorbereitung von Prüfungssituationen mit Gaming-Effekten." In *Digitale Führungskräfteentwicklung: Konzepte, Impulse und Trainingsformate aus der Praxis*, edited by M. A. Ciesielski and T. Schutz, 51–67. Gabler, Berlin, Heidelberg: Springer. 10.1007/978-3-662-54557-7_5

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

Jacobs, E., O. Garbrecht, R. Kneer, and W. Rohlfs. 2021. "HeatQuiz: An App Framework for Game-Based Learning in STEM Education." In *IEEE Global Engineering Education Conference (EDUCON)*, 1358–1368.doi:10.1109/EDUCON46332.2021.9453955

Joiner, R., I. Iacovides, J. Darling, A. Diament, B. Drew, J. Duddley, M. Owen, and C. Gavin. 2013. "Racing Academy: A Case Study of a Digital Game for Supporting Students Learning of Physics and Engineering." In *Cases on Digital Game-Based Learning: Methods, Models, and Strategies*, edited by Y. Baek and N. Whitton, 509–523. Hershey, USA: IGI Global.doi:10.4018/978-1-4666-2848-9.ch026

Kellman, P. J., C. M. Massey, and J. Y. Son. 2010. "Perceptual Learning Modules in Mathematics: Enhancing Students' Pattern Recognition, Structure Extraction, and Fluency." *Topics in Cognitive Science* 2 (2): 285–305. doi:10.1111/tops.2010.2.issue-2.

Krathwohl, D. R.. 2002. "A Revision of Bloom's Taxonomy: An Overview." *Theory Into Practice* 41 (4): 212–218. doi:10.1207/s15430421tip4104_2.

Krosnick, J. A.. 1991. "Response Strategies for Coping with the Cognitive Demands of Attitude Measures in Surveys." *Applied Cognitive Psychology* 5 (3): 213–236. doi:10.1002/(ISSN)1099-0720.

Malliarakis, C., M. Satratzemi, and S. Xinogalos. 2016. "CMX: The Effects of an Educational MMORPG on Learning and Teaching Computer Programming." *IEEE Transactions on Learning Technologies* 10 (2): 219–235. doi:10.1109/TLT.2016.2556666.

Mccabe, J.. 2010. "Metacognitive Awareness of Learning Strategies in Undergraduates." *Memory & Cognition* 39 (3): 462–476. doi:10.3758/s13421-010-0035-2.

Menold, N., and K. Bogner. 2016. Design of Rating Scales in Questionnaires. In *GESIS Survey Guidelines*. GESIS – Leibniz Institute for the Social Sciences, Mannheim, Germany. doi:10.15465/gesis-sg_en_015

Mourtos, N., N. Okamoto, and J. Rhee. 2004. "Defining, Teaching, and Assessing Problem Solving Skills." In *7th UICEE Annual Conference on Engineering Education*, 1–5.

Paciarotti, C., G. Bertozzi, and M. Sillaots. 2021. "A New Approach to Gamification in Engineering Education: The Learner-Designer Approach to Serious Games." *European Journal of Engineering Education* 46 (6): 1092–1116. doi:10.1080/03043797.2021.1997922.

Rohrmann, B.. 1978. "Empirische Studien Zur Entwicklung Von Antwortskalen Für Die Sozialwissenschaftliche Forschung." *Zeitschrift Für Sozial-Psychologie* 9 (3): 222–245.

Rutten, N., W. R. van Joolingen, and J. T. van der Veen. 2012. "The Learning Effects of Computer Simulations in Science Education." *Computers & Education* 58 (1): 136–153. doi:10.1016/j.compedu.2011.07.017.

Ryan, R. M., and E. L. Deci. 2000. "Intrinsic and Extrinsic Motivations: Classic Definitions and New Directions." *Contemporary Educational Psychology* 25 (1): 54–67. doi:10.1006/ceps.1999.1020.

Ryan, R. M., and E. L. Deci. 2020. "Intrinsic and Extrinsic Motivation From a Self-Determination Theory Perspective: Definitions, Theory, Practices, and Future Directions." *Contemporary Educational Psychology* 61: 101860. doi:10.1016/j.cedpsych.2020.101860.

