JOURNAL OF CHEMICAL EDUCATION

Article

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A Game-Based Approach to an Entire Physical Chemistry Course

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Ⓢ *Supporting Information*

ABSTRACT: We designed, implemented, and evaluated a game-based learning approach to increase student motivation and achievement for an undergraduate physical chemistry course. By focusing only on the most important game aspects, the implementation was realized with a production ratio of 1:8 (study load in hours divided by production effort in hours). Student motivation was found to increase significantly: compared to the traditional lecture format, self-study time was estimated to increase more than 3-fold to 4.6 h per week on average by the students. The failure rate in the final examination was also reduced, mainly because of bonus points that students could receive upon successful participation in the game. However, there is some indication that application of game-based learning might not improve higher-order thinking skills.

KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Physical Chemistry, Phases/Phase Transitions/Diagrams, Distance Learning/Self-Instruction*

■ INTRODUCTION

The motivation of students for self-learning of study content outside the lecture hall is one of the challenges in higher education. Recent studies have shown that students do not seem to tap the full potential of self-study hours that have been accorded to them by the examination regulations and study module descriptions.[1,2] In this context, it seems necessary for universities to develop concepts to activate students to engage them with study content. In addition, the second challenge seems to be that we are currently facing a generation of learners who have grown up with and are used to digital communication technologies.[3] It has been hypothesized that this might also have an influence on the way students learn and that the utilization of game-based learning in education may lead to higher student motivation.[4,5] The term "game-based learning" in the context of this article refers to the usage of games in academic education, for example, to facilitate the illustration of abstract concepts. The issue for higher education is that game-based learning has been associated with addressing a lower learning level (memorization of facts) rather than improving higher-order thinking skills (transfer of knowledge, development of problem solving skills).[5,6] However, game-based learning has been successfully applied in tertiary, especially higher, education.[4−13] Examples of successful implementation of games in education includes many academic disciplines: psychiatric pharmacy,[4] environmental science,[5] psychology,[5] education,[5] physics,[6] information and communication technology (ICT),[8] medicine,[14−17] nursing,[18] pharmacy,[19−23] and chemistry.[7,9−12] As to the advantages, applying game-based learning in the classroom has been reported to result in higher student motivation[5,7−9,24] or better student performance.[10,11] However, application of game-based learning will not automatically improve student achievement, as some authors report that they did not observe a higher student performance associated with game-based learning.[5,6,8,9,24]

Beyond using a mere game-based approach, a more recent concept, gamification, accentuates "the use of game design elements in non-game contexts".[25] This includes application of elements such as leaderboards, badges, levels, challenges, or rewards in an educational context. Several examples of gamification have been reviewed in the scientific literature.[26] However, given the limited amount of data so far, the potential of gamification for higher education is not obvious.

One obstacle that hinders the use of game-based learning in higher education might be the development effort that is required. In this context, Westera et al. proposed a framework for reducing the development effort without compromising the advantageous side effects of game-based learning by reducing design complexity (e.g., by focusing on the key design elements and by omitting any unnecessary content).[5] According to their results, they were able to reduce the production ratio (study load in hours divided by production effort in hours) from the previous 1:600 down to 1:25.

The development and the evaluation of a game-based learning approach for teaching the topic "phase equilibria" in higher chemical education is presented in the work at hand. First, the conceptual design and implementation of the approach are described. Second, the results obtained in an anonymous student survey are presented. And finally, it was investigated whether the game-based learning approach assisted in enhancement of student motivation and improvement of student achievement.

