Effective Orbital Mechanics Knowledge Training Using Game Mechanics

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***Abstract*—Computer games consist of game mechanics (GMs) that encode a game's rules, principles and overall knowledge thus structuring the gameplay. These knowledge rules can also consist of information relevant to a specific learning content. This knowledge then is required and trained by periodically executing the GMs during the gameplay. Simultaneously, GMs demonstrate the encoded knowledge in an audiovisual way. Hence, GMs create learning affordances for the learning content thus requiring its application and informing about the underlying principles. However, it is still unclear how knowledge can directly be encoded and trained using GMs. Therefore, this paper analyzes the GMs used in the computer game Kerbal Space Program (KSP) to identify the encoded knowledge and to predict their training effects. Also, we report the results of a study testing the training effects of KSP when played as a regular game and when used as a specific training environment. The results indicate a highly motivating and effective knowledge training using the identified GMs.**

I. Introduction

Computer games consist of *game mechanics* (GMs) that define a game's rules, encode the underlying principles and hence determine a player's capabilities inside of a particular computer game [1]. GMs can be distinguished in *player-bound* and *game-bound* GMs. Player-bound GMs allow a player to interact with the game world [2] being created and controlled by the game-bound GMs [1]. Game-bound GMs also create a game's goals and challenges. The *interaction* between the two constructs creates a game's gameplay and informs a player about the effects and correctness of the performed actions. The encoded principles and rules are trained and mastered [3], [4] during the gameplay due to repetition [5]. Thus, GMs and their interaction possibilities create *learning affordances* for the encoded knowledge by requiring a knowledge's application and informing learners about the underlying principles [6], [7].

The ultimate goal of using computer games for training purposes is to achieve a total internalization of the encoded knowledge allowing for a training transfer from the training environment to a real world context [8], [9]. This can be achieved by using GMs as they present, demonstrate, and require the learning content in an audiovisual way that supports the *compilation of mental models* [10], [11]. Mental models are mental representations of a particular knowledge that allow for an internal visualization, problem solving, and knowledge transfer [12], [13]. In addition, GMs can create similar requirements for the knowledge application to the targeted real world context thus facilitating a training transfer [14] as mental models are situation-specific.

So far, no clear model describing the actual process of encoding knowledge in GMs has been defined. One approach suggests the *Learning Mechanics-Game Mechanics* model that combines pedagogy, learning, and entertainment [15], [16]. However, this model still has a lot of uncertainties concerning the concrete encoding of knowledge in GMs and their respective training effects. Therefore, we propose the *Gamified Knowledge Encoding* model (*GKE*) that maps the learning content in form of game rules to interacting GMs [17]. We define *gamified knowledge encoding* as the process of implementing, demonstrating, and requiring specific knowledge in a gamified training environment for the purpose of achieving a transfer-oriented knowledge training using GMs.

Our contribution: In order to validate the GKE, it is necessary to analyze the training effects of GMs that encode a particular knowledge as their rules. Also, it is critical to test the GKE for its predictability allowing for an analysis of defined GMs and predicting their training effects. The study presented in this paper aims to close this gap by 1) identifying relevant GMs encoding the learning content and 2) analyzing the efficiency of knowledge training using the identified GMs. For this purpose, this paper examines the learning outcome of playing the computer game *Kerbal Space Program* (KSP) [18]. The game indicates a strong potential of educating its players in the field of orbital mechanics and other spaceflight related knowledge, such as the ideal rocket equation [19]. This knowledge represents the grounding principles every aerospace student has to understand. Hence, facilitating and improving the training of this learning content can result in a better performance in later courses of an aerospace program's curriculum.

In particular, the game's core GMs are analyzed in respect to the encoded knowledge. This is done using the GKE to identify GMs that require or demonstrate the application of the orbital mechanics knowledge. Subsequently, KSP is implemented as a training environment in an optional class-based orbital mechanics tutorial for aerospace students. Finally, the survey analyzes the joy of use of utilizing KSP as a learning environment by examining its motivational aspects.

This study is guided by the following hypotheses: H1) Players learn new knowledge about orbital mechanics by playing KSP. H2) Utilizing KSP as a training environment to visualize and verify spaceflight problems results in an increased training outcome. H3) Utilizing KSP as a training tool results in a higher motivation to practice the encoded knowledge.

