Better Learning with Gaming: Knowledge Encoding and Knowledge Learning Using Gamification

Inaugural-Dissertation
zur Erlangung der Doktorwürde der
Fakultät für Humanwissenschaften
der
Julius-Maximilians-Universität Würzburg

Vorgelegt von
Sebastian Oberdörfer
aus Berlin-Spandau

Würzburg
2020

Erstgutachter: Professor Dr. Marc Erich LATOSCHIK
Zweitgutachterin: Professorin Dr. Silke GRAFE
Dritter Prüfer: Professor Dr. Sebastian VON MAMMEN

Betreuer: Professor Dr. Marc Erich LATOSCHIK

Vorgelegt am: 21. JUNI 2019
Tag der Disputation: 14. DEZEMBER 2020

Acknowledgements

I would like to thank Marc Erich Latoschik for having given me the chance and the support to find my way into academia. In general, I would like to thank my supervisors Marc Erich Latoschik, Silke Grafe, and Sebastian von Mammen for providing me with fantastic feedback throughout the years. Lastly, I would like to thank Johannes S. Hewig for his great help in completing my PhD process.

For moral support and scientific as well as technical help, I would like to thank Andrea Bartl, Andreas Knote, Anna Riedmann, Chris Zimmerer, David Heidrich, Fabian Unruh, Florian Niebling, Jan-Philipp Stauffert, Kristof Korwisi, Marietta Herrmann, Martin Fischbach, Philipp Schaper, and Sophia Steinhäußer. You were there for me even in the darkest times. Thank you!

For further moral support, I would like to thank my parents and my grandpa. My grandpa always asked me what I was doing, but never quite understood.

Finally, I would like to thank the teams of the Chair for Human-Computer Interaction and Chair for School Pedagogy of the University of Würzburg.

Abstract

Computer games are highly immersive, engaging, and motivating learning environments. By providing a tutorial at the start of a new game, players learn the basics of the game's underlying principles as well as practice how to successfully play the game. During the actual gameplay, players repetitively apply this knowledge, thus improving it due to repetition. Computer games also challenge players with a constant stream of new challenges which increase in difficulty over time. As a result, computer games even require players to transfer their knowledge to master these new challenges. A computer game consists of several game mechanics. Game mechanics are the rules of a computer game and encode the game's underlying principles. They create the virtual environments, generate a game's challenges and allow players to interact with the game. Game mechanics also can encode real world knowledge. This knowledge may be acquired by players via gameplay. However, the actual process of knowledge encoding and knowledge learning using game mechanics has not been thoroughly defined, yet. This thesis therefore proposes a theoretical model to define the knowledge learning using game mechanics: the Gamified Knowledge Encoding. The model is applied to design a serious game for affine transformations, i.e., GEtiT, and to predict the learning outcome of playing a computer game that encodes orbital mechanics in its game mechanics, i.e., Kerbal Space Program. To assess the effects of different visualization technologies on the overall learning outcome, GEtiT visualizes the gameplay in desktop-3D and immersive virtual reality. The model's applicability for effective game design as well as GEtiT's overall design are evaluated in a usability study. The learning outcome of playing GEtiT and Kerbal Space Program is assessed in four additional user studies. The studies' results validate the use of the Gamified Knowledge Encoding for the purpose of developing effective serious games and to predict the learning outcome of existing serious games. GEtiT and Kerbal Space Program yield a similar training effect but a higher motivation to tackle the assignments in comparison to a traditional learning method. In conclusion, this thesis expands the understanding of using game mechanics for an effective learning of knowledge. The presented results are of high importance for researches, educators, and developers as they also provide guidelines for the development of effective serious games.

Zusammenfassung

Computerspiele stellen attraktive, spannende und motivierende Lernumgebungen dar. Spieler erlernen zu Spielbeginn die grundlegenden Spielregeln und wenden dieses Wissen während des Spielablaufs an. Dadurch wird das dem Spiel zu Grunde liegende Wissen durch Wiederholung geübt und verinnerlicht. Durch einen konstanten Fluss an neuen Herausforderungen, die in ihrer Schwierigkeit ansteigen, müssen Spieler das Wissen auf neue Szenarien übertragen. Innerhalb eines Computerspiels sind Spielmechaniken für eine Anwendung als auch Demonstration des Spielwissens verantwortlich. Die Spielmechaniken regeln den Spielablauf, in dem sie die Spieleraktionen definieren, die virtuelle Umgebung generieren und die Herausforderungen des Spiels festlegen. Das in den Spielmechaniken kodierte Wissen kann jedoch auch der realen Welt entstammen. In diesem Fall entwickeln Spieler Kompetenzen, die später auch in der Realität Anwendung finden können. Das Kodieren von Wissen in Spielmechaniken und der damit einhergehende Lernprozess wurde allerdings noch nicht genau theoretisch erfasst. Diese Dissertation versucht diese Forschungslücke zu schließen, indem ein theoretisches Model der Wissenskodierung in Spielmechaniken entworfen wird: das Gamified Knowledge Encoding. Dieses Model wird sowohl für das Design einer Lernanwendung für das Wissen der Affinen Transformationen, GEtiT, als auch zur Vorhersage von Lerneffekten eines Computerspiels, Kerbal Space Program, herangezogen. In einer Usability-Studie wird sowohl die Anwendbarkeit des Modells für ein effektives Spieldesign als auch das Gesamtdesign von GEtiT bewertet. Das Lernergebnis, das beim Spielen von GEtiT und Kerbal Space Program erzielt wird, wird in vier weiteren Nutzerstudien überprüft. Die Studien validieren den Einsatz des Gamified Knowledge Encoding Models zur Entwicklung von computerspielbasierten Lernumgebungen und die Vorhersage von Lerneffekten. GEtiT und Kerbal Space Program erzielen ein ähnliches Lernergebnis bei einer höheren Motivation im Vergleich zu einer traditionellen Lernmethode. Als Endergebnis erweitert das präsentierte Forschungsprojekt das generelle Verständnis über die Verwendung von Spielmechaniken für ein effektives Lernen. Die präsentierten Ergebnisse sind von großer Bedeutung für Forscher, Pädagogen und Entwickler, da sie auch Richtlinien für die Entwicklung effektiver Serious Games hervorbringen.

Contents

1 Introduction

The truth is this: in today's society, computer and video games are fulfilling genuine human needs that the real world is currently unable to satisfy. Games are providing rewards that reality is not. They are teaching and inspiring and engaging us in ways that reality is not. They are bringing us together in ways that reality is not. – Jane McGonigal (2011)

1.1 Motivation

Learning new knowledge is a challenging task that requires a high degree of motivation, self discipline, and hard work (Ur, 1996). The challenge even increases when the learning content is highly complex and can neither be demonstrated nor comprehended easily. When failing to quickly understand a certain learning content, learners often experience a high degree of frustration. Aside from the knowledge's complexity, a learner's personal attitude is another critical element. A strong personal interest in a particular knowledge positively affects a learner's motivation to practice it. In general, the more challenging and unappealing a learning process seems, the harder it becomes to continue with it. Therefore, finding a way to render learning processes more exciting and more engaging could greatly increase the learning outcome. Learners would then be highly motivated to tackle the learning process more intensively.

Conditions for optimal learning are a *high motivation* to tackle learning exercises that *require preexisting knowledge* as well as a *repetitive application* of the learning content and provide *immediate feedback* (Ericsson, Krampe, and Tesch-Römer, 1993). Well designed computer games automatically fulfill these conditions. Computer games are highly engaging virtual environments (VEs). They provide players with clear goals, a constant stream of new challenges, and immediate feedback which can induce the state of flow (Csikszentmihalyi, 1990; McGonigal, 2011). Flow is a central construct that mainly influences enjoyment and performance of gaming action (Weibel and Wissmath, 2011) and hence knowledge learning. Computer games encode certain knowledge in their game mechanics which is learned and mastered during the gameplay (Gee, 2007). Gameplay results from the interaction of player-bound game mechanics with game-bound game mechanics (Oberdörfer and Latoschik, 2018a). Game-bound game mechanics create the VE as well as a game's challenges (Adams and Dormans, 2012). Player-bound game mechanics provide a player's abilities inside a computer game and allow for an interaction with the game-bound game mechanics (Sicart, 2008). Internally, game mechanics encode a game's underlying principles and knowledge in form of game rules (Adams and Dormans, 2012). Players must develop an understanding for the knowledge encoded in a game's game mechanics to successfully interact with the VE. As players repetitively execute the player-bound game mechanics, they practice the knowledge during their gameplay and receive immediate feedback about the correctness of their actions. Also, computer games' powerful graphics engines can visualize complex information and are even used to demonstrate complex scientific problems (Lv, Tek, Da Silva, Empereur-mot, Chavent, and Baaden, 2013). Thus, computer games can simulate and visualize any knowledge in any form (Perry and DeMaria, 2009). Therefore, computer games are optimal learning environments for the game-based knowledge. They keep players motivated, require preexisting knowledge, provide immediate feedback about the correctness of a player's approach, and achieve a constant repetition of the learning content.

The computer game's educational potential was not only supported by research but also led to different forms of *gamification of learning*. For the remainder of this thesis, gamification of learning is used as an umbrella term comprising game-based learning (Merchant, Goetz, Cifuentes, Keeney-Kennicutt, and Davis, 2014), gamification of learning systems (Seaborn and Fels, 2015), e.g., learning management systems, and serious games (de Freitas and Liarokapis, 2011). Game-based learning utilizes regular computer games for knowledge learning, e.g., practicing surgery skills (Rosser, Lynch, Cuddihy, Gentile, Klonsky, and Merrell, 2007) and learning about the Alaska Native culture while playing *Never Alone* (E-Line Media, 2016). Gamification implements game mechanics in non-gaming environments to increase their attractiveness (Deterding, Dixon, Khaled, and Nacke, 2011). This mostly results in the utilization of feedback game mechanics that reward users with points or other virtual items. Serious games have an educational aspect and are not solely developed for entertainment (Anderson, McLoughlin, Liarokapis, Peters, Petridis, and de Freitas, 2009; de Freitas and Liarokapis, 2011). They feature the same characteristics as regular computer games which are combined with pedagogical elements to create engaging and vivid learning environments (Charsky, 2010). In this way, players remain engaged even when the game content goes beyond the normal entertaining purpose.

Game mechanics have not yet been thoroughly tested for their applicability and utility to educate specific knowledge. Also, no model clearly explaining the knowledge encoding in game mechanics has been defined so far. A first approach is the *Learning Mechanics-Game Mechanics* model that combines pedagogy, learning and entertainment (Arnab, Lim, Carvalho, Bellotti, de Freitas, Louchart, Suttie, Berta, and De Gloria, 2015; Moser, dos Santos, and Corcini, 2017). However, this model still has a lot of uncertainties concerning the actual encoding of learning contents and the effects of using game mechanics for educational purposes. Other models, such as the *Serious Games Modeling Environment*, only provide a technical methodology for designing serious games without describing the educational effects of individual game mechanics (Tang, Hanneghan, and Carter, 2013). To overcome these shortcomings and to use the gamification of learning effectively, the present research project tackles four main research goals. It is critical to 1) understand how the interaction between game mechanics leads to an acquisition of knowledge. Also, it is important to 2) understand how this learning process is structured and to 3) define the process of encoding knowledge in game mechanics. Finally, it is essential to 4) analyze the effectiveness of a training transfer from a serious game to a real world context. Training transfer describes the effect when knowledge training in one context leads to an increased performance in applying the knowledge in a different context (Dede, Jacobson, and Richards, 2017). Completing these four goals allows for a proposal of a model that not only represents a guideline for the development of serious games, but also allows for a structured analysis of existing games in respect to their learning effects.

This thesis analyzes the knowledge encoding in game mechanics as well as the resulting learning effects when executing these game mechanics from a theoretical standpoint. Based on these results, the *Gamified Knowledge Encoding* model is proposed (Oberdörfer and Latoschik, 2018a). The Gamified Knowledge Encoding defines how game mechanics encode and hence assist the learning of specific knowledge. This model is applied to develop a serious game targeting the education of affine transformations, i.e., *GEtiT* (Oberdörfer, Heidrich, and Latoschik, 2019), and to predict the learning effects of a serious game, i.e., *Kerbal Space Program* (Take-Two Interactive, Inc, 2011–2019). Subsequently, the learning effects of both games are analyzed to validate the theoretical assumptions of the model. Finally, this thesis takes a look at the negative sides of using game mechanics in the context of gambling to not only encode, but also to hide specific gambling-related knowledge. The thesis ultimately draws a comprehensive conclusion from the underlying research to expand the definition of the gamification of learning. The scientific results presented in this thesis should be of high interest for researchers, developers, and educators because they provide guidelines for the development of effective and engaging serious games.