dx.doi.org/10.1021/ed5001697 | *J. Chem. Educ.* XXXX, XXX, XXX−XXX

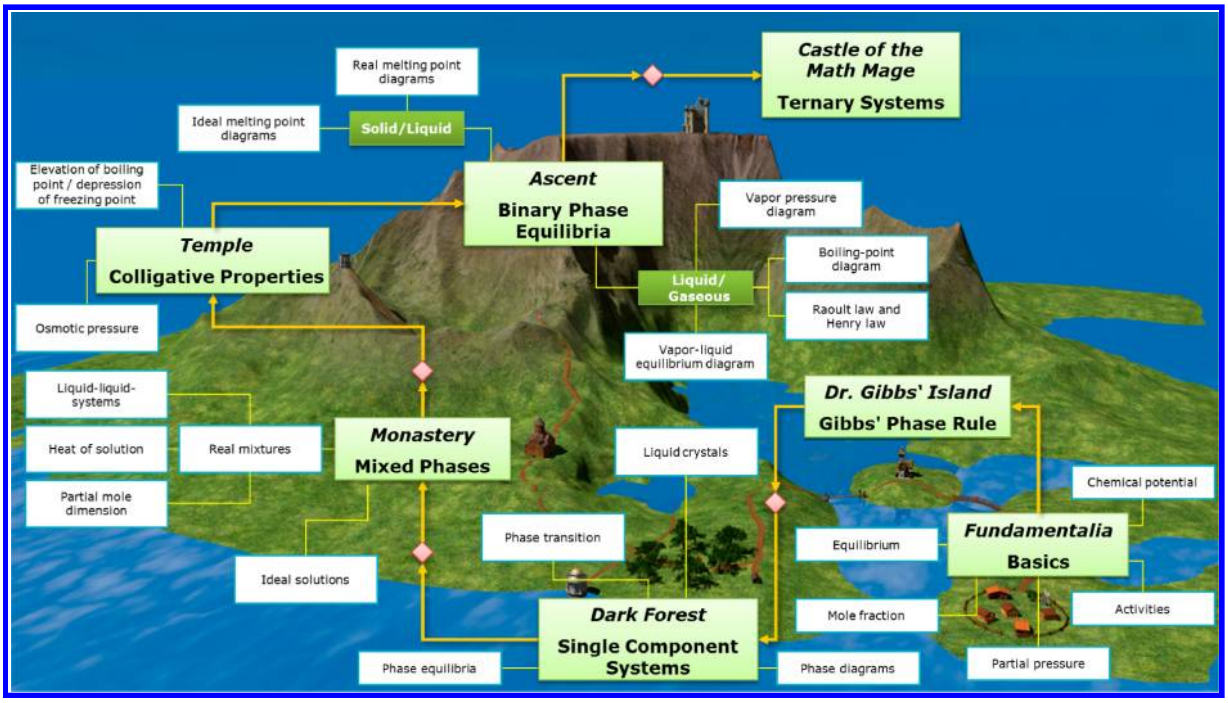

Figure 1. Illustration of the learning pathway as well as the three-dimensional graphic landscape enclosing the study content. Each box represents a chapter of the study content. Diamonds depict points where students had to enter a password in order to proceed.

MATERIALS AND METHODS

Student Population

The approach was tested with 30 students in the module "models of physics and physical chemistry", which is a compulsory part of the bachelor degree programs "Applied Chemistry (B.Sc.)" and "Business Chemistry (B.Sc.)" at the Fresenius University of Applied Sciences (Idstein, Germany). Participation in the game-based learning approach (further also referred to as the "game" within this article) was voluntary for all students and not compulsory to complete the module. However, students who abandoned the game during the term were not allowed to re-enter the game because participation was tied to the adherence to a team that was formed at the beginning of the term (see below).

Game-Based Approach

Students were arranged into teams of 4−5 at the beginning of the term. Prior to the game, students were first grouped in performance quintiles based on their achievement in the prior term by the responsible academic supervisor. Subsequently, the students were given the opportunity of arranging teams in the first compulsory lecture in the term. In order to achieve a balanced performance level between groups, only one student from each performance quintile was allowed in each team and each team was comprised of students of all performance quintiles. The teams then worked through the study content of the physical chemistry part of the lecture (main topic: phase equilibria). The study content was structured into separate chapters, with each chapter containing a set of digitized learning material (lecture screencasts, lecture notes, online tests for self-assessment, weblinks, and references for further reading). In the past, students reported having difficulties in following the topic of phase equilibria in a traditional lecture because they were not able to reproduce the content at home. The digitized learning material allowed students to study the material outside the lecture hall at their own speed. As the material was made available to students at the beginning of the term, students were also able to prepare themselves better for further discussing open issues in the lecture. We hypothesize that these lecture screencasts are an integral part of any such game-based learning approach.

Lecture screencasts were recorded using screen recording software (Camtasia, Techsmith[27]). Recorded lectures were postprocessed with the Camtasia software, uploaded on an in-house media server and made available for students via the University e-learning platform ILIAS.[28] Online tests for self-assessment (mainly numerical questions where a specific number had to be calculated, but also single and multiple choice questions) were also implemented by using the ILIAS learning platform.

The individual chapters were then arranged in order to yield a "learning pathway" that was integrated in a three-dimensional graphic landscape (Figure 1) which was entitled "the island of phases". Each chapter also contained a picture of the location on this "island" and part of a background story that framed the whole learning path (Figure 2). Graphic design was implemented using the three-dimensional design and animation software package Maxon Cinema 4D Studio.[29]

At the beginning of the term, students were able to access only the first chapters (referred to as "first level"). In order to pass to the next "level", they had to pass a short oral or written examination held by the responsible academic professor (symbolized by the diamonds in Figure 1). In each examination (excluding the final in-game examination, described below), one randomly selected team member competed as representative for the whole team. Thus, it was not possible for one student to take the whole team through all examinations, as it was not apparent in advance which team member had to pass the exam. Using this random selection mode should ensure that all team members had to prepare themselves equally for each examination.

Figure 2. Sample chapter structure. From top to bottom: background story (A) and picture of the location in the three-dimensional landscape (B), embedded lecture screencasts (C), and further learning content such as weblinks, references, digitized lecture notes, and download version of lecture screencast as well as online tests for self-assessment (D).