Saris, W., M. Revilla, J. A. Krosnick, and E. M. Shaeffer. 2010. "Comparing Questions with Agree/Disagree Response Options to Questions with Item-Specific Response Options." *Survey Research Methods* 4 (1): 61–79. doi:10.18148/srm/2010.v4i1.2682.

Schiefele, U., and L. Streblow. 2006. "Motivation Aktivieren." In *Handbuch Lernstrategien*, edited by H. Mandl and H. F. Friedrich, 232–247. Hogrefe Verlag.

Schwartz, D. L., and T. Martin. 2004. "Inventing to Prepare for Future Learning: The Hidden Efficiency of Encouraging Original Student Production in Statistics Instruction." *Cognition and Instruction* 22 (2): 129–184. doi:10.1207/s1532690xci2202_1.

Schwarz, N., and B. Scheurig. 1991, August. *Selbstberichtete Verhaltens- und Symptomhäufigkeiten: Was Befragte aus Antwortvorgaben des Fragebogens lernen*. ZUMA-Arbeitsbericht. Zentrum für Umfragen, Methoden und Analysen (ZUMA), Mannheim.

Silva, E. D., M. Macedo, C. Teixeira, E. Lanzer, and Á. P. Graziani. 2017. "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*, edited by J. I. Kantola, T. Barath, S. Nazir, and T. Andre , Vol. 498, 933–945. Cham: Springer.

Staacks, S., S. Hütz, H. Heinke, and C. Stampfer. 2018. "Advanced Tools for Smartphone-Based Experiments: Phyphox." *Physics Education* 53 (4): 045009. doi:10.1088/1361-6552/aac05e.

Sweller, J.. 1988. "Cognitive Load During Problem Solving: Effects on Learning." *Cognitive Science* 12 (2): 257–285. doi:10.1207/s15516709cog1202_4.

Thielsch, M. T., T. Lenzner, and T. Melles. 2012. "Wie Gestalte Ich Gute Items und Interviewfragen?" In *Praxis der Wirtschaftspsychologie II. Themen und Fallbeispiele für Studium und Praxis*, edited by M. T. Thielsch and T. Brandenburg, 221–240. Münster: Monsenstein u. Vannerdat.

Troussas, C., A. Krouska, and C. Sgouropoulou. 2019. "Collaboration and Fuzzy-Modeled Personalization for Mobile Game-Based Learning in Higher Education." *Computers & Education* 144: 103698. doi:10.1016/j.compedu.2019.103698.

Udeozor, C., R. Toyoda, F. R. Abegao, and J. Glassey. 2022. "Digital Games in Engineering Education: Systematic Review and Future Trends." *European Journal of Engineering Education*. doi:10.1080/03043797.2022.2093168.

Visser, P. S., J. A. Krosnick, J. F. Marquette, and M. F. Curtin. 2000. "Improving Election Forecasting: Allocation of Undecided Respondents, Identification of Likely Voters, and Response Order Effects." In *Election Polls, the News Media, and Democracy*, edited by P. J. Lavrakas and M. Traugott. New York: Chatham House.

Wieman, C. E., W. K. Adams, and K. K. Perkins. 2008. "Phet: Simulations that Enhance Learning." *Science* 322 (5902): 682–683. doi:10.1126/science.1161948.

Wieman, C. E., and K. K. Perkins. 2006. "A Powerful Tool for Teaching Science." *Nature Physics* 2 (5): 290–292. doi:10.1038/nphys283.

Winne, P. H.. 2017. "Cognition and Metacognition within Self-Regulated Learning." In *Handbook of Self-Regulation of Learning and Performance*, edited by P. A. Alexander, D. H. Schunk, and J. A. Greene, 36–48. Routledge. doi:10.4324/9781315697048.ch3

Winner, L.. 2004. "Technologies as Forms of Life." In *Readings in the Philosophy of Technology*, edited by D. Kaplan, Chapter 8, 103–113. Rowman & Littlefield Publishers.

Zimmerman, B., and D. Schunk. 2001. *Self-Regulated Learning and Academic Achievement: Theoretical Perspectives*. 2nd ed. New York: Routledge.

Zydney, J. M., and Z. Warner. 2016. "Mobile Apps for Science Learning: Review of Research." *Computers & Education* 94: 1–17. doi:10.1016/j.compedu.2015.11.001.