1.2 Objectives

The overall research goal of the thesis, i.e., to understand the gamification of learning, was broken down in the following main research questions (RQs):

RQ1: How can knowledge be acquired and practiced using a computer game?

RQ2: How do game mechanics demonstrate and require the application of knowledge during the gameplay?

RQ3: How can (abstract) knowledge be directly encoded in computer games using game mechanics?

RQ4: How effective is knowledge learning using game mechanics?

1.3 Structure

Chapter 2 provides an analysis of related work and embeds the thesis into the context of the current state of research. Chapter 3 presents a first attempt to trace the knowledge application requirements in a computer game's game mechanics. Chapter 4 extends the theoretical analysis and proposes the Gamified Knowledge Encoding model. This model defines how knowledge can be encoded in game mechanics and how the encoded knowledge is learned during the gameplay. Chapter 5 discusses the development of a serious game, i.e., *GEtiT*, using the Gamified Knowledge Encoding. Chapter 6 analyzes the serious game's usability to validate the game design capabilities of the theoretical model. Chapter 7 analyzes the learning outcome of the serious game to validate the Gamified Knowledge Encoding's definition of knowledge learning using game mechanics. This validation process is supported with an attempt to use the model to predict the learning outcome of a computer game, i.e., *Kerbal Space Program*. Chapter 8 provides an outlook for future research directions by discussing the utilization of game mechanics in other contexts, e.g., to realize virtual gambling games. This chapter also analyzes the effects of immersion on specific harm-inducing factors that are targeted by the game mechanics of a virtual slot machine. Chapter 9 discusses the core findings of this thesis. Finally, chapter 10 concludes the thesis and discusses future directions of research.

2 Context

Some of these topics are much further researched than others. There are definitely some opportunities here. – Wernher von Kerman, Kerbal Space Program (2011–2019)

2.1 Computer Games

Computer games are highly immersive and engaging environments that keep players motivated even when the gameplay becomes repetitive or very challenging (McGonigal, 2011). *Gaming immersion* describes the effect of a good computer game experience and features three stages: engagement, engrossment, and total immersion (Brown and Cairns, 2004; Jennett, Cox, Cairns, Dhoparee, Epps, Tijs, and Walton, 2008). Depending on the gaming immersion's stage, a player's attention is partly or even completely absorbed by the gameplay. When in total immersion, players lost their self-awareness and are completely detached from reality (Cheng, Shet, and Annetta, 2014). In this stage, all that matters to a player is the game. The immersive effect of computer games is so strong that it allows players to experience moral problems or to face ethical questions (Power and Langlois, 2010), thus training moral decision making (Schulzke, 2009). A computer game's immersive effects further depend on two additional aspects: presence and flow (Weibel and Wissmath, 2011). Presence describes the subjective sensation of being personally inside of the VE created by a computer game (Slater, 2009; Lombard and Ditton, 1997; Wirth, Hartmann, Böcking, Vorderer, Klimmt, Schramm, Saari, Laarni, Ravaja, Gouveia, Biocca, Sacau, Jäncke, Baumgartner, and Jäncke, 2007) despite being physically located in a different environment. Presence depends on the *immersion* describing objective system properties that reduce sensory inputs from the real world and replace them with computer generated information (Slater, Linakis, Usoh, and Kooper, 1996), e.g., wearing a Head-Mounted Display (HMD) (Slater and Wilbur, 1997). In contrast to gaming immersion and presence, *flow* describes an immersion due to the active performance of an activity, i.e., the gameplay (Sherry, 2004; Voiskounsky, Mitina, and Avetisova, 2004). Good computer games provide players with a constant stream of new challenges, clear goals, and immediate feedback (McGonigal, 2011). These factors are critical for the experience of flow and hence playing computer games can induce flow in a player (Csikszentmihalyi, 1990; Weibel and Wissmath, 2011). While in flow, a person is completely immersed in an activity and derives joy from simply performing it.

Offering meaningful rewards plays another central role for the engaging effects of computer games. These rewards give players an incentive to continue playing the game which is especially important when the gameplay starts to become repetitive. Massively Multiplayer Online Role Playing (MMORPG) games like *World of Warcraft* (Blizzard Entertainment, 2004–2019) are designed to keep players busy over a very long time. For keeping players interested in the game, they feature reward-based retention mechanisms. These game mechanics motivate players to return to the game on a regular basis to repeat certain activities over and over again until they collect all the rewards, e.g., virtual items and achievements (Debeauvais, Nardi, Schiano, Ducheneaut, and Yee, 2011). The game mechanic of providing collectable virtual items simultaneously provides an additional motivational aspect. Vested players of a game know what items are hard to get and hence they apply a certain value to them. Players who collected many of those highly valuable items automatically have a higher standing in the game's community (Krzywinska, 2009). Thus, players who want to increase their own standing experience a higher motivation to continue playing the game. Providing these game mechanics is the key concept of gamification (Deterding et al., 2011).

However, meaningful rewards are not necessarily virtual items or points. Meaningful rewards are also emotions players experience when they overcome a very difficult challenge or when they achieve a major game goal for the very first time. Players can experience a so-called *epic win* which describes the joy of achieving a surprising outcome of a team effort, a perfect execution of a tactic or a hard earned victory over a very strong enemy (McGonigal, 2011). Also, a game's story can emotionally involve players in events that affect more virtual inhabitants of the VE than just the players themselves, e.g., a narrative that puts the fate of the entire world into the hands of a player (McGonigal, 2011). These emotions, despite being experienced in an VE, are *real* to a player and thus directly affecting them, i.e., by evoking a high motivation to continue playing.

In conclusion, computer games have the potential to completely absorb a player's attention as well as to provide game mechanics that keep a player motivated even when the gameplay becomes repetitive. In contrast to the real world, a computer game provides a player with clear information on the requirements that need to be fulfilled to complete a goal (McGonigal, 2011). Hence, computer game players exactly know what they need to do to complete a certain task. Subsequently, while they are progressing towards the completion of the goal, the game provides an immediate feedback about their progress. Exploiting these characteristics for educational purposes might lead to a more effective learning and a potentially higher perceived learning quality. A learning process leads to a permanent improvement of performance or of performance potential being caused by experience and interaction with the world (Driscoll, 2013). Good computer games require a repetitive application of various skills and knowledge to successfully interact with the provided VEs, thus allowing players to gain experience. Also, when engrossed or immersed in the gameplay, players do not realize that they are engaged in extended practice sessions (Gee, 2007). As a result, the learning process is turned into a playful experience even when the game's content is very complex or abstract.

2.2 Knowledge and Human Performance

Knowledge can generally be described as facts, information, and skills related to a particular subject which are acquired through education, practice, and experience. This broad definition can be further refined: *Declarative knowledge* consists of information, facts, methods, and principles describing *what* a subject is, whereas *procedural knowledge* reflects motor or cognitive skills, hence describes *how* an action is performed (Anderson, 2015; Nickols, 2000). The two knowledge types are internally encoded in multiple cognitive systems forming a corresponding declarative and a procedural or nondeclarative memory (Squire, 1992). The hippocampus and related structures (Squire, 2004) responsible for the declarative memory rapidly form connections between arbitrarily different stimuli. Thus, the declarative memory rapidly stores and modifies information. It is conscious and flexibly available to multiple response systems. In contrast, the non-declarative memory is, depending on the used response systems, managed by multiple cognitive systems (Hoffmann and Engelkamp, 2013; Martin, 2007). It forms new associations slowly and gradually, is nonconscious and less flexible because it only provides limited access to response systems which are not involved in the training process. From an evolutionary perspective, the declarative memory potentially evolved from procedural memory as it provided the ability to analyze and to mentally simulate outcomes of actions, hence improving the overall chances to survive or gather food (ten Berge and van Hezewijk, 1999; Pezzulo, 2011). An alternative explanation for the evolution of modern human behavior lies in the development of social structures and the requirement to develop the ability to learn a language to enable detailed communication for the purpose of complex planning (Ambrose, 2010).

While declarative knowledge is rapidly memorized, the acquisition of a skill requires a periodical repetition and passes through three stages (Fitts and Posner, 1967). At first, during the *cognitive* stage, the development of a skill's declarative encoding is required (Anderson, 2015; ten Berge and van Hezewijk, 1999). This declarative encoding consists of facts and steps relevant to the skill's performance which are followed closely when the skill is executed for the first time. The skill performance during this stage is very poor as the knowledge merely exists in a declarative form. In the *associative* stage, the second stage of skill acquisition, the performance gradually improves as errors are iteratively detected and removed. In addition, the links between the individual steps are strengthened and the respective transitions are smoothed out. However, the developed procedural knowledge is not necessarily replacing the declarative knowledge. For instance, a person can rapidly solve simple mathematical problems, e.g., multiplying numbers, but still recall the underlying mathematical principles. Finally, during the last stage, i.e., the *autonomous* stage, the performance is gradually automated, thereby increasing the performance further and achieving true mastery of the skill.

Similarly, although declarative knowledge is acquired quickly, it requires training (Woltz and Shute, 1993) and periodical deliberate practice (Ericsson et al., 1993) to gain expertise and to master it (Anderson, 2015). As a general rule, it takes an individual learner 10 years of experience to completely master the knowledge of a particular field (Simon and Chase, 1973; Gladwell, 2008). By gaining expertise, a learner deepens the understanding of the knowledge (Craik and Tulving, 1975) by removing errors in the encoded rules and by generalizing them to form schemata (Gagné, 1984). Developing an expertise in a specific domain also stores more information about encountered problems in the long-term memory and facilitates their retrieval (Anderson, 2015). Experts in a particular field perceive a new problem in a different way, rapidly visualize it, and find more effective solutions (Chi, Feltovich, and Glaser, 1981). As a result, the deliberate use of declarative knowledge starts to shift to a more pattern-driven and model-driven application.

By applying and practicing procedural and declarative knowledge, learners compile situation-specific mental models (Johnson-Laird, 1983; Lynam, Mathevet, Etienne, Stone-Jovicich, Leitch, Jones, Ross, Du Toit, Pollard, Biggs, and Perez, 2012). Mental models reflect a complex and flexible mental representation of the applied specific knowledge allowing for an internal visualization and simulation (Tulodziecki, Herzig, and Grafe, 2010). Due to their flexibility, mental models are easily updated and hence used for the purpose of either rapidly applying the knowledge in a familiar situation or analyzing and solving unfamiliar problems (Seel, 2003; Tobinski, 2017). Mental models not only reflect the gain of expertise and automatization of a skill, but also allow for knowledge transfer from the learning environment to a new target context.

Therefore, a repetitive knowledge application, especially in the case of complex learning content, is one of the most important aspects of acquiring and internalizing new knowledge (Brophy, 2000). Practice achieves knowledge automatization, i.e., the acquisition of a new skill, deepening as well as generalization, i.e., gaining expertise, and a facilitation of a training transfer from the

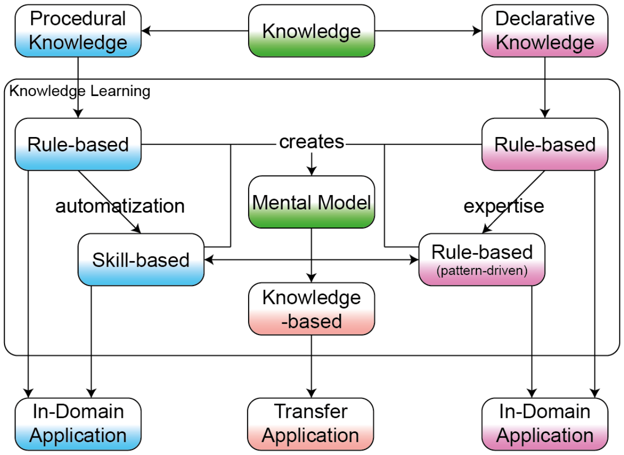


Figure 1: Knowledge can be distinguished in procedural and declarative knowledge. By repetitively utilizing a specific knowledge, its application gets automated or pattern-driven depending on the category. Simultaneously, the training process results in the compilation of mental models allowing for an internal visualization. Mental models not only affect the actual in-context application, but also allow for a knowledge transfer to a different context. The actual application takes place on a skill-based, rule-based, and knowledge-based layer of human performance.

learning context to a different context (Mestre, 2002; Dede, 2009).