The examinations usually had a length of 10 min and consisted of solving one problem that represented the level in question. Generally, the problem consisted of a numerical question where a specific value had to be calculated combined with a conclusion that had to be drawn from this value. The observations of the authors show that students often seem to have difficulties in developing and applying this skill to physical chemistry problems. Confronting the students with such types of problems in the examinations in the game-based learning approach should yield more opportunities for students to reflect on this skill and give the lecturer the opportunity to support students in developing or improving this skill, for example, by discussing the outcome of such an examination exercise with the student group.

For these examinations, students were only allowed to use a pocket calculator. Additional material (such as a reference book with thermodynamic tables and values) was provided by the academic professor if required for solving the question. In one exemplary first level examination (dealing with fundamental terms of phase equilibria and the equilibrium constant K), students were asked to calculate whether the formal reaction of benzoic acid with hydrogen and nitrogen to aniline and carbon dioxide is a thermodynamically spontaneous reaction or not. In order to solve this problem, they had to apply the Gibbs–Helmholtz equation. However, they first had to calculate values for the reaction enthalpy and reaction entropy from standard enthalpies of formation and standard entropies of the reactants, which they had to retrieve from the tables in a reference book provided for the examination.

After successful passing of the examination, students obtained the level password and also received bonus points that were added to the result of the final written examination at the end of the term. This form of examination resembles the "strategic performance feedback" methodology proposed by Westera et al.[5] and was chosen to give the participants personal and immediate feedback on their progress without the need to track and evaluate each individual question in the online tests.

In the final in-game examination, the whole student group was examined and had to work together in order to successfully pass the examination. This last examination took about 1 h per group and aimed at probing three different student skills that were also required in order to pass the final module examination at the end of the term (see also Supporting Information for more information about the three different exercises/games described in the following). The skills probed ranged from mere memorization of facts to higher-order learning skills such as knowledge transfer and problem solving. Students first had to demonstrate that they are able to memorize the most important facts of the topic "phase equilibria" and to stay concentrated. For this, we designed a memory-like game where the whole student group had to "play" against the academic supervisor and to identify a maximum of correct "question–answer" pairs (Figure 3).

Figure 3. Representative picture of the "Chemory" game where corresponding pairs of questions and answers had to be identified.

Second, students had to show that they are able to reliably operate the pocket calculator in stress situations, simulating the situation in the final examination. For this, the whole student group had to calculate the mole fractions in a three component mixture (based on different components, volumes, and a given temperature) and to correctly position a counter in the ternary phase diagram (Figure 4) faster than the academic supervisor.

Finally, the students had to demonstrate their problem solving skills. For this, they had to precisely identify the two mole fractions in a binary eutectic mixture for a given equilibrium melting temperature. The correct mole fractions indicated the right way through a labyrinth the students had to cross in order to reach the end of the examination (Figure 5).

The number of accessible bonus points increased with each level in order to reflect the increasing complexity of the topic. In total, students could obtain 35 points (out of a total of 200 points) of the final examination. This exceeds previously reported bonus point reward systems.[9] If the chosen student passed the exam, then the whole team obtained the password and bonus points. Otherwise, the exam had to be repeated at a later point in time.

Additionally, puzzles were integrated at certain locations in order to verify if students were able to transfer the acquired knowledge and to apply it to new problems. One example ("the alchemy puzzle") is shown in Figure 6.

The game-based learning approach supplemented the existing lecture, which was held in parallel and for which attendance also was not compulsory.

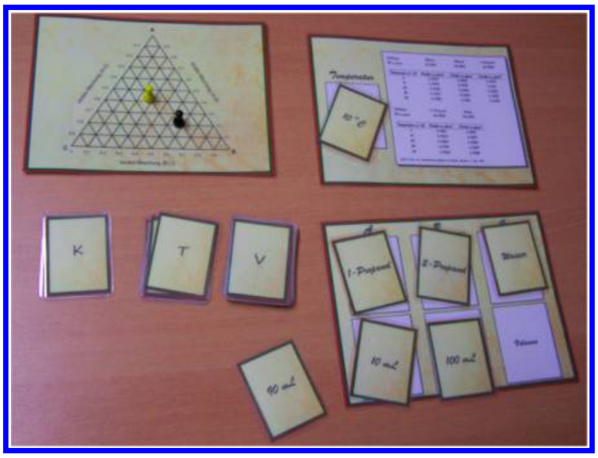

Figure 4. Representative picture of the "three-component game". Three components, their corresponding volumes and a temperature were randomly drawn and the correct mole fractions had to be calculated with subsequent positioning of a counter on a ternary phase diagram.