The paper begins with an overview over game-based training and introduces KSP. Then, the paper presents the concept of the GKE and identifies the GMs that encode the orbital mechanics in KSP. Subsequently, the study design is described and the results are presented. The paper concludes with a discussion of the results and an outlook for future research.

II. Related Work

A. Game-based Training

Computer games fulfill the conditions for optimal learning [20] by requiring a *repetitive* application of the encoded knowledge throughout the gameplay [5]. As the game goals increase in difficulty to compensate a game's training effect, a player's *pre-existing* knowledge is required. Aside from providing clear goals and *immediate feedback*, this difficulty increase is important for maintaining the flow-inducing aspects by keeping players challenged throughout the gameplay [21], [22]. Flow mainly influences enjoyment and performance of gaming action thus also affecting and increasing a player's *motivation* for knowledge training [23].

Research has shown that complex sets of human skills [24], such as skills of surgery [25], communication [26], [27], collaboration [28], [29], and leadership [30], [31] can be practiced by playing computer games. Computer games can also be used to train human abilities such as cognitive flexibility [32], spatial resolution [33] and spatial visual attention [34]. The immersive effect of computer games allows players to experience moral problems or to face ethical questions [35]. Hence, computer games can be even utilized as a training environment for moral decision making [36].

The knowledge training capabilities of computer games have lead to the emergence of serious games [37]. These special games are developed for an educative purpose [38] that goes beyond the usual entertaining approach of computer games [39]. In the case of complex, expensive or even dangerous learning content, serious games and simulations represent good training environments. They provide a safe environment where learners have not to fear bad consequences and where even death is reversible [40].

B. Kerbal Space Program

KSP, in the current version 1.4.4, is a regular computer game that allows its players to manage a space agency and to conduct spaceflight missions in a fictional solar system. KSP demonstrates spaceflight in a vivid and engaging way and helps its users to develop a thorough understanding of common spaceflight terms and procedures. Players are able to construct (see Figure 1) and launch their own spacecrafts, to perform orbital maneuvers, to fly to other celestial bodies,

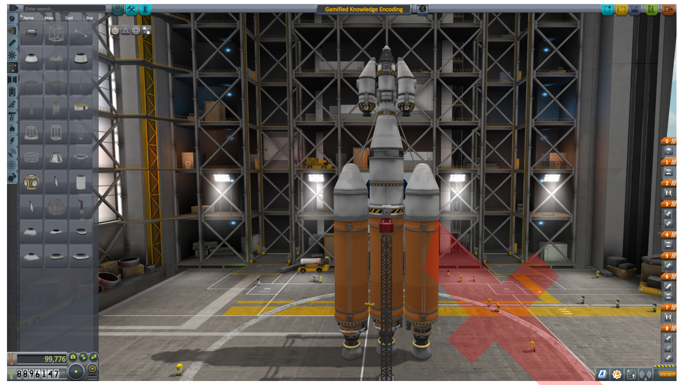

Fig. 1. Assembling a rocket in KSP: players can choose from a broad selection of various parts (left) and attach them to their spacecraft (center). KSP provides an interface to adjust a rocket's staging sequence (right).

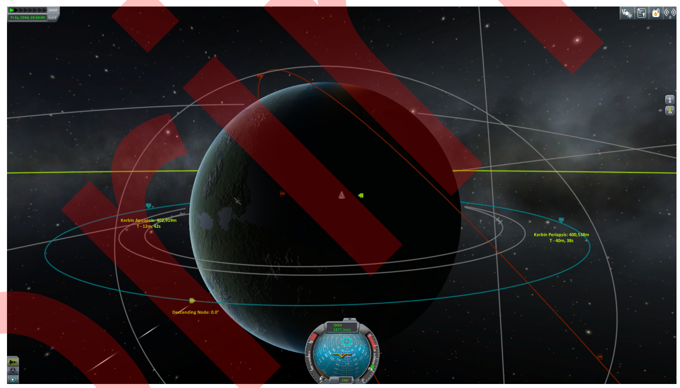

Fig. 2. The orbital map displays essential information about the trajectories of all flying spacecraft. This screen allows players to develop an understanding of an orbit's characteristics. Here, the apoapsis, periapsis, and inclination is shown.

and to land on them. KSP implements a realistic physics-engine that allows for the application of spaceflight related equations, such as the ideal rocket equation and the calculation of transfer orbits [19]. Although the game can be played by 'trail and error', developing an in-depth understanding of orbital mechanics allows players to construct more efficient spacecraft and/or to perform more efficient maneuvers.