The actual learning and application of knowledge manifests in the three levels of human performance (Rasmussen, 1983) as Figure 1 depicts. *Skill-based performance*, the application of procedural knowledge in the autonomous stage, is automatically performed without a person's conscious attention and cannot be defined in terms of information needed and actions performed by the person. The next higher level, the *rule-based performance*, is based on specific declarative knowledge rules which can be explained by the performing person. Hence, the rule-based level is the application of procedural knowledge during the cognitive and partly associative stage as well as the explicit application of declarative knowledge. Periodical skill-based and rule-based performance results in a deliberate knowledge learning, i.e., skill acquisition and gain of expertise, and the compilation of situation-specific mental models. Finally, during unfamiliar situations, a person must move to the *knowledge-based performance*, the next higher cognitive level. This level allows the person to test the created mental models against the new situation for the purpose of solving problems and completing self-defined goals.

2.3 Fostering Knowledge and Abilities Using Computer Games

As any other form of media, computer games can be categorized into genres characterized by certain key features, i.e., the provided game mechanics. The gameplay of action games, for example, is fast-paced and requires players to react to events immediately. In contrast, strategy games and adventure games require skills of visualization, logic, memory as well as problem-solving (Amory, Naicker, Vincent, and Adams, 1999). Hence, a computer game's genre already indicates a key set of human skills required and thus trained during the gameplay. For instance, fast-paced action games require a player to constantly check the VE for visual stimuli and to quickly react to them. This gameplay trains a player's spatial navigation (Joorabchi and El-Nasr, 2011) as well as spatial visual attention, enhances the allocation of the spatial attention over the visual field, and improves task-switching abilities (Green and Bavelier, 2003). Action games improve a player's spatial resolution which results in a better visual acuity and smaller regions of spatial interaction (Green and Bavelier, 2007). The requirement to quickly react to events additionally improves a player's reaction time as well as the capacity to maintain and update the working memory (Colzato, van den Wildenberg, Zmigrod, and Hommel, 2013). Finally, the fast-paced gameplay trains the ability to track multiple objects and to filter out task irrelevant stimuli (Oei and Patterson, 2013). In contrast to action games, real time strategy games require rapid and simultaneous maintenance, assessment, and coordination between multiple information and action sources. This allows for an analysis of the opponent's strategy and quick as well as thorough decision-making. Thus, the gameplay of strategy games results in a training of cognitive flexibility (Glass, Maddox, and Love, 2013; Oei and Patterson, 2013).

The 3D and 2D visualizations of the gameplay lead to a training of a player's mental rotation skills independent of a game's genre (Cherney, 2008). During the gameplay, players see the virtual objects that may be explored from various angles. Many games even require players to manipulate objects in a certain way to solve puzzles. This requires a mental analysis of the puzzles to find the correct solution and hence leading to a mental rotation and spatial skill training (Shute, Ventura, and Ke, 2015).

Training transfer from a computer game context to a real world context is facilitated when the VE and the targeted context share similar requirements (Oei and Patterson, 2013). Achieving a high degree of similarities increases the authenticity of the presented knowledge. Also, it allows for the compilation of mental models that can directly be used for solving problems in the target context. For instance, laparoscopic surgery requires fine motor control, visual attention processing, eye-hand coordination, and reaction time. Playing action games for short game sessions successfully trains these skills: surgeons with action computer game experience yield a better performance in a laparoscopic training scenario than non-player surgeons (Rosser et al., 2007).

Computer games also foster specific knowledge. For instance, MMORPGs provide challenges that require and hence train teamwork and effective leadership during the gameplay (Yee, 2006; Williams, Ducheneaut, Xiong, Zhang, Yee, and Nickell, 2006; Reeves, Malone, and O'Discoll, 2008; Yee, 2009). As successfully managing groups and even guilds, i.e., permanent groups of players united by their interests and goals, has a lot of similarities to managing real world organizations, players can directly transfer their knowledge to a real world context (Goh and Wasko, 2009; Andrews, 2010). Leaders in MMORPGs have to combine two very different leadership styles to maintain a social stability and to yield successful outcomes: an efficiency-focussed style and a human-needs-focussed style (Prax, 2010). During progress-oriented group activities, the leadership style is similar to a military leadership style whereas outside group activities, the leadership style often changes to the style used in voluntary organizations. Also, the gameplay during progress-oriented phases often requires a quick decision making. This allows players to practice leadership styles under pressure (Siewiorek and Gegenfurtner, 2010). During stressful situations, the communication has to be very precise to clearly convey a message. As a result, players learn to express themselves in a direct way (Schroeder, 2011). In general, the gameplay of cooperative computer games positively affects real-world collaboration. Groups that successfully played such a game showed more effective teamwork (Qiu, Tay, and Wu, 2009). Collaborative gameplay helps groups to develop a team mental model allowing for a more effective communication during further group activities. This establishes trust and coordination among team members (Richter and Lechner, 2011).

Aside from using regular computer games, serious games are developed to educate players in a broad variety of topics like identifying phishing attacks (Wen, Lin, Chen, and Andersen, 2019), genetics (Annetta, Minogue, Holmes, and Cheng, 2009) or biological consequences of alcohol abuse (Klisch, Miller, Beier, and Wang, 2012). Also, serious games are not only used to teach about scientific aspects forensics, but also to motivate players to consider a science career (Miller, Chang, Wang, Beier, and Klisch, 2011).

In conclusion, playing computer games not only leads to a learning of game specific knowledge, but also to an acquisition as well as training of real world knowledge and human abilities. The learning outcome can be transferred to real world contexts, thus allowing for a knowledge training in a highly motivating environment. Computer games also represent a safe learning environment. Learners can explore the learning content without the fear of bad consequences as even death is reversible (Riegle and Matejka, 2006). This especially is critical for expensive or even dangerous learning contents.

2.4 Learning Paradigms

Computer games can also be analyzed in respect to the three main learning paradigms, i.e., behaviorism, cognitivism, and constructivism (Tulodziecki et al., 2010; Kerres, 2018). According to the paradigm of *behaviorism*, an individual learning process is seen as a black box. Learning is achieved through reinforcement by the environment and by a repetition of the learning contents which are divided into small units and increase in difficulty (Kerres, 2018). Reinforcement is realized by rewarding correct as well as desired behavior and not rewarding or even punishing undesired behavior. The provision of small units also achieves a coherence between a learner's actions and the subsequent reinforcement. In the context of a computer game, providing typical reward game mechanics, e.g., rewarding players with experience points or loot after defeating a foe, achieves a reinforcement of a player's actions. Some computer games like *World of Warcraft* even punish too ambitious player behavior by reducing the durability of a player's items by a certain percentage after their death. By providing short learning units, e.g., levels in a computer game, the learning content is not only repeated, but also presented in short and manageable challenges. These two game elements ultimately support behavioristic learning.

Based on the paradigm of *cognitivism*, learning requires an active application of the learning contents. In contrast to behaviorism, cognitivism defines learning as a process that leads to the development of internal cognitive structures storing the acquired knowledge (Kerres, 2018). Learning depends on the interaction processes between the learning content as an external condition, e.g., media-based presentations, and mental structures as an internal condition (Tulodziecki et al., 2010). Learning is partly controlled, guided, and supported by providing instructions as well as further materials that support the acquisition of knowledge. According to the cognitivism, preexisting knowledge and experience affect the learning process. In the context of a computer game, the learning process is guided by the provision of a problem evoking a motivation in the learner, e.g., by telling a story that embeds the player's assignment. Computer games either explicitly or implicitly demonstrate the underlying principles of the learning contents. For instance, a highly realistic car racing game might start with a tutorial, i.e., instructions how to successfully play the game, and subsequently challenge a player to further apply the knowledge during the actual gameplay. During this gameplay, the learning content, e.g., how to drive a car at its limits, and the results of a player's actions are explicitly demonstrated in an audiovisual way. Computer games increase in their difficulty as players progress through the gameplay to compensate for the training effect and to keep them challenged. Well-designed computer games adjust the learning content to a player's current skill or knowledge level (McGonigal, 2011).

Constructivism defines learning as an individual knowledge construction process that is initiated by the experience of a situation (Kerres, 2018). In this way, learning is a self-directed process requiring a learner's active participation. Also, learning has a social aspect because it is culturally as well as temporally embedded and takes place in interaction. Systems allowing for an effective constructivistic learning require a design that provides learners with information as well as tools for a self-directed learning process but that avoids guiding the learning (Tulodziecki et al., 2010). As a result, the learning process can be self-organized as well as reflective. In the context of a computer game, an open world design that requires a self-driven exploration of the VEs allows for a constructivistic learning. For instance, players of *Kerbal Space Program* may construct virtual spacecraft out of a selection of various parts and subsequently launch them. During this simulation phase, players experience effects of their designs as well as orbital maneuvers and thus can construct spaceflight-relevant knowledge (see subsection 7.3).

In conclusion, the design as well as the genre of a computer game determines its categorization in respect to the three learning paradigms. Some behavioristic game elements, e.g., reward game mechanics, are also used in constructivistic open world computer games. Thus, the categorization in respect to the learning paradigms takes place on the level of the game mechanics provided by a computer game. As a result, computer games might fulfill some aspects of different learning paradigms at the same time.

2.5 Game Mechanics

Game mechanics are a computer game's building blocks and classified into two different groups: Player-bound and game-bound game mechanics (Oberdörfer and Latoschik, 2018a). In analogy to the two knowledge types, player-bound game mechanics can be categorized as procedural *direct control* game mechanics and declarative *value configuration* game mechanics (see Table 1). The former type realizes direct movement, steering, and general action performance inside an VE. The latter type allows for an explicit application of specific rules, such as equipping gear in a role-playing game, choosing skills in a skill-tree, ordering helpful units in a strategy game, or using radio navigation in a flight simulation. Game-bound game mechanics only encode declarative knowledge. Depending on the player-bound game mechanic's category and the play-

Table 1: Overview of game mechanic categories, the corresponding level of human performance and the internally encoded knowledge

Game Mechanic	Human Performance	Knowledge
Direct control	Skill-based Partly rule-based	Procedural
Value configuration	Rule-based	Declarative
Game-bound	Rule-based	Declarative

ers' training stage, executing game mechanics takes place on the skill-based or rule-based level of human performance (Rasmussen, 1983). This results in a deliberate practice of the knowledge (automatization or gaining expertise) and the compilation of situation-specific mental models (Johnson-Laird, 1983; Lynam et al., 2012; Palmunen, Pelto, Paalumäki, and Lainema, 2013). The compilation of mental models is also supported as game mechanics present, require and demonstrate the encoded knowledge in an audiovisual way (Dalgarno and Lee, 2010; Weidenmann, 2009). Players internalize the knowledge's visualization and include it in their situation-specific mental models.

Consider the first time a first-person computer game is played by a new computer game player. In this instance, the movement, view and general action game mechanics are used on a rule-based level of human performance. Instead of automatically and subconsciously using established WASD keyboard inputs for navigating, the user has to focus on providing the right input at the right time. They follow clear rules and perform conscious actions, i.e., the cognitive stage of skill acquisition. During this stage, a new player often experiences difficulties with the performance of a sequence of different game mechanics. It may be difficult for new players to successfully jump over a gap in an VE because they have to keep the forward movement key pressed and execute the jump game mechanic in the correct moment. However, executing direct control game mechanics is a constant requirement throughout the gameplay. Hence, players entrain the encoded knowledge and achieve an automatization as well as a subsequent shift, i.e., the associative and autonomous stage of skill acquisition, from the rule-based to a skill-based level of human performance. Simultaneously, situation-specific mental models of the game's movement controls are compiled. They are used for a knowledge application inside of the game as well as a knowledge transfer between different games, e.g., achieving an interaction in a different first-person game (Joorabchi and El-Nasr, 2011).