Student Evaluation

At the end of the term, one week before the final examination, students were given the opportunity of assessing their perception of the game-based learning approach by means of an anonymous and voluntary survey. The questions in the survey first probed the extent to which students utilized the online learning material by asking for an estimate of the time spent by each student. Second, the students had the opportunity of rating given statements concerning the different elements of the game by using a four-point Likert scale (1 = strongly agree, 2 = agree, 3 = disagree, 4 = strongly disagree). Third, they were asked to assess the quality of each element used on a six-point Likert scale (from 1 = grade "A" to 6 = grade "F"). Additionally, they were asked to assess the necessity of the individual elements in the game on a four-point Likert scale (1 = indispensable, 2 = nice to have, 3 = rather unnecessary, 4 = completely unsuitable). Finally, they were given the opportunity to add free text comments on the most positive and negative aspects of the game.

Student Performance

Student performance was evaluated according to the examination regulations of the degree programs. Each student had to attend written examinations in physics (without the game-based approach, total of 100 points) and physical chemistry (applying the game-based approach, total of 100 points). The results of both examinations were totalled to give the final result of the module (maximum of 200 points). Each student was allowed to obtain full points in the final examination itself, irrespective of participation in the game. For the physical chemistry part, bonus points from the game were added to the result of the examination. Students could obtain a maximum of 35 bonus points for the physical chemistry examination upon successful completion of the game. The sum of examination result and bonus points in physical chemistry was cut off at 100 points and then added to the result of the final physics examination to give the total result.

Student achievement was compared both between the physics and the physical chemistry result in the winter term 2013/14 (n = 23) as well as with the results obtained in the same examination in the winter term 2012/13 (n = 23).

■ RESULTS

Student Participation

All 30 students in the degree programs Applied Chemistry (B. Sc.) and Business Chemistry (B. Sc.) participated in the game.

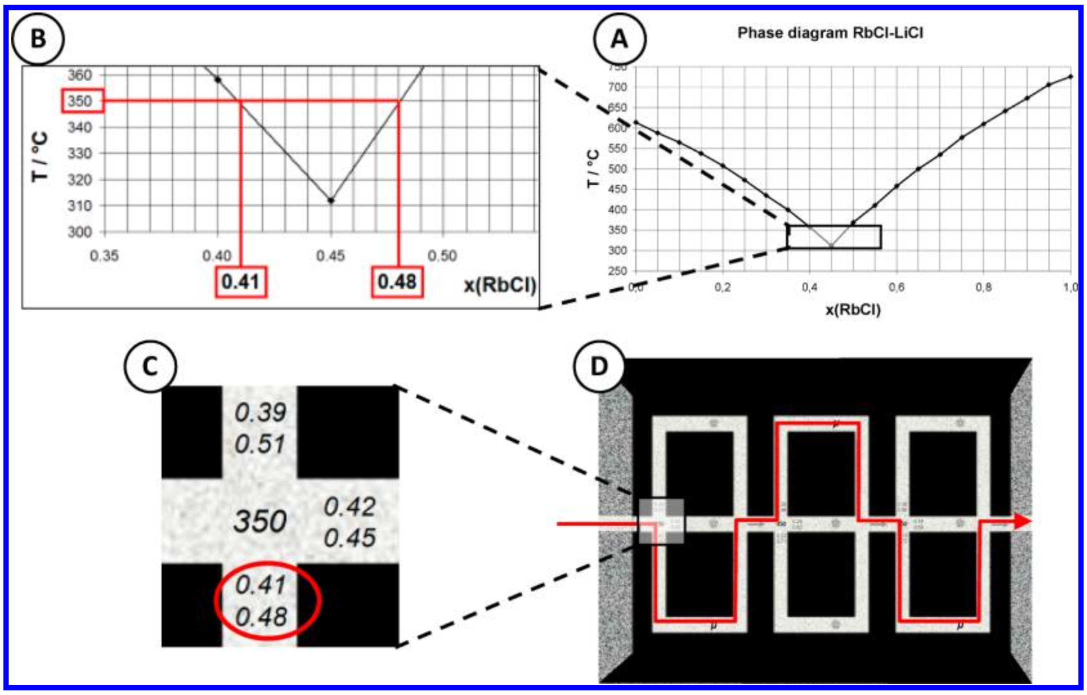

Figure 5. Description of problem solving skill probing in the final examination. In a given phase diagram (A), students had to identify the different mole fractions for a component for which a given temperature (in this case: 350 °C) represented the melting temperature (B). The mole fractions identified indicated the right route (C) through a labyrinth (D) the students had to cross in order to finish the examination (see red path in part D of the figure).