As KSP is a simulation game, players can apply their spaceflight knowledge by directly controlling their virtual spacecraft. By changing a spacecraft's attitude and executing a burn, the current trajectory can be changed thus performing orbital maneuvers. KSP is normally played using the keyboard but also supports other input devices like joysticks and gamepads. In order to effectively play the game, the user interface provides players with important information, such as the velocity, the altitude and the heading. Furthermore, players can switch to an orbital map that displays the current trajectory and orbital parameters, such as the apoapsis, the periapsis and the inclination (see Figure 2).

Although KSP is an open world exploration game that allows its players to set their own goals, players can also decide to play in career mode. This mode requires them to manage their very own space agency by fulfilling contracts to earn currencies mandatory for unlocking new technologies and expanding the infrastructure.

III. Gamified Knowledge Encoding

In order to create effective learning affordances, a gamified training environment must require the application of the learning content and simultaneously inform the users about the underlying principles. The GKE utilizes the interaction between a game-bound and a player-bound GM to create effective learning affordances [17]. This is achieved by requiring the periodical application of the learning content using player-bound GMs. They then interact with game-bound GMs demonstrating and visualizing the underlying principles and providing learners with immediate feedback about the correctness of their inputs.

The actual encoding of the knowledge is achieved by segmenting it into clear rules that can be mapped to GMs. Hence, the sets of knowledge rules are used as the underlying principles that define and structure the gameplay of the resulting training system. The selection of the encoded knowledge rules, i.e., the *moderation* of the level of abstraction, and the design of the GMs, i.e., the *mediation* of the encoded rules, can be used to demonstrate the learning content in an intuitive way. Depending on the design of the GMs and the moderation of the level of abstraction, the gamified training environment can range from an accurate simulation to a very intuitive presentation of the knowledge.

The knowledge presentation using the GKE can even achieve *implicit learning* causing a subconscious acquisition and training of complex knowledge [41]. This requires an adjustment of the moderation and mediation in such a way that the resulting gameplay intuitively demonstrates the underlying principles. As a result, players subconsciously internalize the knowledge by repetitively interacting with the game and observing the results of their actions [42].

In the end, the GMs that encode a particular knowledge create a gamification metaphor for it. A gamification metaphor represents the learning content inside of a computer game, requires its application, provides immediate feedback about the correctness of a user's inputs, and demonstrates the underlying principles.

IV. Game Mechanics of Kerbal Space Program

KSP consists of seven core GMs, of which three are player-bound and four are game-bound GMs. KSP also provides other GMs, such as currencies, a tech-tree, upgradeable buildings, and contracts, that are utilized to implement a career mode and are not encoding any orbital mechanics related knowledge. Working with the GKE, the core GMs of KSP are analyzed in respect to the encoded knowledge to predict their training outcome when executed during the gameplay. This analysis follows the concept of identifying human skills that are required by GMs [24].

In general, KSP encodes the *ideal rocket equation* and the *orbital mechanics* knowledge [19]. The ideal rocket equation

Fig. 3. Inside of the vehicle assembly screen, KSP displays technical information about each individual spacecraft part. This allows players to develop an understanding for the technical information and to compute the performance of their vehicles.

is used to determine a spacecraft's performance and the orbital mechanics include the laws of Newton and Kepler defining the properties and characteristics of an orbit. Hence, the orbital mechanics allow for a calculation of spaceflight maneuvers like the computation of a maneuver needed to fly from low Earth orbit to the Moon. Also, the encoded physical principles define and explain a rocket's ascent phase and the challenges of it.