Table 2: Overview of computer game genres, the encoded knowledge and the used player-bound game mechanics.

Genre	**Knowledge**	**Game Mechanics**
Action Simulation	Procedural	Direct control
Mixed-genre Real-time strategy	Procedural, Declarative	Direct control & Value configuration
Adventure Management Turn-based strategy	Declarative	Value configuration

However, direct control game mechanics represent the declarative form of procedural knowledge. They define the individual steps and effects of the encoded skill's performance. In this way, it is necessary to inform players about the encoded rules at the start of a new game. Well-designed computer games provide a tutorial that demonstrates the underlying principles by explaining the existing game mechanics, showing the inputs needed to execute a particular game mechanic and providing an opportunity for practicing the presented knowledge (Gee, 2007). Afterwards, players start with the main part of the game which furthers the training of the encoded knowledge.

Lastly, as player-bound game mechanics reflect the two knowledge types, a computer game's genre not only indicates a game's gameplay, but also classifies games by the required knowledge type (see Table 2). Action games, such as first-person shooters and platforming games, and simulation games, like racing games and flight simulations, mainly consist of direct control game mechanics and hence can be seen as procedural knowledge games. Mixed-genre games, such as role-playing and action-adventure games, as well as real-time strategy games combine direct control with value configuration game mechanics. A player is simultaneously required to perform direct interactions and deliberately use declarative knowledge. Games belonging to these genres combine both knowledge types and are probably the most effective games for a deliberate knowledge learning (Amory et al., 1999). Finally, (point-and-click) adventure games, management games and turn-based strategy games mainly implement value configuration game mechanics and hence represent declarative knowledge games.

In conclusion, while progressing through a game, players are constantly using the required abilities and applying the game specific knowledge on a skill-based and rule-based level of human performance. This ultimately leads to the compilation of mental models due to deliberate practice of the encoded knowledge (Gee, 2007; Sauvé, 2010). In this way, game mechanics enhance the learning outcome of edutainment software (Ritterfeld and Weber, 2006) by directly encoding and requiring the learning content's application on a skill-based and rule-based level of human performance. Learning transfer between the game world and the real world is facilitated when the game as well as the target context share similar requirements (Dalgarno and Lee, 2010; Oei and Patterson, 2013; Squire, 1992). It is important to design and adjust the game mechanics in such a way that they achieve similar requirements to the real-world application of the knowledge to be learned.

3 Human Skill Training with Game Mechanics

Well-designed video games provide engaging, challenging learning experiences that motivate players and provide them with the opportunity to master the knowledge that exists in the game world. – Anthony Gurr (2010)

3.1 Develop Your Strengths By Gaming

The theoretical considerations in chapter 2 identified game mechanics as the key elements for realizing a gamification of learning. For validating these assumptions, an expert review of game mechanics used in *World of Warcraft* was conducted. *Develop your strengths by gaming* analyzes two game scenarios to compile a mapping between provided game mechanics and the required skills. The resulting mapping supports the theoretical approach of encoding knowledge in game mechanics to achieve a knowledge acquisition and knowledge training during the gameplay.

Table 3: Develop your strengths by gaming: Towards an inventory of gamificationable skills

Author	**Contribution**
Oberdörfer, S.	Literature review, manuscript preparation and revision
Latoschik, M. E.	Manuscript revision

Oberdörfer, S. and Latoschik, M. E. Develop your strengths by gaming: Towards an inventory of gamificationable skills. In Horbach, M., editor, *Informatik 2013 – Informatik angepasst an Mensch, Organisation und Umwelt*, pages 2346–2357, Koblenz, Germany, September 2013. Gesellschaft für Informatik e.V

Develop your strengths by gaming: Towards an inventory of gamificationable skills

Sebastian Oberdörfer, Marc Erich Latoschik

Mensch-Computer-Interaktion
Julius-Maximilians-Universität Würzburg
Am Hubland
97074 Würzburg
s.oberdoerfer@learning-by-gaming.net
marc.latoschik@uni-wuerzburg.de

Abstract: This paper analyses existing gamification approaches to build a mapping between game genres and potential human skills required by and potentially trained by the specific genres. This mapping is then applied during an expert review of two typical game scenarios: an action- and reaction-oriented mini game and a collaborative group raid implemented in World of Warcraft. Both scenarios undergo an individual and detailed analysis to identify specific skill-related aspects. Relevant aspects characterizing each type are listed as a basis for a skill-mapping based on specific game mechanics utilized by each type. That is, the identified specific game mechanics require gaming skills which are then mapped to general physiological as well as cognitive and social human skills. This detailed game-mechanics-based skill-mapping is a first step towards a gamification index. Used in reverse order, from human skills to game mechanics, such an index will support the design of edutainment applications using gamification as a means to enhance skills required in real-world scenarios. The article concludes with a description of future work in the area of gamified skills as motivated by the work presented here.

1 Introduction

Computer games motivate users, in this context also known as *players*, using a variety of different techniques and game design strategies potentially resulting in a high feeling of immersion and a state of „flow“ [Cs10] for players [Mc11]. One key element is to constantly challenge players in a well-balanced way. By solving a challenge, a player trains the skills required by the particular challenges. After a task is completed, the player‘s improved skills enable the player to deal with the next and even more difficult mission. A well-balanced game forces players to always play at the edge of their current skill levels. Hence, gameplay also involves a personal training process based on the required gaming skills.

Potential skill-transfers from virtual game worlds to real world scenarios provide an interesting alternative to existing training techniques. Hence, first approaches already use games for education and training of various sets of professional skills and/or human capabilities. For example, they have been utilized to train surgery skills [Ro07], leadership styles [SG10], as well as communication and cooperation skills [RL11]. Several other examples already identify skill-related benefits of typical computer game mechanics, which we will discuss in the upcoming related work review. This article proposes an expert review evaluation of typical game mechanics to identify gamificationable skills. That is, required game skills are mapped to physiological, cognitive, and social real-world skills of humans, to acquire a deeper insight into how gamified skills can be used as training and learning tools for real-world skills and scenarios. The concrete goal started with this evaluation is a gamification index. Such an index would be greatly beneficial if not necessary during the design of edutainment applications, applications that enhance skills required in real-world scenarios by using game mechanics.

This article is structured as follows. First, we analyze existing approaches that already target skill acquisition and that identify skills trained while playing computer games. This review leads to an identification of potential target skills and an initial mapping of these skills to specific game genres. This initial coarse mapping serves as a starting point and guideline supporting the following expert review evaluation of two gameplay scenarios of World of Warcraft[1] (WoW): The mini game „Whack-a-Gnoll“ as well as a typical raid that requires coordinated actions by multiple players. The initial mapping is guiding the evaluation. Directed by their primary genre, both games are analyzed in terms of their principle game mechanics to identify potential target skills. This results in a detailed and more concise mapping not between game genre and skills but between game mechanics and skills. The evaluation provides the basis for mapping gaming skills to real-world counterparts or fields of application. Finally, the paper presents a prospect of future research directions.

2 Related work

Current computer games can be separated into six genres: action, strategy, sports, simulation, adventure, role-playing game / massively multiplayer role-playing game (MMORPG). Each genre, and in detail even each game, typically involves a unique style of play: Action games, for example, involve action/reaction cycles demanding short reaction times and highly developed hand-eye coordination, whereas adventure games demand increased problem solving skills.

Players actively use the demanded skills and hence train these skills due to repetition [Sa10] or due to the gain of experience caused by an increasing difficulty level. These „gaming“ skills are not restricted to computer game environments. For example, the ability of problem solving [Am99] can directly be used in the real world and visual attention [GB03] can increase the overall performance of certain tasks. Additionally, cooperative computer games support collaboration and increase the competences necessary during teamwork [Mc11] [RL11].

Computer games encode certain knowledge that can be learnt and mastered during active gameplay [Gu10]. This learning happens in a highly motivated way, which is always challenging without overstraining the player–the player can get into a state of „flow“ [Cs10]. Games in general provide a broad spectrum of problem-solving issues testing the potential strategies of a player. The player discovers new problems and multiple ways to solve them through his own actions [Ar06]. The immersive aspect of

---

[1] World of Warcraft, Blizzard Entertainment, 2004 - 2013.

computer games can even help to introduce players to moral problems and encourage them to react in a way considered ethically appropriate [Sc09].

2.1 Gaming skills

Typical computer game genres require different skills and, hence, potentially improve different sets of skills. Adventure and strategy games require mostly imagination and problem-solving skills [Am99]. Action games require and improve the mental rotation skill [Ch08], visual attention, and the skill to handle a number of different tasks at the same time [GB03]. This has already been exploited during the training of laparoscopic surgeons [Ro07].

Players of MMORPGs increase collaboration skills by working together as well as by helping Non-Player-Characters with their needs [Mc11]. One key element of developing collaborative skills is the requirement of playing together to achieve end-game goals: the difficulty of the game and the strengths and weaknesses of roles [Ye09] evoke the necessity to form groups to successfully achieve end-game goals [Ye06a] that promise rewards important to increase the player‘s reputation [Kr09]. Thus, MMORPGs help to develop social behaviors by facilitating players, if not forcing them, to interact with each other in a structured an constructive way [DM05].

Certain games can also be used as training tools of so-called soft skills, e.g., to increase leadership skills [SG10]. Here, MMORPGs provide various game mechanics that require players to develop their behavior into a leading role [DM05][GW09][RMO08]. According to Williams et al. [Wi06], the necessity of leadership arises automatically if a critical mass of players is reached in a certain group. Every player has individual needs and motivations. Joint actions by these individuals require management and rules, e.g., to enforce equal rights necessary for players to not loose their motivation.

Additionally, the gameplay provided by MMORPGs like WoW incorporates different phases of leadership: an efficiency based phase, and a more member-oriented phase [Pr10]. Here, leaders experience short-term as well as long-term aspects of leadership [Ye06a]. Keeping a guild or a raid active is a complex task that needs substantial management [Du06] that often includes the skill to motivate people and to resolve conflicts between them [Ye06b]. Finally, by accumulating in-game experience, players can become advisors and mentors. They will share their knowledge with other players and will try to improve the gameplay of others [SBS09][Wi06].

An additional soft-skill fostered by several game genres is the communication skill. Players of multiplayer games are often forced to express themselves via text or voice chat, which often requires more effort compared to face-to-face encounters in the real world. Hence, they are training the skill to express themselves concise and in a clear way [Sc11].

MMORPGs have a lot of content and are played over a very long time. Keeping all the players active requires time management. Players are conditioned to work more efficiently by doing a high workload on a regular basis [Ye06c].

Games in general are rule-based environments [Hu09] in which the player learns to act under certain constraints. Players are forced to respect the constraints and, as a result, players learn to accept the rules. They develop a certain degree of ethical responsibility and they get rewarded for performing successfully within these boundaries [MEC09].

2.2 Advantages of the virtual gaming environment

Learning in a gaming environment has the advantage of giving the learner a safe way to try something new. MMORPGs offer a safe ground to learn social behaviors. They generate anonymity through the usage of avatars. The players thus do not have to fear negative feedback in their real-world life [RM06].

Role-playing games comprise highly immersive universes, in which entertainment and education are combined [RW06]. Players are immersed in different roles and positions [Hu09]. They learn through direct experience since they act as if they were directly involved in real-world tasks [PK07]. Hence, role-playing provides a higher degree of experience after a crises is solved [Ye09].

The relations between game genres and skills extracted from the existing work is summarized in a first genre-skill mapping as illustrated in Table 1.

Area	Genre	Human skill
G1	Action	Mental rotation ability Visual attention Ability to multitask Reaction time Hand-eye coordination
G2	Adventure	Problem solving Visualization
G3	MMORPG	Collaboration Leadership Conflict management Project management
G4	Multiplayer	Communication
G5	Strategy	Problem solving Decision making Visualization

Table 1: Mapping of game genres and human skills potentially trained by the given game mechanics of the respective genre.

3 Terminology and method description

We apply the following definitions of terms in this article:

- **Game characteristic**: the main game principles and game styles determining the type or genre of a game. Certain genres are determined by their unique set of game styles as implemented by certain game mechanics.
- **Game mechanics**: the technical principles utilized to implement certain game styles. Game mechanics can be fine grained (core mechanics), e.g., moving an entity forward by pressing a key, or coarse grained (general mechanics), e.g., jump-and-run. The latter is describing a set of core game mechanics, often associated with game genres.