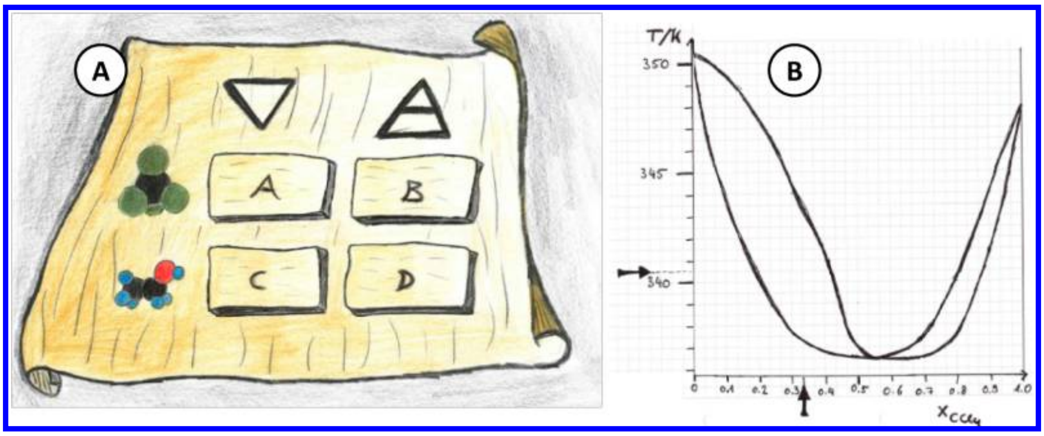

Figure 6. Example of a puzzle that was integrated in the learning pathway. (A) In this puzzle, students had to recognize the exercise of calculating the mole fraction of the two components tetrachloromethane and ethanol (depicted by the two space-filling models on the left-hand side) in the liquid and the vapor phase (depicted by the two pictograms on the top which represent the alchemical symbols for water and air). The calculated mole fractions had to be entered in the matrix (A–D) and should total 100%. (B) Phase diagram that had to be used as basis for the calculation. The arrows indicated the initial composition of the liquid phase as well as the temperature at which calculation should take place. The puzzle was implemented in an online test where students were asked to enter the correct numerical values for A–D, including some tolerances on the answers (the correct answers to be entered in the matrix would be in the following range: A, 0.08–0.10; B, 0.23–0.27; C, 0.32–0.36; D, 0.31–0.35).

Of these, 25 (83%) finished the game at the end of the term (Figure 7).

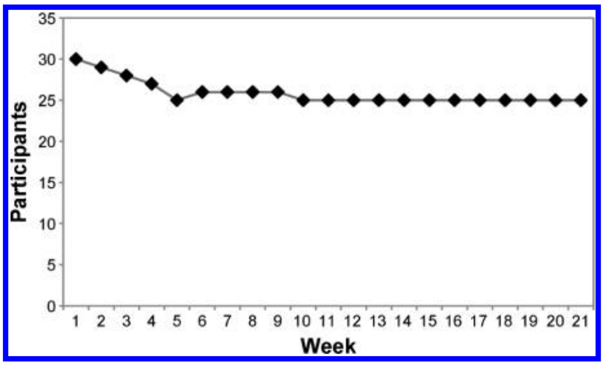

Figure 7. Number of students participating in the game as a function of time.

The drop-out-rate was highest in the first weeks after starting the game. After this phase, participation remained at a constant level until the end of the term (Figure 7). The increase in week 6 is due to a student who started at a later point in time. The participants who quit in the early phase (until week 5, see Figure 7) all reported a lack of time as reason for abandoning the game.

Evaluation of Game-Based Approach by Students

Student estimation of workload showed a significant increase of study time compared to a traditional lecture format. Students participating in the game-based learning approach reported that they spent 4.6 ± 3.4 h per week on average for self-study. According to their estimation, this represents a factor of 2.9 ± 1.2 more study time compared to the physical chemistry lecture in the previous term. This lecture comprises the same workload (as measured in credit points or study hours).

The results also seem to indicate that female participants spent more study time in the game than male participants (Table 1). This concerns both the learning time per week as well as the relative amount of time spent learning physical chemistry as compared to other modules in the term. In these examples, p values indicate a significant difference between male and female participants. Both the learning time per week compared to the physical chemistry lecture of the previous term and the number of times students watched the individual lecture screencasts on average (each lecture was watched approximately two times) did not show a significant difference between male and female participants, according to p values calculated.

However, these results should be taken with caution. Given the small number of total participants there is no certainty of the statistical significance of the data obtained. The results might indicate a difference in behavior between female and male participants, but a larger sample size would be necessary in order to verify the results.

Table 1. Student Assessment of Workload

Survey Questions	Female[a] (n = 11)	Male[a] (n = 15)	Total[a] (n = 26)	p Value[b]
How many hours per week did you spend learning physical chemistry on average?	6.5 ± 4.1	3.1 ± 1.4	4.6 ± 3.4	0.029
How many times more did you spend learning compared to other lectures in the term?	4.3 ± 1.2	2.7 ± 0.8	3.3 ± 1.3	0.004
How many times more did you spend learning compared to the physical chemisty lecture in the previous term?	3.3 ± 1.4	2.5 ± 0.9	2.9 ± 1.2	0.103
How many times did you watch the lecture screencasts on average?	2.1 ± 0.5	2.1 ± 0.8	2.1 ± 0.6	0.932

[a]Figures represent mean ± standard deviation. [b]The p value was calculated using a two-tailed Student's t-test assuming unequal variance between male and female participants.