A. Player-bound Game Mechanics

GM01: Assembly of own spacecraft. As Figure 1 depicts, this feature allows players to construct spacecraft out of a collection of parts (GM06). Aside from designing spacecraft, users are also required to assemble a rocket that is powerful enough to overcome the drag of the atmosphere and the gravitational pull of the planet. Designing such a capable rocket requires a basic understanding of a typical rocket's ascent phase and the concept of separating a rocket into different stages. Also, GM01 requires the application of the ideal rocket equation as changing a rocket's mass, payload or amount of fuel affects its performance. Thus, this GM helps the users to visualize and to apply these knowledge rules.

GM02: Controllable spacecraft. This GM allows for a direct control of the spacecraft to perform orbital maneuvers with them. This GM allows for the application of the encoded orbital mechanics rules (GM05).

GM03: Spacewalk. Players are able to conduct spacewalks with their astronauts and to control them from a third person perspective. As astronauts are similarly affected by the natural laws, this GM also allows for the application of the encoded orbital mechanics rules (GM05).

B. Game-bound Game Mechanics

GM04: Explorable solar system. The solar system consists of a star and seven planets, of which four are orbited by at least one moon. During the gameplay, players can visit those celestial bodies with their spacecraft and try to land on them. Hence, this GM provides players with potential goals they can fulfill.

GM05: Realistic physics engine. This GM simulates the underlying laws of nature and determines the behavior of the spacecraft based on the rules of orbital mechanics.

GM06: Technical data. This GM provides technical data for each individual part a spacecraft can consist of thus allowing for a calculation of a spacecraft's performance as Figure 3 displays. Internally, this data is also used by the physics engine to compute the results of a player's actions. For example, the ideal rocket equation requires the mass of the fully fueled spacecraft, the empty spacecraft, and the specific impulse of the used engine to determine its performance.

GM07: Orbital map. As Figure 2 depicts, the orbital map displays the current trajectory and orbital parameters of a user's spacecraft. This game-bound GM not only provides users with a visual feedback about the outcomes of their orbital maneuvers, but is also putting the orbital elements into context. In this way, this GM visualizes the effects of the encoded knowledge rules and allows learners to compile a mental model for them.

C. Gamification Metaphors

GMs encoding a particular knowledge can be seen as gamification metaphors representing the learning content inside of a computer game. Thus, KSP provides two gamification metaphors: 1) the ideal rocket equation gamification metaphor and 2) the orbital mechanics gamification metaphor.

The ideal rocket equation gamification metaphor consists of GM01, GM05, GM06 and GM07. GM01 is used to require the actual application of the ideal rocket equation by assembling new spacecraft out of the available spacecraft parts. These parts have unique technical properties (GM06) and hence determine a spacecraft's performance (GM05). The achieved performance then can be tried out in the simulation phase. It allows players to launch their spacecraft and follow their trajectories on the orbital map (GM07) which ultimately demonstrates the effects and validity of a player's spacecraft designs.

The orbital mechanics gamification metaphor consists of GM02, GM05 and GM07. Players are required by GM02 to execute orbital maneuvers which follow the grounding physical principles (GM05). For instance, by executing a prograde burn, i.e., a burn into the flight direction of the spacecraft, players can increase the altitude of the spacecraft's orbit. The effects of these spaceflight maneuvers are then visualized and demonstrated using GM07 that automatically adjust the spacecraft's displayed trajectory based on the player's inputs.

V. Methods

A. Experimental Design

The study was designed to examine 1) the *educational effects* of playing KSP as a *regular game* and 2) the *training effects* when used as a *training environment*. Also, the study assessed the *joy of use* of using KSP as a training environment during class. In order to complete the two individual main goals, the study was split into *two phases* of which each focussed on one of the goals.

TABLE I
Overview of the Session Assignments used in the training course

Phase	Session	Goal
1	1	Achieve an orbit around *Kerbin*
1	2	Fly to the *Mun*
2	1	Delta-v calculation and rocket staging
2	2	Delta-v calculation, rocket staging, and thrust to weight ratio
2	3	Computation of orbital maneuvers Changing apoapsis, periapsis and inclination
2	4	Geostationary orbits: Calculating the orbit's altitude Deploying a spacecraft in this orbit using a Hohmann transfer orbit

1) Phase 1: Regular Computer Game: Phase 1 took place during the first two weeks of the lecture period and had to be finished before orbital mechanics were presented and discussed in the lecture. This phase consisted of two 90-minute sessions which took place in two consecutive weeks. At the beginning of the first session, the participants were introduced to KSP's general gameplay and the game controls. Subsequently, the participants were given specific tasks (see Table I) they had to complete.