- **Gameplay**: the performance-related aspects of playing as caused by executing the game mechanics.
- **Challenge**: the individual actions taken and performed by players during gameplay as provoked or forced by certain game mechanics.

The evaluation of potential skills trained by computer games based on an expert review can–in principle–be tackled from two different directions. The first approach is a review-based evaluation of identified game mechanics that challenge human skills. These game mechanics are then traced in the analyzed games to point out the challenged skills. The second approach is a review-based evaluation of human skills as connected to certain use-cases. These use-cases are then traced in the analyzed games, potentially requiring analogy mapping of the use-cases and the analysis of game mechanics causing them. A third option combines the two former approaches bidirectionally.

This article follows the first approach and traces skill-related game mechanics. Thus, the analysis will point out the implemented game mechanics and map them to human skills.

4 Whack-a-Gnoll: Physiological and cognitive skills

11:05Poot says: What if a bird flew into you while you were flying?

Figure 1: Whack-a-Gnoll, an arcade-style reaction game in WoW.

„Whack-a-Gnoll“ is a mini game implemented in WoW. It is almost analog to the arcade game „Whack-a-mole“. However, the WoW version of this game has some additional features (see Figure 1): The player enters the gaming area with his avatar (1) where nine barrels are placed in a square (2). The player‘s aim is to accumulate 30 points within a certain amount of time (6). This is achieved by destroying the targets randomly emerging from the barrels.

The player can choose between three different targets: A minor gnoll (3) granting one point, a major gnoll (4) granting three points, and a baby gnoll (5) which grants no points and which additionally stuns the avatar for a few seconds.

To achieve 30 points, the player has to quickly decide on the target to destroy first since targets only appear for a few seconds. The player also needs to take the velocity of his avatar into account. He has to decide whether it is possible to cover a longer distance and catch a just popped-up major gnoll in time, or to go for a minor gnoll within close reach. If the player misses the major gnoll, he gains no points, destroying the minor gnoll will at least grant him one point.

However, the player has to be careful to avoid the baby gnolls. The resulting stun–as a consequence of hitting one of them–will restrain any player actions for the next few seconds.

Whack-a-Gnoll challenges players using different game mechanics that require several skills simultaneously. At first, players need to locate their avatar and the potential target on the gaming area. Afterwards they have to move their avatar to the target and hit it by pressing the „1“ key on the keyboard. Both actions require spatial orientation in the virtual and in the real world (H1.1.1) as well as a good hand-eye coordination (H1.1).

Before a player is going for a target, he has to choose a specific target by weighing the potential value of each available target type against the approximated time to reach it. This requires a fast decision-making process (H2.1).

Finally, the general reaction time (H1.2) and the reaction time of the aforementioned skills (H1.1.2 and H2.1.1) define a combined requirement: A player needs to achieve 30 points in a given period and the targets only appear for a few seconds. If the player reacts or decides too slow, he will run out of time.

The results of this analysis are summarized in Table 2. Here, in contrast to the genre-to-skill mapping as extracted from the related work, skills are mapped to game mechanics. This provides a more finely graduated mapping considered to be more in-line with current trends to merge and mix game mechanics from various genres into one game. In addition, this type of mapping accounts for the synthesis goal, i.e., to identify game mechanics to be implemented given the skills to be trained.

Area	Game mechanics	Human skill
H1 Physiological		
H1.1	Navigating on the playing field	Hand-eye coordination
H1.1.1	Orientation on the playing field	Spatial orientation
H1.1.2	Navigating in time	Reaction time
H1.2	Scoring points	General reaction time
H2 Cognitive		
H2.1	Choosing a target	Decision-making
H2.1.1	Choosing a target before it disappears	Reaction time

Table 2: Mapping of game mechanics to human skills identified by the Whack-a-Gnoll analysis.

5 The Thorim Encounter: Social skills

The following part analyzes the key game mechanics and required skills of the fight against „Thorim“, an encounter in the WoW Ulduar raid instance. The Thorim encounter incorporates two phases. In the first phase, a group approaching this task has to split up into two smaller groups. Both groups are separated from each other and have to rely on the other group to survive the fight. One group remains in the main arena (1) where it needs to deal with several minor enemies that are attacking the group (see Figure 2). During the first phase, Thorim cannot be attacked directly because he is standing on a higher ledge (3). Therefore, the second group has to fight its way through a narrow passageway (2) to force Thorim into the main arena (3). Once Thorim is pushed into the arena, the two groups reunite for the final battle against this „boss enemy“.

Figure 2: The map of the Thorim encounter.

The first collaborative aspect (H3.1.1) is evoked by the design of different classes players can choose for their own avatar. Each class has some specific strengths and weaknesses, but classes may complement each other. Therefore, if the difficulty level rises, players are encouraged to form heterogeneous groups to compensate their weaknesses by complementation, a game mechanic described as the „necessity of grouping“ [Ye09].

The game mechanic of different classes in combination with the encounter design leads to the next aspect of challenging collaboration (H3.1.2) while fighting against Thorim. Both groups need to be balanced in terms of weaknesses and strengths. Classes also determine roles: A healer has to keep his teammates alive while the tank has to protect his friends from deadly attacks [DM05].

Furthermore, the encounter design creates an additional coordination requirement (H3.2): Both groups need to be successful. If the arena group is overrun, the floor group will not survive for long. If the floor group does not reach Thorim in time, the arena group likewise has no chance to survive.

Finally, the connection between the game mechanics of the encounter and the class design leads to a third challenge to successfully win this fight: Each player has to fulfill a specific task. Thus, the skill of task distribution (H3.3) is challenged by the necessity of assigning an unique task to each member of the raid. A perfect execution of these tactics will give positive feedback of the collaborative aspects to all players.

The game mechanics of this quest require extensive coordination and collaboration as summarized in Table 3, again mapping game mechanics to skills as motivated before.

Area	Game mechanics	Human skill
H3 Social		
H3.1.1	Class design	Collaboration
H3.1.2	Encounter design	Collaboration
H3.2	Encounter design	Coordination
H3.3	Encounter / class design	Task distribution

Table 3: Mapping of game mechanics to human skills resulting from the analysis of the Thorim encounter.

6 Discussion and Potential Skill Transfer

The basic mechanics of the analyzed mini game Whack-a-Gnoll are typical for the whole WoW game. The game mechanics of the mini game are common to almost every situation of the main game: Players are challenged by the same requirements while questing, going on a raid, and dueling in Player-versus-Player situations. The game mechanics of these situations are almost identical to the the game mechanics of action games (G1). Players mostly have to react properly to spontaneous situations. They need a distinctive spatial orientation (H1.1.1) and hand-eye coordination (H1.1) to be successful. The same is true concerning the decision-making skill (H2.1). Every new situation has to be analyzed within seconds or players might be punished in some ways.
Hand-eye coordination trained with games proved to be useful for laparoscopic surgery [Ro07]. A good hand-eye coordination is equally important for the control of many of today‘s transportation systems. Various steering systems use some kind of computer-aided interface or require to map spatial movements between different frames of reference. For example, a pilot completely relies on the indications of the flight control and navigation instruments during certain meteorological conditions. In addition, controlling a plane has some analogies to controlling an avatar [Pr10]. Both situations require a visual analysis of the situation by interpreting the information from the interfaces, and the pilot/gamer has to map potential degrees of freedom from the input devices to the designated target movements.
Decision-making within a short time period can be helpful for any kind of steering situations. A player is used to analyze unknown situations and to react properly to them, a situation very similar, e.g., to driving a car. Both situations require a fast analysis of the given situation and an appropriate decision making.

The results from the analyzed Thorim encounter can be generalized and applied to the whole social gaming idea. Thus, gameplay in social games is combining the effects of the MMORPG (G3) and the multiplayer (G4) genre. The design of WoW encounters always calls for collaboration (H3.1.1). Furthermore, the game mechanics of the class and encounter design challenge the skills of task distribution (H3.3) and coordination (H3.2). All decisions made are crucial for the success of the group. Players rely on the outcomes of the collaboration. Over time, they start to build up faith in their teammates if a group is successful. While playing together, trust is evolving over time and a „shared mental model“ [SSB05] is developed among the teammates. Additionally, the game allows to track the contribution of every player in the group, which provides the basis for feedback of the individual performances.

Training teamwork and collaboration is a viable approach to increase team performance [Sa08]. Organizations are strengthening the collaboration among their employees by group activities and policies encouraging group events [GE07]. Playing multiplayer games like WoW could be one of these activities. Every player has an assigned role and task in a particular group, thus, the player receives feedback about the contribution to the overall group performance. Additionally, the teammates are getting used to work together, even in critical situations.

The outcomes of teamwork training are not only increased in connection to a certain task work [Sa08]. Considering this, players can benefit from their teamwork-oriented gaming experiences during teamwork in the real world. Additionally, in today‘s business life teams are often spread over different locations. Using a virtual world is breaking the distance and allows players to collaborate even if they are far away from each other. Teammates can actively spend time together, get used to collaborate in the virtual world, and take this experience as an advantage in their real-world business.

Finally, the typical game mechanics as found in the example WoW game types train an additional multitasking skill: The capacity to handle different tasks under pressure and in critical situations at the same time while communicating mission-critical information [GB03].

7 Conclusion

This article presented first a literature review which identified the potential of typical computer game genres to train human skills beneficial in real word scenarios. Although the results provided a general overview of possible training effects of certain game types, a genre-based analysis does not identify the particular game mechanic(s) which is/are responsible for the training effect. However, to efficiently use computer games for edutainment, it is important to create an inventory of gamificationable skills in terms of the game mechanics causing the training effect. Developers of edutainment software can then take advantage of the inventory by selecting appropriate game mechanics for their training goals.

Additionally, several of today‘s game designs combine elements of different genres, e.g., action-adventures or strategy games with role-playing elements. The two examples analyzed in this article combine game mechanics of the action (G1), multiplayer (G4), and MMORPG (G3) genre in WoW. This result is additionally indicating the importance of a game-mechanics-based instead of a genre-based approach: Analyzing genres is not accurate and can blur the training effects of a game whereas the game mechanics approach allows an in-depth analysis of computer games and their training effects.

Finally, the article illustrated an expert review method using a game-genre-to-skill mapping only as an initial starting point. The method provided a structured approach for the evaluation of the two example game types in terms of skill-related gameplay and mechanics. The method identified potential game mechanics that target specific skills. This mapping can now be used as a guide during the design of gamified applications which support skill transfer to real-world scenarios. The final goal of this approach is a comprehensive index that maps game mechanics to real-world skills to design and implement edutainment applications to tackle the general research question:

(Q1) *„Which advantages and usability do game mechanics have for training (professional) skills or (professional) competencies?“*

8 Directions for future research

Future research will be directed by the following core questions which outline the evaluation of potential positive effects of gamification as a more general research agenda:

(Q2) *„Which skills are required and trained during gameplay?“*

To be able to describe the gamificationable skills, it is important to create a mapping between the skills learnt during gameplay and the game mechanics requiring and developing these skills.

(Q3) *„Which skill is required and trained by which game mechanics?“*

In some cases, games can train additional skills during gameplay that are not directly predefined by game mechanics. Players come up with alternative methods to increase game success, e.g., using offline communication and collaboration. It is also important to take a look at these side effects too.

(Q4) *„Which kind of games and game mechanics favor developments of non mandatory requirements, which are not directly implemented in the game itself?“*

Having identified potential skill candidates, it is important to search for possible real-world applications of these skills.

(Q5) *„Which are possible fields of application for gaming skills in the real world?“*

The results of the comparison between gaming skills and real-world skills will show matching pairs of skills. However, it is unclear if skills learnt during the process of playing a game can be directly used in the real-world.

(Q6) *„Is it possible to use gaming skills without any adaptation in the real-world?“*

The daily working life is nowadays often based on the use of computer technology. Therefore, an additional examination of a general personal improvement in computer aided working areas will be carried out.

(Q7) *„Can playing computer games on a regular basis improve the use of computer technology performance?“*

Having identified potential skills and game mechanics, it is mandatory to evaluate the correctness of the assumptions, that is, to evaluate if real world skills can really be trained using the identified target skills and game mechanics and how efficient the various training options will be.