The assessment of the game-based learning approach shows that both motivational aspects (bonus points, graphic illustrations) as well as facilitation of learning (better understanding, better preparation for examination, facilitation of learning by lecture screencasts) seemed to be the most important aspects for the students (Figure 8). However, only 17% of students agreed or strongly agreed that the traditional lecture, script, and bonus points would be sufficient.

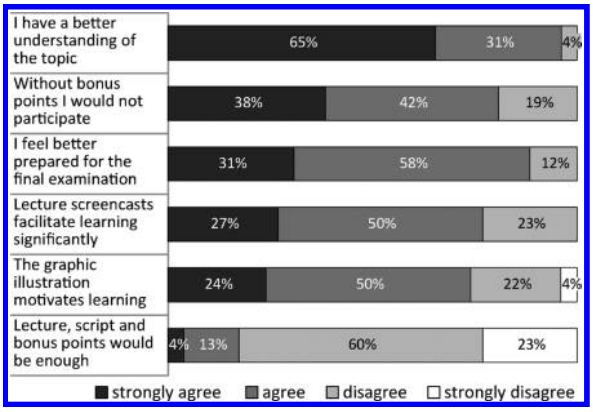

Figure 8. Results of student assessment of different aspects of the game-based learning approach ($n = 26$). No significant difference was observed between female and male participants.

Average grades for the individual elements of the game-based learning approach in the quantitative evaluation by the students were better than 3 ("C") (Table 2). Most importantly, all students unequivocally rated the lecture screencasts as the most important elements, underlining our initial assumption that this element specifically would facilitate learning for students significantly as it gives students the opportunity to study at their own speed and to repeat listening to a lecture, which is not possible in the traditional lecture. Male participants seemed to evaluate the game-based learning approach slightly better (1.6 ± 0.5) compared to female participants (2.0 ± 0.6). Male participants also had a slightly higher preference for the background story (1.5 ± 0.6) compared to female participants (2.1 ± 1.0). However, differences between male and female participants for both the overall evaluation and the assessment of the background story were not significant, as indicated by the p value. The evaluation of lecture screencasts, online tests and graphic illustrations also did not show a significant difference between female and male participants (Table 2).

Table 2. Result of Student Evaluation of Quality of the Individual Elements

Elements	Female[a] ($n = 11$)	Male[a] ($n = 15$)	p Value[b]
Overall evaluation	2.0 ± 0.6	1.6 ± 0.5	0.100
Lecture screencasts	1.9 ± 0.8	1.6 ± 0.5	0.291
Online tests	2.4 ± 0.7	2.3 ± 0.4	0.579
Graphics	2.1 ± 0.9	2.1 ± 1.0	0.915
Background story	2.1 ± 1.0	1.5 ± 0.6	0.137

[a]Figures represent mean ± standard deviation (1 = grade "A" to 6 = grade "F"). [b]The p value was calculated using a two-tailed Student's t-test assuming unequal variance between male and female participants.

Students were also asked to evaluate the necessity of individual elements of the game on a four-point Likert scale (Figure 9). Bonus points, lecture screencasts, and online tests were rated as indispensible elements of the overall approach, in line with the results showed in Figure 8. The importance of group-based learning was rated somewhat lower but is still seen as an important element. Graphics and background story were not seen as being indispensable by the majority of students but still rated as "nice to have" elements not considered as being unnecessary.

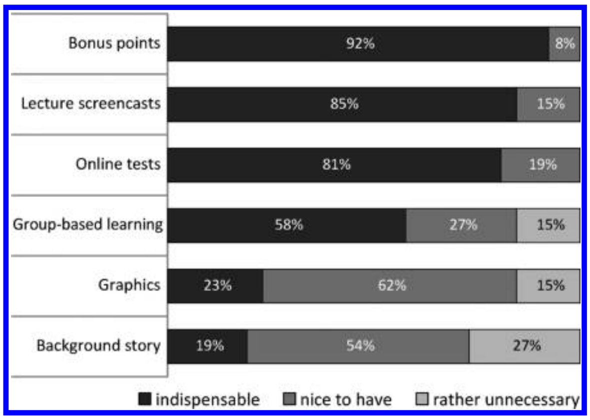

Figure 9. Student assessment of the necessity of the individual elements in the game-based learning approach (four-point Likert scale). No significant difference was observed between female and male participants.

Additionally, students were asked to list the most positive and negative aspects of the game-based learning approach. The total number of positive aspects mentioned (74 comments) was larger than the total number of negative aspects mentioned (43 comments). The most important positive aspects mentioned were bonus points (15), teamwork (10), motivation to continuous learning (10), lecture screencasts (8), online tests for self-assessment (6), facilitation of learning (6), better organization of learning time (5), and the background story (2).