The assignment of the first week required the participants to design a spacecraft and to launch it into an orbit around the home planet Kerbin, i.e., an Earth-like planet in this fictive universe. The second week's assignment challenged the participants to design a new spacecraft and fly it to the Mun, i.e., the moon that orbits Kerbin. Both tasks required no in-depth knowledge about the knowledge encoded in KSP and could have been completed just by playing the game. However, having a basic knowledge would have facilitated the completion of both goals.

During the study's first phase, the advisors were not allowed to assist the participants in a direct way or to provide them with information about orbital mechanics. However, the participants were allowed to do research on the internet to find useful information about orbital mechanics or spaceflight procedures. Although this was an option, doing research on the internet was not mandatory as the participants were also allowed to play the game by 'trial by error'. Furthermore, they were allowed to continue playing the game between the two lab sessions as assembling a spacecraft in KSP is a very time intensive task, especially for new KSP players.

This experimental design ensured that the participants' knowledge gain on orbital mechanics was mainly caused by playing KSP. This design also allowed for an analysis of KSP's motivating effects to search for additional information to play the game more efficiently.

2) Phase 2: Training environment: Phase 2 began after orbital mechanics were discussed in the lecture. During this phase, the participants were required to practice their orbital mechanics knowledge with similar assignments to the ones used in the traditional class-based training (see Table I). However, in contrast to the paper-based assignments, the KSP group was utilizing the game to visualize and validate the assignments and their self-obtained computational results.

The second phase consisted of four 90-minute sessions. Each session began with the discussion of the previous task's sample solution and the presentation of a new assignment. After initial questions were answered, the participants began to solve the assignments and had the chance to discuss further questions with the advisors. These four sessions took place every other week to align with the progress in the lecture and in the traditional class. Also, this design was implemented to give the participants enough time to visualize and solve the assignment in KSP. The assignments were made available via the university's learning management system to allow participants to solve the tasks in the case they missed one of the lab sessions.

B. Measures

1) Effectivity: The effectivity of KSP as a learning environment during *Phase 1* was measured with a pre-test post-test experimental design. Both knowledge assessment tests were designed to be of equal difficulty. They consisted of 9 questions assessing a participant's orbital mechanics and spaceflight knowledge.

The effectivity of KSP as a training environment during *Phase 2* was measured with a final knowledge assessment test consisting of 3 complex orbital mechanics assignments. Students who visited the optional traditional class were invited to take part in this test to form a *control group*. The participants were able to obtain a maximum of 30 points in the test.

2) Joy of Use: At the end of *Phase 1*, qualitative feedback concerning the joy of use was obtained with a short questionnaire consisting of the following questions:

1) Have you enjoyed playing KSP?
2) Have you learned new facts about orbital mechanics during the gameplay?
3) Have you done additional research to understand a specific rocket part or to complete the assignments?
4) Have you done additional research to build more efficient rockets or to solve the assignments in a more efficient way?

At the end of *Phase 2*, the joy of use was measured with a short questionnaire consisting of the following questions:

1) Have you enjoyed playing KSP?
2) Have you learned new facts about orbital mechanics during the gameplay?
3) Have you used KSP to visualize or test certain facts presented in the lecture?
4) Was the KSP-based class interesting?
5) Do you like to see KSP being implemented as a training environment in future classes?
6) Were the KSP-based assignment more engaging than traditional paper-based assignments?
7) Do you think that KSP is a useful tool to visualize and test spaceflight related problems and facts?

Question 4 to 7 use a 5-point Likert scale (1 = completely disagree, 5 = fully agree).