Appendices

Appendix 1 Survey design

The survey is designed with closed-ended questions and direct, fully 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. The decision for this survey design is discussed in the following.

A1.1. Design of the questions

For practical reasons, closed-ended questions were used, i.e. there was a limited choice of response options. Data collection and evaluation can thus be performed faster and in a more efficient way. For closed-ended questions, response options have to be formulated with great care, otherwise problems may occur: If respondents do not find any of the given answers appropriate, the result will be significantly biased (Thielsch, Lenzner, and Melles 2012). Participants either do not answer the question at all (item non-response) or randomly state something (misstatement). In the present study, this was counteracted by tailoring the questions to the situation of the respondents (see Thielsch, Lenzner,

and Melles 2012). The number of questions was kept to a minimum to achieve a low dropout rate in the survey. Given the respondents' lack of prior knowledge about learning strategies and motivation, the authors suppose that more questions would only lead to a seemingly increased precision.

There was a single open-ended question at the very end, the praise and criticism question. Respondents perceive this as appreciation and free text comments can usefully complement the standardised answers (Thielsch, Lenzner, and Melles 2012). In the comments, none of the respondents complained that the given answers were inappropriate or did not reflect his or her opinion. Most comments were related to technical issues and specific problems with heat transfer tasks. In their future work, the authors are going to take this into account. However, since this paper focuses on general guidelines for learning apps in engineering education, a discussion of praise and criticism would be too extensive.

Another problem arises when respondents are influenced by predefined answers. In general, items can be formulated as a question or as a statement. Very common are items of Likert-type (Saris et al. 2010), which are formulated as a statement (e.g. *The practical relevance of learning apps is important to me.*). The corresponding response options are on a multi-level agree/disagree scale, typically ranging from *strongly agree* to *strongly disagree*. A problematic aspect is that agree/disagree scales promote acquiescence and thus bias the results (Bogner and Landrock 2015). Respondents show acquiescence, i.e. they tend to agree with a statement regardless of its content. Therefore, direct rating scales (item-specific response options) were used in the present survey (Saris et al. 2010). The items were formulated as questions and the response options were tailored to each question (e.g. *How important is the practical relevance of a learning app?* with a multi-level rating scale ranging from *very important* to *not important*). Another advantage of direct rating scales is that respondents directly rate a frequency or an importance, which increases the measurement quality (Saris et al. 2010). This way of asking questions automatically makes respondents more attentive. While agree/disagree scales are repetitive and therefore elicit quick and routine answers (so-called satisficing), item-specific response options require more careful reading. As a result, the answers obtained are more reliable. Respondents should be motivated to answer carefully (so-called optimising, see Menold and Bogner 2016).

Regarding content, special care must be taken when asking about a personal mindset. There is a tendency towards social desirability, because any self-assessment is also perceived as a self-presentation. Instead of their true attitudes, respondents can therefore be inclined to state the attitudes they consider socially desirable (Bogner and Landrock 2015). In the present survey, this problem particularly concerned the question about player motivation according to Bartle (1996) (achievers, explorers, socialisers, killers). The response option "killers" was replaced by a less negatively connotated wording in order to reduce the social-desirability bias.

A1.2. Design of the answers

Rating scales have, on the one hand, a variation range defined by the scale poles and, on the other hand, a degree of differentiation (frequency) defined by the number of response options (Menold and Bogner 2016). Rating scales differ in the use of verbal or numerical labels, in the definition of the scale centre, in the scale polarity and in the number of response options.

Rating scales should meet some requirements (Menold and Bogner 2016): They should be generally understandable and balanced, i.e. symmetrical with the same number of positive and negative response options. They should be precise and the response options should be equidistant.

For the present survey, the question of how to label the rating scale was answered on the basis of a review of scientific literature. For the endpoints of the rating scale, verbal labels were introduced to define the variation range in an easily understandable way. The intermediate points could have been labelled with numbers. The advantage of this approach would be precision: Symmetry and equidistance of the scale could easily be accomplished. However, in the present survey, verbal labels were used instead. Review studies conclude that fully verbal scales increase reliability and validity (Menold and Bogner 2016). Additionally, they are preferred by most respondents (Rohrmann 1978). As reliability is considered to be the most important criterion, the slightly lower precision resulting from the use of verbal labels was accepted.