The most important negative aspects mentioned were the oral examinations (6), puzzles (6), technical issues such as low compatibility with different mobile devices (6), errors in online tests (3), high consumption of time (2), graphic illustration (2), and the background story (2).

Production Ratio Is Lower Than in Other Studies Reported So Far

The production effort for the "island of phases" comprised a total of about 640 h, given that two people developed the system starting from scratch within 8 weeks (with a weekly estimated work load of 40 h). The study load was approximately 80 h (mean value of 4.6 h per week for all students and term duration of 18 weeks). Based on these numbers, we obtained a production ratio of 1:8. This is significantly lower than the production ratio reported by Westera et al.[5] (1:25) and seems to underline the importance of focusing on the most important elements when developing such a learning scenario. However, it is important to note that it was not necessary for us to develop a dedicated technical infrastructure as we implemented our approach using the pre-existing learning platform ILIAS. In addition, it was not necessary to involve an external graphic designer as the corresponding expertise was available in house (DZ).

Table 3. Comparison of Student Performance between the Previous Cohort, A, and the Cohort Using the Game-Based Learning Approach, B

Group	Physical Chemistry	Physics	Total
Cohort A[a] (Winter Term 2012−2013)	65 ± 16	53 ± 22	118 ± 34
Cohort B[b] (Winter Term 2013−2014)	72 ± 21 (exam: 47 ± 20) (bonus points: 26 ± 9)	51 ± 16	123 ± 32
p Value[c]	0.216 (with bonus) 0.002 (only exam)	0.688	0.643

[a]Figures represent mean ± standard deviation for the previous cohort. [b]Figures represent mean ± standard deviation for the cohort using the game-based learning approach. [c]The *p* value was calculated using a two-tailed Student's *t*-test assuming unequal variance between male and female participants.

No Unequivocal Conclusion on Student Achievement Possible

In order to examine whether the game-based learning approach results in better student achievement in the final examination at the end of the term, we compared the results obtained with the student cohort using the game (cohort B) with the results obtained with the student cohort in the previous winter term (cohort A) that did not rely on the game. In cohort B, overall student achievement was observed to slightly improve compared to cohort A (Table 3). Despite this slight improvement (118 ± 34 points from 200 for cohort A versus 123 ± 32 points from 200 for cohort B), and although the failure rate decreased from 26% (6 out of 23 students) in cohort A to 13% (3 out of 23 students) in cohort B, statistical analysis of the data revealed no significant difference in the overall examination result (Table 3).

It is interesting to note that students performed better in the physics part of the final examination (where no game-based learning was applied): students achieved on average 51 ± 16 points in the physics examination (comparable to the result of the previous year), whereas in the physical chemistry part of the final examination, only 47 ± 20 points was achieved (lower than the result in the previous year). Statistical analysis revealed that this difference in the performance in the final examination is significant. Applying game-based learning, therefore, did not seem to improve student achievement in the final examination itself. This finding has also been reported by other groups.[6,8] However, in our approach, students also did not seem to learn less about the topic than with a traditional approach.

■ DISCUSSION

The high participation rate of 100% at the beginning of the term and the low drop-out rate (83% of participants completed the game) seem to show that students were motivated to follow such a game-based learning approach during the whole term. The motivation of the student group is also corroborated by the high weekly learning time, both for female and male participants (Table 1), and the results from the survey (Figure 8). This would also be in line with the findings of other groups who reported an increase in student motivation upon using a game-based learning approach.[5,7−9,24]

According to our results, there seem to be some differences concerning the usage and the appreciation of the game-based learning concept between female participants and male participants. Female students spent more learning time in the game (Table 1). As this difference does not stem from the number of times the lecture screencasts were viewed (both female and male students viewed them on average two times), we hypothesize that female students either studied the lecture screencasts more intensely or spent more time working on the online tests for self-assessment. Interestingly, this higher usage does not seem to correlate with the appreciation of the game-based learning approach, as male students had a tendency to rate the different aspects of the game slightly better than female participants (Table 2). However, given the small overall number of participants, these results should be viewed with caution. Additionally, we are not aware of any studies that differentiate usage or appreciation of a game-based learning approach according to gender.

Overall student achievement seemed to slightly improve as the failure rate in the final examination was reduced. However, given the relatively small student population, we cannot exclude statistical variation. Further observations in subsequent student cohorts are required to increase the amount of data available. The observation that cohort B performed lower in the final examination itself than cohort A (Table 3) might be explained with the results obtained in previous studies where introduction of game elements such as tasks and achievements[8] or competition[6] to an educational context did not improve higher-order thinking skills (knowledge transfer) but rather memory of the content.[6] As the final examination also required a significant amount of knowledge transfer, our findings are in line with these observations. This explanation is corroborated by the fact that students mentioned game aspects where higher-order thinking was required (such as oral examinations, puzzles, and errors in online tests) rather as negative aspects. However, it is not possible to link this finding with the final examination in the game as described above as individual student performance in the three different parts of the examination ("chemory", "three-component game", and "labyrinth") was not tracked individually for each student. Moreover, it was surprising that students performed rather poorly in the "Chemory" game in the final in-game examination (the student teams won only one game out of 12), although this challenge was rather associated with memory skills than with higher-order thinking skills.