References

[Am99] Amory, A. et al. (1999): The use of computer games as an educational tool: identification of appropriate game types and game elements. British Journal of Educational Technology, 30(4), 311–321.

[Ar06] Arnseth, H. C. (2006): Learning to play or playing to learn-A critical account of the models of communication informing educational research on computer gameplay. Game Studies, 6(1).

[Ch08] Cherney, I. D. (2008): Mom, Let Me Play More Computer Games: They Improve My Mental Rotation Skills. Sex Roles, 59(11-12), 776–786.

[Cs10] Csikszentmihalyi, M. (2010): Flow: Das Geheimnis des Glücks (15 ed.). Stuttgart: Klett-Cotta.

[DM05] Ducheneaut, N., & Moore, R. J. (2005): More than just "XP": learning social skills in massively multiplayer online games. Interactive Technology and Smart Education, 2(2), 89–100.

[Du06] Ducheneaut, N. et al. (2006): "Alone together?" Exploring the social dynamics of massively multiplayer online games. CHI 2006 Proceedings of the SIGCHI conference on Human Factors in computing systems, 407–416.

[GE07] Gratton, L., & Erickson, T. J. (2007): Eight ways to build collaborative teams. Harvard Business Review, 85(11).

[GB03] Green, C. S., & Bavelier, D. (2003): Action video game modifies visual selective attention. Nature, 423(6939), 534–537.

[Gu10] Gurr, A. (2010): Video Games and the Challenge of Engaging the "Net" Generation. In D. Kaufman & L. Sauvé (Eds.), Educational gameplay and simulation environments: case studies and lessons learned (1st ed., pp. 119–131). Hershey, PA.

[GW09] Goh, S. H., & Wasko, M. M. (2009): Leadership in MMOGS: Emergent and transformational leadership candidates. AMCIS 2009: Proceedings of the 15th Americas Conference on Information Systems.

[Hu09] Huizinga, J. (2009): Homo ludens: Vom Ursprung der Kultur im Spiel (21st ed.). Reinbek bei Hamburg: Rowohl Taschenbuch-Verlag.

[Kr09] Krzywinska, T. (2009): Arachne Challenges Minerva: The Spinning Out of Long Narrative in World of Warcraft and Buffy the Vampire Slayer. In P. Harrigan & N. Wardrip-Fruin (Eds.), Third person : Authoring and exploring vast narratives (1st ed., pp. 385–398). Cambridge, Mass: MIT Press.

[Mc11] McGonigal, J. (2011): Reality is broken: why games make us better and how they can change the world (1st ed.). New York: Penguin Press.

[MEC09]Moeller, R. M., Esplin, B., & Conway, S. (2009): Cheesers, Pullers, and Glitchers: The Rhetoric of Sportsmanship and the Discourse of Online Sports Gamers. Game Studies, 9(2).

[PK07] Pivec, M., & Kearney, P. (2007): Games for learning and learning from games. Organizacija, 40(6), 267–272.

[Pr10] Prax, P. (2010): Leadership Style in World of Warcraft Raid Guilds. Proceedings of DiGRA Nordic 2010.

[RL11] Richter, S., & Lechner, U. (2011): Communication content relations to coordination and trust over time: a computer game perspective. C&T'11 Proceedings of the 5th International Conference on Communities and Technologies, 60–68.

[RM06] Riegle, R. P., & Matejka, W. A. (2006): The learning guild: MMORPGs as educational environments. Proceedings of the 22nd Annual Conference on Distance Teaching and Learning.

[RMO08]Reeves, B., Malone, T. W., & O'Discoll, T. (2008): Leadership's Online Labs. Harvard Business Review, 86(5), 58–66.

[Ro07] Rosser, J. C. et al (2007): The impact of video games on training surgeons in the 21st century. Archives of Surgery, 142(2), 181.

[RW06] Ritterfeld, U., & Weber, R. (2006): Video games for entertainment and education. In P. Vorderer & J. Bryant (Eds.), Playing video games: Motives, responses, and consequences (1st ed., pp. 399–413). Lawrence Erlbaum Assoc Inc.

[Sa08] Salas, E. et al. (2008): Does Team Training Improve Team Performance? A Meta-Analysis. Human Factors, 50(6), 903–933.

[Sa10] Sauvé, L. (2010): Effective Educational Games. In D. Kaufman & L. Sauvé (Eds.), Educational gameplay and simulation environments : case studies and lessons learned (1st ed., pp. 27–50). Hershey, PA: Information Science Reference.

[SBS09] Simon, B., Boudreau, K., & Silverman, M. (2009): Two Players: Biography and "Played Sociality" in EverQuest. Game Studies, 9(1).

[Sc09] Schulzke, M. (2009): Moral decision making in fallout. Game Studies, 9(2).

[Sc11] Schroeder, R. (2011): Being There Together : Social Interaction in Virtual Environments (1st ed.). New York: Oxford University Press.

[SG10] Siewiorek, A., & Gegenfurtner, A. (2010): Leading to win: the influence of leadership styles on team performance during a computer game training. ICLS '10 Proceedings of the 9th International Conference of the Learning Sciences, 1, 524–531.

[SSB05] Salas, E., Sims, D. E., & Burke C. S. (2005): Is there a "Big Five" in Teamwork?. Small group research, 36(5), 555-599.

[Wi06] Williams, D. et al. (2006): From Tree House to Barracks: The Social Life of Guilds in World of Warcraft. Games and Culture, 1(4), 338–361.

[Ye06a] Yee, N. (2006a): The demographics, motivations, and derived experiences of users of massively multi-user online graphical environments. Presence: Teleoperators and virtual environments, 15(3), 309–329.

[Ye06b] Yee, N. (2006b): The Psychology of Massively Multi-User Online Role-Playing Games: Motivations, Emotional Investment, Relationships and Problematic Usage. In R. Schroeder & A.-S. Axelsson (Eds.), Avatars at Work and Play: Collaboration and Interaction in Shared Virtual Environments (1st ed., pp. 187–207). London: SpringerVerlag.

[Ye06c] Yee, N. (2006c): The Labor of Fun: How Video Games Blur the Boundaries of Work and Play. Games and Culture, 1(1), 68–71.

[Ye09] Yee, N. (2009): Befriending Ogres and Wood-Elves: Relationship Formation and The Social Architecture of Norrath. Game Studies, 9(1).

3.2 Discussion

The paper answers the first RQ:

RQ1: How can knowledge be acquired and practiced using a computer game?

Table 4: Mapping of game mechanics to the identified human skills

Game Mechanic	Category	Area
Avatar steering	Player-bound	H1.1, H1.1.1, H1.1.2
Hit target	Player-bound	H1.2
Emerging targets	Game-bound	H1.1.2, H1.2, H2.1, H2.1.1
Class design	Game-bound	H3.1.1, H3.3
Encounter design	Game-bound	H3.1.2, H3.2, H3.3

Develop your strengths by gaming not only identified game mechanics causing a learning of specific knowledge, but also proposed a first approach of analyzing computer games in respect to the potential learning outcome when played. In the context of this thesis, the paper discussed how the interaction between player-bound game mechanics and game-bound game mechanics requires the application of specific human skills. To successfully execute a player-bound game mechanic, players need to apply the required skills and thus practice them during the gameplay due to repetition. Table 4 provides a mapping of the identified human skills areas to the concrete game mechanics. The table also demonstrates the interactions between player-bound game mechanics and game-bound game mechanics. For instance, the *emerging targets* game mechanic challenges players to *steer their avatar* over the playing field to *hit the targets* in time. By executing the player-bound game mechanics, players apply and hence train their skills. This theory-based expert review confirms the theoretical assumptions discussed in chapter 2. Also, it supports the theory of using game mechanics to encode specific knowledge rules is an effective method to create well-targeted learning environments.

4 Gamified Knowledge Encoding Model

Good video games involve the player in a compelling world of action and interaction, a world to which the learner has made an identity commitment, in the sense of engaging in the sort of play with identities we have discussed. Thanks to this fact, the player practices a myriad of skills, over and over again, relevant to playing the game, often without realizing that he or she is engaging in such extended practice sessions. – James Paul Gee (2007)

4.1 Defining Gamified Knowledge Encoding

The expert review's results led to further considerations of the theoretical relationship between game mechanics and knowledge learning discussed in chapter 2 to propose the *Gamified Knowledge Encoding* model (see also subsection 7.2). The Gamified Knowledge Encoding model defines the process of knowledge encoding and knowledge learning using game mechanics. Players entrain the encoded knowledge on a skill-based and rule-based level of human performance during the gameplay. In this process, they compile a mental model for the learning content that allows them to transfer their knowledge to a different context, e.g., a real world application (Lynam et al., 2012).

Table 5: Gamified Knowledge Encoding: Knowledge Training Using Game Mechanics

Author	**Contribution**
Oberdörfer, S.	Literature review, conceptual design, manuscript preparation and revision
Latoschik, M. E.	Conceptual design, manuscript revision

Oberdörfer, S. and Latoschik, M. E. Gamified Knowledge Encoding: Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games '18)*, Würzburg, Germany, September 2018a. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493425

Gamified Knowledge Encoding: Knowledge Training Using Game Mechanics

Sebastian Oberdörfer
Human-Computer Interaction
University of Würzburg
Würzburg, Germany
Email: sebastian.oberdoerfer@uni-wuerzburg.de

Marc Erich Latoschik
Human-Computer Interaction
University of Würzburg
Würzburg, Germany
Email: marc.latoschik@uni-wuerzburg.de

***Abstract*—Game mechanics (GMs) encode a game's rules, underlying principles and overall knowledge. During the gameplay, players practice this knowledge due to repetition and compile mental models for it. Mental models allow for a training transfer from a training context to a different context. Hence, as GMs can encode any knowledge, they can also encode specific learning contents as their rules and be used for an effective transfer-oriented knowledge training. In this article, we propose the *Gamified Knowledge Encoding* model (GKE) that not only describes a direct knowledge encoding of a specific learning content in GMs, but also defines their training effects. Ultimately, the GKE can be used as an underlying guideline to develop well-tailored game-based training environments.**

I. INTRODUCTION

A computer game consists of multiple *Game Mechanics (GMs)* that define and structure the gameplay by encoding the game's rules and underlying principles [1]. The *interaction* between the individual GMs not only creates a game's gameplay, but also provides players with feedback about the effects, correctness, and results of their actions. One can distinguish between *Game-Bound* (GBGMs) and *Player-Bound* GMs (PBGMs). GBGMs are related to the game story, game type, and underlying principles which ultimately create the overall game environment [1]. PBGMs, such as movement-control and action-performance GMs, are executed by the players for the purpose of interacting [2] with the GBGMs.

For instance, a computer game might feature moving platforms on which a player is required to jump to proceed with the game. The moving platform element is a GBGM that cannot be controlled by a player. In contrast, the ability to jump is a PBGM that can be executed by a player to achieve an interaction. Based on the outcome of this interaction, a clear feedback is provided as players either hit or miss a platform.

In general, the execution of individual GMs requires and hence trains a specific set of human skills [3]. In particular, a player's periodical execution of PBGMs [4] during the gameplay results in a training of *procedural* and *declarative knowledge* [5] on the *level of rule-based human performance* [6]. As the execution of some PBGMs, such as movement and view-control GMs, results in a sensorimotor direct interaction with the game, computer games also achieve a training of procedural knowledge on the level of *skill-based* performance. The acquisition of procedural knowledges is slow, requires a periodical repetition, and passes through three stages [7]. Although declarative knowledge can be acquired quickly, it requires training and periodical deliberate practice [8] to gain expertise [5] and to shift to a more pattern-driven application.

Training transfer is the application of knowledge trained in one context to a different context [9]. The training transfer takes place on the *knowledge-based* performance which is used in unfamiliar situations to complete self-defined goals. At this level of human performance, the reasoning and problem-solving abilities can be explained with *mental models* [10]. Mental models store specific knowledge in complex mental representations that allow for an internal visualization. They can be compiled with repetitive knowledge training on a rule-based and skill-based level [11]. Gamified Training Environments (GTEs), e.g., serious games, support the compilation of mental models as they audiovisually demonstrate and require the learning content [12].