When looking for accurate wording for fully verbal rating scales, particular attention should be paid to symmetry. The options are either bipolar or unipolar scales. In general, bipolar rating scales present two opposing dimensions (antonyms), e.g. *courageous* vs. *anxious*. The main disadvantage is that respondents do not necessarily perceive antonyms as such (Menold and Bogner 2016). In the given example, the opposite of *courageous* could as well be *shy*. Additionally, for some respondents, the perception of a word's intensity differs between antonyms. For example, respondents may not consider the intensity of *very courageous* to be equal to *very anxious* (but with opposing signs). In this case, the neutral point is off-centre and the scale is therefore asymmetrical. Consequently, a unipolar scale was used in the present survey. Unipolar rating scales present a continuum from low to high, e.g. from *not satisfied* to *very satisfied* (Menold and Bogner 2016). For respondents, unipolar scales are easier to reflect on and they are methodologically more consistent. Special care has been taken to ensure that one end of the scale is the exact opposite of the other.

Verbal scales should meet minimum psychometric requirements: They should measure almost equidistantly, differentiate sufficiently, and be understood by most respondents (Rohrmann 1978). For verbal scales in German (language in which the survey was conducted), Rohrmann (1978) determined which wording is most appropriate. The response

options should accurately fit the questions. With vague quantifications, e.g. *rarely* or *often*, respondents have to decide for themselves which exact frequency they are going to interpret. This interpretation can vary considerably between two participants (Schwarz and Scheurig 1991, August). In the present survey, concrete questions were asked (wherever possible) and precise answers were offered: *How often do you need more than five minutes to solve a task in HeatQuiz?*, with the corresponding answers *for every task*, *for more than half of the tasks*, *for less than half of the tasks*, or *for none of the tasks*. Here, introducing additional precision significantly increases the validity of the answers. Due to the nature of language, verbal scales always leave at least some scope for interpretation. Consequently, the results cannot be converted into numerical values.

In the present survey, symmetry of the rating scales was ensured. However, no neutral point in the centre was provided, because of the response tendency towards answers in the middle. Respondents tend to choose the neutral answer, regardless of the question and irrespective of whether or not the answer reflects their true attitude (Bogner and Landrock 2015). This bias, just as acquiescence, is often the consequence of so-called satisficing, where respondents want to reduce their cognitive effort. Several experimental studies show that a middle category can lead to less thorough answers (Bogner and Landrock 2015). Most respondents tend in one direction of the scale and would report this attitude, if there were no middle category (Krosnick 1991 as cited in Bogner and Landrock 2015). For example, more accurate election predictions were obtained when respondents who had chosen a *don't know* answer were then emphatically re-asked for a contextual answer (Visser et al. 2000 as cited in Menold and Bogner 2016). On the other hand, if respondents actually do have a neutral attitude, they are unable to express it without a neutral response option, which also results in a bias. However, this case is very unlikely in the present survey: Given the market penetration of smartphones among students in 2020, it can be assumed that all respondents have already used apps. Furthermore, the respondents are dealing with HeatQuiz App and its content as part of their studies. Accordingly, they are very likely to have formed an opinion by the time the survey was conducted. For the present survey, symmetrical answer scales with an even number of response options were chosen. Consequently, the respondents were unable to make evasive statements, which helps to identify tendencies in the respondents' view (Thielsch, Lenzner, and Melles 2012). As a valid alternative to the neutral response, filter questions were used, i.e. it is asked in advance whether a person has an attitude towards a certain topic (Menold and Bogner 2016). Here, a preliminary question was asked to find out whether the respondent had already tried the HeatQuiz App. If so, they were asked about their experience in detail.

In addition, the even-numbered scale was advantageous in the evaluation, as answers could be clearly divided into a tendency *yes* and a tendency *no*. This provides a high degree of certainty, even when the imprecision of verbal scales is taken into account. For most questions in the present survey, a dichotomous answer would already have been sufficient to draw initial conclusions. However, the differentiated answers are obviously more informative. For one single question, a neutral response was provided because it is conceptually required by the question (Thielsch, Lenzner, and Melles 2012): *How difficult do you find the tasks in HeatQuiz?* On a scale ranging from *too difficult* to *too easy*, the answer *just right* in the centre corresponds to the optimum and not to a neutral response.