A second explanation would be that students prioritized their learning effort before the final examination to the part of the lecture where they did not have the opportunity to achieve bonus points. As they could obtain a maximum 100 points for the physical chemistry part of the examination (the sum of examination result and bonus points for physical chemistry was cut off at 100 points), they would increase the probability of passing the final examination by concentrating their learning effort on the physics part of the module. However, it is not possible to verify this hypothesis based on the data available. Therefore, we cannot conclude with certainty the effect of game-based learning on overall student achievement, although our results might point toward a slight improvement.

Not surprisingly, errors in online tests were mentioned as negative effects in the game. However, these errors could represent a measure for the intensity with which students dealt with the corresponding test: the correct answers for online tests were accessible to students after the first test run. However, only those students who tried to solve the test by themselves (instead of only entering the correct answer to pass the test) were able to identify these errors. Although this aspect was not analyzed in detail, some of the students in question showed a better performance in the final examination. However, more research effort has to be spent on this aspect to verify if there is a correlation between study intensity and examination result, as has been reported by Liberatore.[11]

The high production ratio of 1:8 shows that it is possible to develop a game-based learning approach for higher chemical education with limited resources (two people developed and integrated the illustrated approach within two months) by focusing on the most important elements, as has been proposed by Westera et al.[5] The most important elements implemented in our case were reward (bonus points), community (teamwork), levels (access to new learning content after successfully passed examination), the graphic illustration of the learning pathway, and the background story. According to student feedback (Figure 9), it seems that graphic illustration and background story could also be omitted if they constitute a time or budget constraint in development. However, we suggest that they should be integrated where possible as students appreciated their usage.

CONCLUSION

Game-based learning can contribute to stimulation and increase in student motivation in higher chemical education, as shown in our case for undergraduate chemistry students in physical chemistry. However, we cannot conclude without ambiguity if there is a positive correlation between application of a game-based learning approach and student achievement in the final examination, although the reduced overall failure rate in the module might be interpreted as a slight increase. We strongly encourage further research to analyze this aspect in more detail.

As to the development of such an approach, it seems important to identify the most critical challenges and content upfront to ensure a game development that is neither too time consuming nor too cost intensive in the implementation. Our results show that a production ratio of 1:8 for a game-based learning approach, including graphic illustration and a background story, is rendered possible by following such an approach.

The game was successfully implemented for an undergraduate physical chemistry lecture. However, we cannot rule out that the additional learning time for physical chemistry came at the expense of learning time for other lectures in the same term. We therefore think that implementing such an approach in more than one lecture in the same term requires significant coordination between the different modules as it represents a time-consuming activity for the students.

Furthermore, we cannot make any conclusions on the long-term effect of such an approach into the teaching and learning of physical chemistry. In this context, several questions need to be investigated in further research.

First, it is not clear how far motivation of the student cohort investigated will further develop in the course of their studies. We hypothesize that our approach is best suited for first and second year undergraduate students in order to ease the transition from secondary school to university and help them to become familiarized with the process of explorative learning. For more experienced students, less game-design elements and more "real-life" examples should be appropriate. Further research should investigate whether there is any relationship between the effectiveness of game-based learning and the seniority of students.

Second, we cannot rule out a potential wearout process in future student cohorts and, thus, cannot conclude whether the game-based learning approach described will also work in future. We hypothesize that integration of the lecture screencasts and the possibility of earning bonus points will also be motivating aspects for future student generations, thus assuring the sustainability of our approach. We think that it will be helpful for the scientific community to discuss the sustainability of such game-based learning approaches upon repeated application, particularly when the development effort is kept in mind.

Finally, it would be of interest to investigate whether such an approach could be a substitution of the traditional lecture, not only an extension as in our approach. We could envisage applying our game-based learning approach in the context of an inverted classroom scenario, with lecture screencasts serving as compulsory study material in order to prepare for the live lecture. However, making the approach compulsory would not only require significant amendment of the examination regulations but would also impose obligatory time constraints on students. Although we think that a voluntary participation in such a game-based learning approach better suits the need of our students, we would strongly encourage further research to investigate whether such integration of game-design and technology in chemistry learning and teaching could be equivalent to the traditional lecture.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information includes ready-to-use material for the three exercises ("learning games") in the final examination ("chemory", "three-component game", "labyrinth") as well as a description of how to use them. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors would like to thank the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) for financial support in the context of the ANKOM initiative.[30] Thanks also to Catherine Croghan (Fresenius University of Applied Sciences) for proofreading.

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