TABLE II
RESULTS OF THE PRE-TEST AND POST-TEST SPACEFLIGHT KNOWLEDGE ASSESSMENT IN PHASE 1 (NEW KSP PLAYERS, $n = 11$)

Test	Mean Result (%)	SD	Min	Max
Pre	43.69	23.31	8.33	71.67
Post	70.12	13.70	42.04	93.70

C. Technology

The participants played the free demo version of KSP (based on version 0.18.3) on their own computers. In contrast to the game's full version, the demo only provided a limited selection of spacecraft parts which made the design process simpler for new players. Participants who owned the full version were allowed to use it instead of the demo. Using the own computers was critical as most of the assignments were too complex to be visualized and completed during a single lab session.

D. Participants

The KSP-based training session was offered as an alternative optional class to the participants of the lecture "Introduction Into Spaceflight" held at the University of Würzburg. All participants were enrolled as freshmen in the Bachelor of Aerospace Informatics program. The curriculum of the lecture also offered a traditional paper-based optional class which was used as a control group to compare the training effects of both methods at the end of Phase 2. In total, thirteen participants (12 males, 1 female) volunteered to take part in the study. All of these participants had previous experience with computer games, 7 participants reported to play computer games on a regular basis, and 2 participants had played KSP before.

VI. RESULTS

A. Educational Effects of Playing KSP

1) Phase 1: The two participants who reported to have played KSP before were removed from the results of Phase 1. Their previous gameplay potentially resulted in a compilation of a mental model for the encoded knowledge.

The remaining new KSP players ($n = 11$, 1 female, 10 males) achieved a mean result of 43.69% ($SD = 23.31$) in the pre-test knowledge assessment test. In the post-test, they scored a mean result of 70.12% ($SD = 13.70$) as Table II and Figure 4 display. Thus, they achieved a mean knowledge gain of 26.43% ($SD = 15.97$). A paired t-test revealed a significant improvement ($t(10) = 5.49$, $p < 0.001$) in the participants' knowledge with a strong effect size ($CohensD = 1.65$). Aside from the two game sessions in the lab, the new KSP players played the game for additional 207.27 minutes ($SD = 98.09$) based on self-report. Calculating Pearson's correlation ($cor = 0.76$, $p = 0.007$) revealed a significant correlation between the time played and the player's knowledge gain.

However, some participants reported to be frequent computer game players, thus it is necessary to analyze their playtime in detail. Five of the eleven new KSP players were frequent computer game players and achieved a mean knowledge gain of 29.22% ($SD = 17.17$). They played the

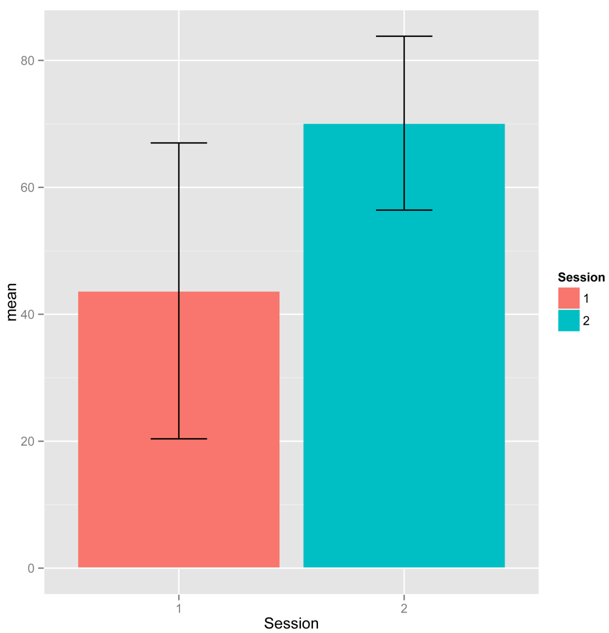

Fig. 4. Comparison of the mean results between pre-test and post-test spaceflight knowledge assessment results of the new KSP players ($N = 11$).

TABLE III
OVERVIEW OF THE FINAL KNOWLEDGE ASSESSMENT TEST RESULTS AT THE END OF PHASE 2

Group	n	Mean Points	SD	Min	Max
All participants	21	12.81	7.41	1	26
KSP Group	10	14.00	8.93	1	26
Control Group	11	11.73	5.93	2	21
KSP players	4	14.75	4.65	10	21
Non-KSP players	7	10.00	6.19	2	17

game for additional 216 minutes ($SD = 109$) on average between the two lab session. The remaining six participants yielded a mean knowledge gain of 24.11% ($SD = 16.13$). These participants played KSP for additional 200 minutes ($SD = 97.98$) on average between the two sessions. A two sample t-test revealed no significant difference ($p = 0.623$) between both groups thus indicating no moderating effect of previous computer game experience on the knowledge gain.