An answer scale allows respondents to express their opinion and gives a differentiated result when the survey is evaluated. However, a balance needs to be found between allowing for precision and overstressing the participants' capacity to remember. Based on recalling individual episodes, respondents struggle to remember the frequency of occurrence for a certain behaviour (Schwarz and Scheurig 1991, August). Consequently, they need to estimate the frequency, so that more entries on the answer scale only lead to a seemingly increased precision.

Review studies conclude that the optimum – with regard to a survey's reliability, validity, and the achieved level of differentiation – is a scale with five to seven response options (Menold and Bogner 2016). Since verbal rating scales were used in the present study, the distinction between categories is blurred. In order to achieve a higher level of differentiation, only four categories were introduced.

In summary, the present form of the questionnaire supports participants in giving correct and true answers. This increases the reliability and validity of the questionnaire. Due to its form, however, the survey cannot be tested in a meaningful way using statistical measures such as Cronbach's Alpha or Factor Analysis. The prerequisite for Cronbach's Alpha is that all variables are measured at an interval level. This is the case, e.g. with Likert-type scales where results can consistently be converted into numerical values. In addition, a Factor Analysis requires a sufficiently large sample size (10–15 participants per item). Both statistical measures are not fully compatible with the way the present questionnaire was designed. To perform a Factor Analysis regardless of these problems, two options would be available: First, questions could be skipped. This seems inappropriate, as it would exclude key questions. Second, questions could be used as filters, e.g. filtering all participants who state to be Archivers and subsequently perform a factor analysis where possible. For this option, the number of participants is too small. If the survey was to be designed for these metrics, the reliability and validity of the individual questions would be compromised (see discussion above on acquiescence bias, satisficing, lower measurement quality of indirect rating scales and numerical labels). In the present case, analysis options would not compensate for the shortcomings of an alternative questionnaire design.

Appendix 2 Survey: List of questions and response options

A2.1. First part of the survey

- Would you like to use learning apps to prepare for exams?
  yes / no
- Would you like to use learning apps to gain knowledge beyond the content of an exam?
  yes / no
- How important is the practical relevance of the app content?
  very important / rather important / rather not important / not important
- What is the main purpose of a learning app?
  comprehending teaching content
  structuring teaching content
  memorising teaching content
- Which element of a game is most important to you in a learning app?
  achievements (levels, points, medals)
  discovering rules and completing quests
  socialising and interaction with others
  victory over others (ranking)
- How important is using a learning app on-the-go (without aid like book, pen and paper)?
  very important / rather important / rather not important / not important
- How important is using a learning app when you are studying (with aid like book, pen and paper)?
  very important / rather important / rather not important / not important
- How important is using a learning app in five-minute breaks?
  very important / rather important / rather not important / not important

A2.2. Second part of the survey

- Did you try HeatQuiz, the learning app for heat and mass transfer? (filter question)
  yes / no
- How do you like the concept of HeatQuiz ?
  very good / rather good / rather not good / not good
- Would you like the development of HeatQuiz to be continued?
  yes / no
- How often do you use HeatQuiz while preparing for the exam in heat and mass transfer?
  every study session
  in more than half of the study sessions
  in less than half of the study sessions
  in none of the study sessions
  I do not participate in the exam.
- How much does HeatQuiz help you to understand heat and mass transfer?
  very good / rather good / rather not good / not good
- How difficult do you find the tasks in HeatQuiz ?
  too easy / rather easy / just right / rather difficult / too difficult
- How do you rate the practical relevance of the app content?
  very related to practice / rather related to practice / rather not related to practice / not related to practice
- How often do you need aid (like books, pen and paper) when using HeatQuiz ?
  for every task / for more than half of the tasks / for less than half of the tasks / for none of the tasks
- How often do you need more than five minutes to solve a task in HeatQuiz ?
  for every task / for more than half of the tasks / for less than half of the tasks / for none of the tasks
- In which situation do you use HeatQuiz most frequently?
  on-the-go
  while studying at a desk
  in five-minute breaks
  in my free time
- Your comments: praise and criticism.