These theoretically grounded aspects of knowledge, human performance, mental models, and GMs are used to define the *Gamified Knowledge Encoding* model *(GKE)*. The GKE describes how a specific learning content can be encoded in GMs and how the training process in a GTE is structured.

II. GAMIFIED KNOWLEDGE ENCODING

The GKE utilizes the interaction between at least one GBGM and one PBGM to require the application of the learning content on a rule-based or skill-based level of human performance. As a result, the training process allows learners to compile a mental model for the encoded knowledge which allows for the training transfer to a targeted real world context. The GMs that encode a knowledge's rules and interact with each other create metaphors for the learning content. They are responsible for a player's knowledge gain by acting as *learning affordances* [13]. Learning affordances require the application of the encoded knowledge and inform about the underlying principles thus providing a means of periodic knowledge training. Hence, we define a gamification metaphor as a knowledge's gamified meta-model which can be fully internalized in the form of mental models during the gameplay.

Working with the GKE (see Figure 1), the learning content first is segmented into smaller and coherent knowledge packages. Then, these knowledge packages are transformed into

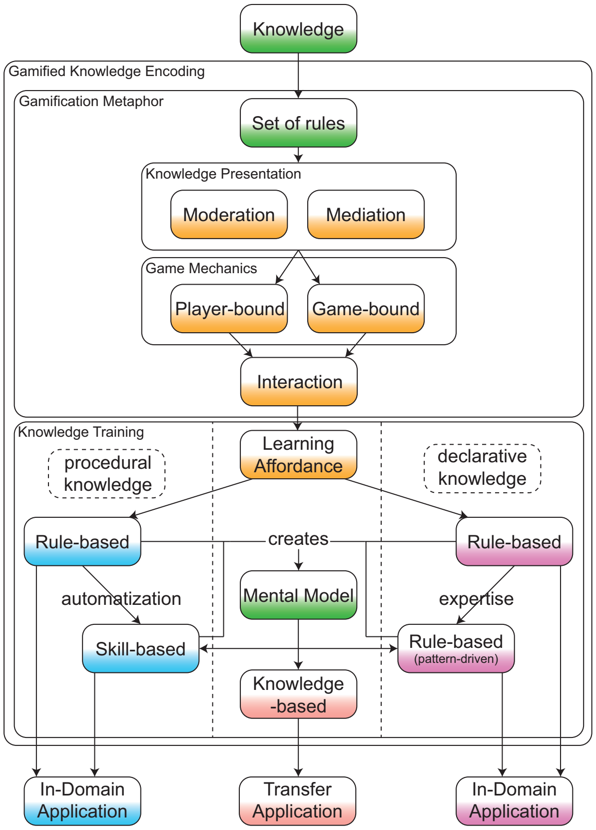


Fig. 1. The GKE describes the process of knowledge encoding and training using GMs. At first, the knowledge gets segmented into coherent sets of rules which can be mapped to GMs. The mapping process is determined by the knowledge presentation allowing for a scaling of the knowledge's level of abstraction by moderating its complexity and/or mediating it using intuitively designed GMs. The GMs used to encode the sets of rules generate a gamification metaphor representing the knowledge inside of the GTE. PBGMs require the application of the knowledge, whereas GBGMs provide learners with feedback or demonstrate the encoded principles. The interaction between individual GMs creates a learning affordance initiating the theoretically grounded knowledge training process.

clear and well-defined rules that are encoded as the game-knowledge rules of interacting GMs. This mapping process includes a *knowledge moderation* and a *knowledge mediation*. The knowledge moderation scales the level of abstraction of the encoded knowledge by adjusting the accuracy and selection of the knowledge rules mapped to the GMs. A moderation can be adjusted over time, e.g., difficulty levels, thus achieving an intuitive knowledge training. The knowledge mediation is the choice and the design of the used GMs which partly depends on the degree of the moderation. A low degree requires GMs that accurately encode the knowledge rules thus simulating the learning content. A high degree reduces the constraints and allows for GMs that represent complex knowledge rules with generalized and intuitive interactions. For instance, a racing simulation can allow for an individual utilization of the clutch or automatically include it in a shifting process.

Utilizing the GKE creates GTEs that fulfill the conditions for optimal learning [8]. By encoding the learning content in interacting GMs, the GTE provides learners with *immediate feedback* about the correctness of their inputs. By adjusting the knowledge moderation, a requirement for *pre-existing knowledge* is achieved. A *periodical knowledge application* is established by the repetitive requirement to execute the gamification metaphor's GMs. Simultaneously, this gameplay results in *highly motivating* flow keeping learners engaged.

III. CONCLUSION

The GKE is, to our best knowledge, the first approach describing how specific knowledge can be directly encoded and trained in GTEs. The model utilizes the general training effects of interacting GMs to encode and require a specific learning content. For this purpose, the knowledge is segmented into coherent packages that are encoded as a GM's internal rules. The GMs require the knowledge's application during the gameplay and visualize the resulting effects thus demonstrating the underlying principles. Players train the encoded knowledge on a *rule-based* and *skill-based level of human performance*. This leads to the compilation of a *mental model* allowing for a knowledge transfer from the GTE to a target context. The GKE ultimately provides a guideline for the development of transfer-oriented GTEs.

REFERENCES

[1] E. Adams and J. Dormans, *Game Mechanics*, ser. Advanced Game Design. Berkeley: New Riders, 2012.
[2] M. Sicart, "Defining game mechanics," *Game Studies*, vol. 8, no. 2, 2008.
[3] S. Oberdörfer and M. E. Latoschik, "Develop your strengths by gaming," *Informatik 2013 - Proceedings of 43rd annual German conference on informatics*, vol. P-220, pp. 2346–2357, 2013.
[4] J. P. Gee, *What video games have to teach us about learning and literacy*, 1st ed. New York: Palgrave Macmillan, 2007.
[5] J. R. Anderson, *Cognitive Psychology and Its Implications*, 8th ed. Worth Publishers, 2015.
[6] J. Rasmussen, "Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 13, no. 3, pp. 257–266, 1983.
[7] P. M. Fitts and M. I. Posner, *Human performance*. Brooks Cole, 1967.
[8] K. A. Ericsson, R. T. Krampe, and C. Tesch-Römer, "The role of deliberate practice in the acquisition of expert performance," *Psychological Review*, vol. 100, no. 3, pp. 363–406, 1993.
[9] C. J. Dede, J. Jacobson, and J. Richards, "Introduction: Virtual, augmented, and mixed realities in education," in *Virtual, Augmented, and Mixed Realities in Education*, ser. Smart Computing and Intelligence, D. Liu, C. J. Dede, R. Huang, and J. Richards, Eds. Singapoore: Springer, 2017.
[10] P. N. Johnson-Laird, *Mental Models. Towards a Cognitive Science of Language, Inference, and Consciousness.* Harvard University Press, 1983.
[11] T. Lynam, R. Mathevet, M. Etienne, S. Stone-Jovicich, A. Leitch, N. Jones, H. Ross, D. Du Toit, S. Pollard, H. Biggs, and P. Perez, "Waypoints on a journey of discovery: Mental models in human-environment interactions," *Ecology and Society*, vol. 17, no. 3, 2012.
[12] L.-M. Palmunen, E. Pelto, A. Paalumäki, and T. Lainema, "Formation of novice business students' mental models through simulation gaming," *Simulation & Gaming*, vol. 44, no. 6, pp. 846–868, 2013.
[13] B. Dalgarno and M. J. W. Lee, "What are the learning affordances of 3-d virtual environments?" *British Journal of Educational Technology*, vol. 41, no. 1, pp. 10–32, 2010.

4.2 Direct Knowledge Encoding

The comprehensive definition of the Gamified Knowledge Encoding bases on the following article which is presented and discussed in subsection 7.2:

Oberdörfer, S. and Latoschik, M. E. Knowledge Encoding in Game Mechanics: Transfer-Oriented Knowledge Learning in Desktop-3D and VR. *International Journal of Computer Games Technology*, 2019, 2019. doi: 10.1155/2019/7626349

The Gamified Knowledge Encoding maps a learning content as game rules to interacting game mechanics. The knowledge encoding is determined by the *moderation*, i.e., the degree to which knowledge rules are simplified, and the *mediation*, i.e., the concrete realization of a game mechanic. The resulting gameplay creates learning affordances for the knowledge to be learned (Dalgarno and Lee, 2010). A learning affordance requires an interaction with the learning environment and simultaneously informs about the underlying principles (Kaptelinin and Nardi, 2012). Generally, the term affordance describes an action possibility in an environment that exists relative to an actor's capabilities but is independent of the actor's ability to perceive it (Gibson, 1979). Affordances are a fundamental concept in Human-Computer Interaction and interaction design in general. Here, an affordance refers to the actual and the perceived properties of an object and suggests how the object should by used by an actor (Norman, 1988, 1999).

A *direct knowledge encoding* is achieved by segmenting the learning content into smaller packages of which each describes a coherent part of the knowledge. Each knowledge package then is transformed into clear and well-defined gameplay rules. Subsequently, interacting game mechanics encode these rules as their internal rules. Player-bound game mechanics encode rules defining and requiring the actual knowledge application as game inputs. Game-bound game mechanics act as a verification system to check if a player's inputs are correct or as a demonstration system to visualize the inputs' effects. The interaction between a gamification metaphor's game mechanics requires the knowledge's application and informs about the underlying principles by providing immediate feedback. This mapping process ultimately generates a *gamification metaphor* representing and requiring the learning content inside of a serious game. At least one of a gamification metaphor's interacting game mechanics requires a knowledge application to overcome the learning environment's challenges, whereas the other game mechanic acts as a fixed point providing feedback about the correctness of a learner's approach.

For instance, a simple gamified learning environment for formulas of the alkanes may be implemented with a single gamification metaphor consisting of three interacting game mechanics: a player-bound control interface, a game-bound display, and a game-bound unlockable door. Working with the Gamified Knowledge Encoding, the knowledge is segmented into two packages. One package contains the list of the alkanes with their respective formulas. The other package contains the underlying principles of generating correct chemical formulas. Subsequently, the rules of the list are mapped to the display and the rules of generating chemical formulas are mapped to the control interface. The resulting gameplay requires players to apply their knowledge to generate the corresponding formula of an alkane being shown on the display. The control interface provides two rotatable disks which are labeled with a C (for carbon) and an H (for hydrogen). Similar to a telephone dial, the disks feature numbers, thus allowing players to enter the alkane's respective formula by rotating the disks. As soon as the correct formula is generated, i.e., it matches the expected formula, the door gets unlocked and the player may proceed to the next challenge.

4.3 Knowledge Moderation

The more complex or abstract a knowledge is, the more difficult it becomes to comprehend it. This is mainly due to the fact that abstract knowledge and related problems are hard to demonstrate or to visualize. It often escapes an intuitive approach and causes solving learning assignments to be even more challenging. As a result, learners may experience a high degree of frustration that negatively impacts their motivation to continue with the learning process. This leads to a reduced learning outcome. Thus, to limit these issues, it is critical to provide them with intuitive as well as motivating learning methods. These learning methods should allow them to visualize the underlying principles in a clear way and provide them with immediate feedback about their learning progress.

The *knowledge moderation* scales the level of abstraction of the encoded knowledge by adjusting the accuracy and the selection of the sets of knowledge rules mapped to the gamification metaphor. This creates a direct knowledge encoding that ranges from a non-moderated accurate simulation to a highly moderated simplified and intuitive knowledge application as well as demonstration. By adjusting the moderation to a player's performance, the level of abstraction matches a learner's knowledge gain. This relies on the game design principle of continuously increasing the difficulty to keep players challenged and in flow (McGonigal, 2011).

A learning process of abstract knowledge may begin with a very intuitive demonstration of the learning contents. This is achieved by merely encoding a simplified set of rules, thus establishing a certain distance to the knowledge. Subsequently, as the learners progress through the gameplay, more complex sets of rules are mapped to the game mechanics. This reduces the initial distance to the knowledge over time. Finally, the complete and non-moderated set of rules is mapped to the game mechanics to completely close the distance and to achieve the knowledge's simulation. When adjusted well, the game's challenge and difficulty increase matches with the current knowledge or skill level of the players.