2) Phase 2: The final knowledge assessment test was completed by 21 students (3 females, 18 males) of which 10 belonged to the KSP group. Hence, three participants dropped out between the beginning and the end of Phase 2. Four of the control group students reported to have independently played KSP. As the overview Table III displays, the *KSP group* achieved a mean result of 14 points ($SD = 8.93$) and the *control group* scored an average result of 11.73 points ($SD = 5.93$). A two sample t-test was applied, but no significant difference between the two groups could be found ($p = 0.5$).

The KSP group had the greatest difference in the performance with a range of 25 points. One participant of the KSP group achieved the worst result of the test, four participants of the KSP group achieved a result above 20 points and two of them even achieved a result above 24 points. The best participant of the control group achieved a result of 21 points and was a KSP player based on self-report. The subset of the control group students, who reported to have independently played KSP, achieved a mean result of 14.75 points ($SD = 4.65$). The seven remaining students, who never played KSP, achieved a mean result of 10 points ($SD = 6.19$). A one way ANOVA was applied to compare all three groups, but no significant difference was found ($F = 0.75$, $p = 0.49$).

B. Joy of Use

1) Phase 1: All thirteen participants agreed that they have enjoyed playing KSP (Q1) and that they have learned new facts about orbital mechanics (Q2). Ten of them also reported that they did some research on orbital mechanics to develop a better understanding of the encoded spaceflight knowledge thus allowing them to complete the two tasks given during Phase 1 (Q3). Nine of them reported that they did some research to build more efficient rockets or to complete a task in a more efficient way (Q4).

2) Phase 2: All ten participants agreed that they have enjoyed playing KSP (Q1) and that they have learned new facts about orbital mechanics (Q2). Nine of them reported that they utilized KSP to test and/or to visualize facts they have learned in the lecture (Q3). The question (Q4), if the KSP tutorial was interesting, received an average rating of 4.4. The question (Q5), if they like to see KSP as a learning environment in future training sessions, received an average rating of 4.4. The question (Q6), if the KSP related tasks were more engaging than the regular assignments, received an average rating of 4.1. The final question (Q7), if KSP is a useful tool to visualize problems related to orbital mechanics, received an average rating of 4.4.

VII. DISCUSSION

A. Educational Effects of Playing KSP

1) Phase 1: The results of Phase 1 revealed a significant knowledge gain about orbital mechanics during the participants' first hours of playing KSP. Also, the study has revealed a strong correlation between the playtime and the knowledge gain. This strong educational effect can be explained with the general structure of KSP and the resulting first gameplay hours of new players. KSP is a spaceflight simulator that features a steep learning curve as players have to develop a basic understanding of the encoded underlying physical principles when they play the game for the very first time. In order to reach space and enter an orbit with one of their self-designed spacecraft, they need to develop a basic understanding of the two main knowledge packages encoded in KSP's gamification metaphors. Only when new players have developed a basic understanding of the encoded knowledge rules, they can successfully launch a virtual rocket into an orbit around the virtual home planet. While new players are progressing towards this goal, they subconsciously internalize the encoded knowledge by observing the results of their actions. As a result, KSP potentially achieves implicit learning [41], [42].

This knowledge is required with every subsequent launch of a space-going mission thus players periodically practice the application of this knowledge and gain expertise with it [5], [43]. Hence, the results indicate a compilation of mental models of the knowledge encoded in KSP's gamification metaphors [10], [11].

Therefore, *hypothesis H1 is supported* as KSP successfully educated new players in orbital mechanics and simultaneously provided an environment allowing for a training of this specific knowledge.

2) Phase 2: The test results of phase 2 revealed no significant difference in the overall knowledge of the KSP group in comparison to the control group. Thus, the results indicate that KSP has a similar training effect to traditional training methods using paper-based assignments. However, the three best results in the test were scored by participants of the KSP group. Moreover, some of the control group participants have independently played KSP and achieved a mean result that lies above the overall mean result. This outcome indicates a potential positive impact of playing KSP on the understanding of orbital mechanics. Playing KSP helped the students to visualize the effects of orbital mechanics which resulted in the compilation of mental models. These mental models finally allowed for an effective knowledge transfer between the training sessions and the final knowledge assessment test.

The relative low mean result and the huge range in the results of the KSP group participants can be explained by the fact that the second phase of the study suffered under several issues. The date for the lab sessions overlapped with another optional course which resulted in a drop of the participants during the first and second lab session. In addition, the participants had to prepare themselves for upcoming midterm exams during the second half of this phase. This resulted in a greatly reduced amount of participants in the lab during the last two sessions. In the end, it is possible that the best three participants of the KSP group were present until the very end of Phase 2. The participants who achieved a result below average potentially have never visited one of the Phase 2 lab sessions or tried to solve the assignments at home. If this assumption is true, then KSP would greatly enhance the training outcome. Unfortunately, due to the requirements of the aerospace informatics department, a completely anonymous test was written, thus no validation of this assumption is possible.

Therefore, *hypothesis H2 cannot be verified* as there is no clear evidence for a better training outcome on the side of the KSP group. Nevertheless, the results indicate a positive impact of playing KSP on the training outcome that can be beneficial for future aerospace classes.

B. Joy of Use

At the end of both phases, all participants reported that they have enjoyed playing KSP and that they have developed a better understanding of spaceflight and orbital mechanics. They additionally reported that they were inspired to search for additional knowledge about orbital mechanics by playing KSP. Finally, they used KSP to visualize spaceflight problems that were discussed in the lecture to develop a better understanding of them.

The participants enjoyed the optional KSP-based class and would like to utilize the game as a training environment in future courses to visualize problems. Furthermore, the participants reported that using KSP as a tool to verify the self-obtained computational results was enjoyable and more interesting than solving only paper-based assignments.

All these results combined revealed a strong joy of use of KSP as a training environment. Therefore, *hypothesis H3 is supported*.

C. Overall Effectivity

In conclusion, KSP yielded a similar training outcome to the traditional paper-based training method, but achieved a higher motivation to tackle the training assignments. Hence, KSP represents a very effective training method that not only allows learners to visualize spaceflight-related principles but also to validate their computational results. The visual demonstration allows for the compilation of mental models for the learning content that ultimately allow for a training transfer. Lastly, the results validate our concept of the GKE that creates gamification metaphors acting as learning affordances by mapping knowledge rules to interacting GMs. Also, the GKE's training predictions and the overall concept of transfer-oriented knowledge training using GMs were validated.

VIII. Conclusion

This paper first analyzed the structure of KSP using the GKE and identified relevant GMs that encode the orbital mechanics knowledge as their rules thus creating gamification metaphors for the learning content. By executing the player-bound GMs to interact with the game, players are required to apply the encoded knowledge thus training it due to repetition. The game-bound GMs provide players with immediate feedback and demonstrate the underlying principles. This visualization and training process leads to a compilation of mental models for the learning content that allow for a knowledge transfer from the game to a different context.

Subsequently, this paper presented a study analyzing the training effects of playing KSP as a regular game and implementing it as a training environment in a class-based knowledge training. The study revealed that KSP effectively educates players in orbital mechanics and even motivates them to search for additional information to successfully and efficiently play the game. When used as a training environment, KSP achieves a similar training outcome to a traditional paper-based training method. However, the participants reported a high motivation to tackle the training assignments. Hence, knowledge training using KSP yields a higher learning quality. In addition, knowledge training using KSP allows for a visualization of spaceflight relevant problems that would otherwise be hard to demonstrate due to the high costs and risks of a real world demonstration. Thus, KSP can be recommended as a supplementary training environment for grounding aerospace courses that are aimed at the education of orbital mechanics. Finally, the results of the present study validated the GKE's potential to predict the training effects of GMs and the concept of transfer-oriented knowledge training using game mechanics.

Future research is needed to validate the findings and to examine the training effects of KSP when used as a training environment under more controlled conditions. Also, future research is needed to further analyze the training effects of GMs and to validate the process of gamified knowledge encoding.

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