4.4 Knowledge Mediation

The *knowledge mediation*, i.e., the selection and the realization of game mechanics, allows for an adjustment of the accuracy of the learning content's presentation and application. It can either be direct or mediated. A direct knowledge presentation demonstrates and requires the knowledge in a way which is similar to the knowledge's target context. A knowledge mediation, however, reduces the complexity of the presentation as well as the application, thus achieving a more intuitive approach to the learning content. However, the knowledge mediation partly depends on the degree of the knowledge moderation. A low degree of knowledge moderation requires game mechanics that accurately encode the knowledge rules, i.e., they remodel and simulate a particular real world application. In contrast, a high degree of knowledge moderation reduces the constraints and allows for game mechanics that represent complex knowledge rules with generalized and intuitive interactions.

For instance, a driving simulation can require an individual utilization of the clutch but also automatically include it during a shifting process. In the former version, two separate game mechanics are needed while in the latter implementation one game mechanic combines both activities resulting in a more simplified knowledge presentation. Thus, knowledge mediation can also scale the level of abstraction. It allows for a direct encoding of non-moderated knowledge rules in game mechanics that integrate and combine several sets of rules to achieve an intuitive application. In conclusion, the moderation and the mediation define a knowledge's application and demonstration.

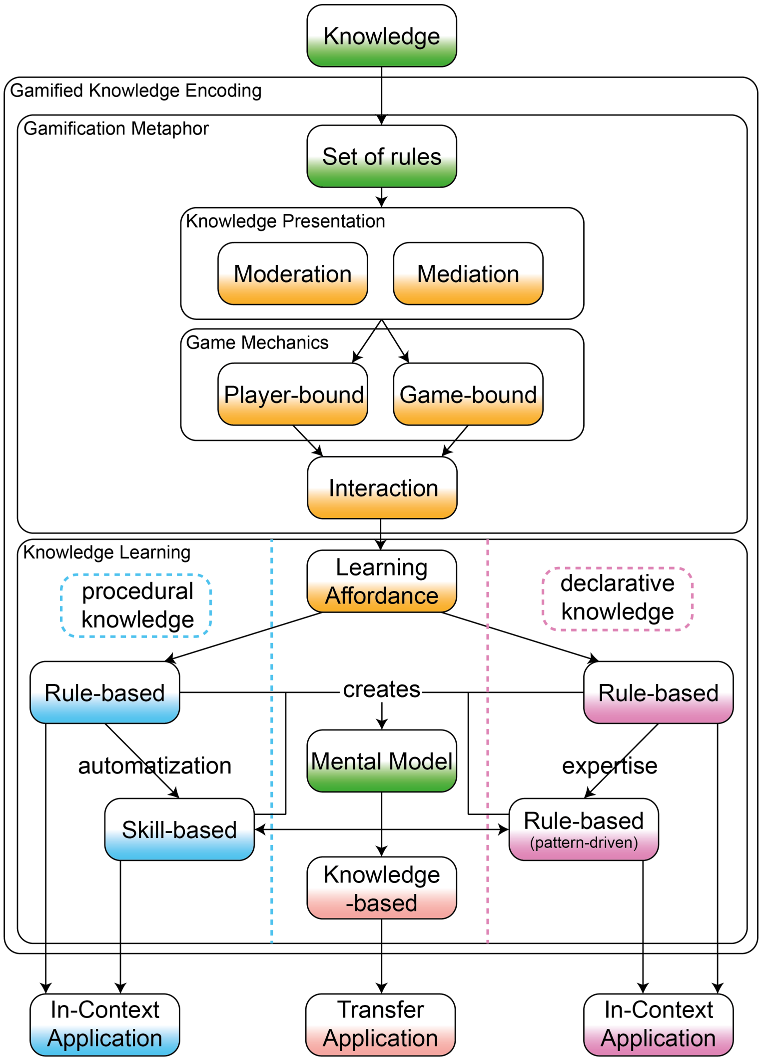


Figure 2: The Gamified Knowledge Encoding describes the process of knowledge encoding and learning using game mechanics. The knowledge gets segmented into coherent sets of rules which are mapped as game rules to interacting game mechanics. The interaction between these game mechanics creates a learning affordance for the encoded learning content. This initiates the theoretically grounded learning process.

4.5 Discussion

The definition of the Gamified Knowledge Encoding model answers the following RQs:

RQ2: How do game mechanics demonstrate and require the application of knowledge during the gameplay?

RQ3: How can (abstract) knowledge be directly encoded in computer games using game mechanics?

Utilizing the Gamified Knowledge Encoding model creates serious games that fulfill the conditions for optimal learning (Ericsson et al., 1993). By encoding the learning content in interacting game mechanics, the serious game automatically provides learners with *immediate feedback* about the correctness of their inputs. By moderating the knowledge's level of abstraction, *highly motivating* flow as well as a requirement for *preexisting knowledge* are created. Finally, a *repetitive knowledge application* is established by the requirement to frequently execute the gamification metaphor's game mechanics during the gameplay.

The Gamified Knowledge Encoding defines the direct knowledge encoding in game mechanics and the resulting learning process during the gameplay. However, to ensure for a good playability, additional game mechanics targeting either entertaining aspects or providing further gameplay enhancements may be provided. For instance, *Kerbal Space Program* encodes knowledge of orbital mechanics in its core game mechanics. As a result, players learn and practice this knowledge during the gameplay (see subsection 7.3). In addition to the orbital mechanics gamification metaphors, *Kerbal Space Program* implements further game mechanics to increase the overall playability, e.g., by realizing a career mode or by allowing players to plant flags and to conduct experiments on the surface of a celestial body. By providing further game mechanics in addition to the ones used in the gamification metaphors, a serious game's overall entertaining and motivating aspects is improved.

In conclusion, the Gamified Knowledge Encoding utilizes game mechanics as an educational tool by mapping knowledge rules to them, thus directly encoding the learning content (see Figure 2). The model utilizes the interaction between at least one game-bound game mechanic and one player-bound game mechanic to require the application of the encoded principles on a rule-based or skill-based level of human performance. Learners are provided with immediate feedback about the effects of their actions, i.e., a demonstration of the underlying principles, and their learning progress. This gamified learning process allows learners to compile a mental model for the knowledge. The mental model ultimately is utilized to apply the knowledge on a knowledge level, i.e., transferring it from the serious game to a real world context. The game mechanics that encode the knowledge's rules and interact with each other are metaphors for the learning content. They are responsible for a player's knowledge gain by acting as learning affordances. A gamification metaphor is defined as a *knowledge's gamified metamodel* which can be fully internalized in form of mental models during the gameplay.

5 Game Development Using the Gamified Knowledge Encoding

The game consists of the need to find or continue at once a response which is free within the limits set by the rules. – Roger Caillois (2001)

The validation of the Gamified Knowledge Encoding model was approached with a two-step process by 1) developing a serious game using the Gamified Knowledge Encoding and 2) analyzing the game's learning outcome. As learning content, the affine transformations knowledge was selected and encoded in game mechanics. These game mechanics subsequently were implemented in the serious game *GEtiT (Gamified Training Environment for Affine Transformations)*. While *GEtiT*'s central goal is to educate players about affine transformations, the system is used as a demonstrator for the validity of the Gamified Knowledge Encoding in this thesis. This chapter reports on the game design process guided by the Gamified Knowledge Encoding.

5.1 GEtiT

An in-depth understanding of affine transformations is essential for many engineering areas including 3D computer graphics (Foley, van Dam, Feiner, and Hughes, 1990), robotics (Fu, Gonzalez, and Lee, 1987), and the development of immersive Virtual Reality (VR) and Augmented Reality (AR) applications. Affine transformations are part of linear algebra, a sub-field of mathematics, and are specialized functions that map between affine spaces, thus preserving points, straight lines as well as planes. Usually, in the case of 3D space, they are expressed as 4x4 homogeneous matrices and their operations as matrix-matrix multiplications of which each matrix represents one particular mapping. In contrast to more simplistic geometric tasks that allow for an intuitive understanding, the utilization of homogeneous coordinates to express affine transformations often escapes an intuitive approach. As the affine transformation cannot easily be demonstrated, it is difficult for learners to visualize problems and to comprehend the effects of certain operations.

Therefore, developing a serious game for affine transformations can greatly increase the learning outcome and help learners to visualize and to test problems. Also, the computer games' potential to visualize complex information and to achieve a spatial skill training can facilitate the learning process (see subsection 2.3). This is crucial for *GEtiT* as training spatial abilities simultaneously improves 3D geometry thinking (Pittalis and Christou, 2010). Vice-versa, training descriptive geometry assists the development of spatial abilities (Gittler and Glück, 1998). In addition, 3D graphics engines already use affine transformations for the purpose of displaying the 3D environments. *GEtiT* not only demonstrates the effects of affine transformation, it is even based on them thus giving students an immediate example of potential real world use cases.

Table 6: Interactive Gamified 3D-Training of Affine Transformations

Author	**Contribution**
Oberdörfer, S.	Literature review, conceptual design, manuscript preparation and revision
Latoschik, M. E.	Manuscript preparation and revision

Oberdörfer, S. and Latoschik, M. E. Interactive gamified 3D-training of affine transformations. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*, pages 343–344, Munich, Germany, 2016. ACM. doi: 10.1145/2993369.2996314

Interactive Gamified 3D-Training of Affine Transformations

Sebastian Oberdörfer[*] Marc Erich Latoschik[†]
Chair for Human-Computer Interaction, University of Würzburg

Figure 1: *Symbols displayed on the cards indicate the different transformation types and their effects in GEtiT.*

Abstract

This article presents the Gamified Training Environment for Affine Transformations (GEtiT). GEtiT uses a 3D environment to visualize the effects of object rotation, translation, scaling, reflection, and shearing in 3D space. It encodes the abstract knowledge about homogeneous transformations and their order of application using specific game mechanics encoding 3D movements on different levels of abstraction. Progress in the game requires mastering of the game mechanics of a certain level of abstraction to modify objects in 3D space to a desired goal position and/or shape. Each level increases the abstraction of the representation towards a final 4×4 homogeneous matrix representation. Executing the game mechanics during the gameplay results in an effective training of knowledge due to a constant repetition. Evaluation showed a learning effect that is equal to a traditional training method while it achieved a higher enjoyment of use indicating that the learning quality was superior to the traditional training method.

Keywords: gamification, education, serious games, virtual reality

Concepts: •Software and its engineering → Interactive games; Virtual worlds training simulations; •Computing methodologies → Virtual reality;

1 Introduction

In-depth understanding of homogeneous transformations (HTs) is essential for many engineering areas including Virtual and Augmented Reality (AR, VR), 3D computer graphics, or robotics. However, in contrast to simple geometric tasks with an intuitive understanding, the homogeneous representation of transformations, their matrix form with potentially interdependent values, and the dependence of the order of application (i.e., multiplication of matrices) often escape an intuitive approach. Students have to understand how the theoretical grounded abstract aspects of transformations result, e.g., in changes of the object's position, rotation or dimensions and more but often encounter problems that ultimately lead to a high degree of frustration.

We developed a training system to master the application of Affine Transformations (AT), an important subset of transformations encoding rotation, translation, scaling, reflection, and shearing which are expressible as HTs. The Gamified Training Environment for Affine Transformations (GEtiT) visualizes the effects of an AT in an immersive 3D environment and encodes the learning content in its game mechanics. Each computer game consists of several game mechanics [Sicart 2008; Adams and Dormans 2012]. Here, they are used to encode the game's knowledge which is subsequently trained due to repetition [Gee 2007]. Furthermore, game mechanics demand and hence train a certain set of human skills [Oberdörfer and Latoschik 2013]. Finally, game mechanics have the potential to directly encode even abstract knowledge thus creating intuitive training environments for complex learning contents.

The GEtiT game mechanics were designed to increase in their level of abstraction as well as in the complexity of the mutual application of multiple transformations thus resulting in a gradual increase of the learning content's as well as game's difficulty. This increase in difficulty combined with constant feedback in 3D and new challenges ultimately creates a desired game flow [Csikszentmihalyi 2010; McGonigal 2011]. Hence, GEtiT is also intended to demonstrate our method describing how abstract knowledge can be directly encoded in game mechanics and to subsequently evaluate the game mechanics' potential to directly encode abstract knowledge.

2 System Design

GEtiT needs to fulfill three main requirements as an effective training system: (1) The different levels of abstraction in specification of transformations require tailored input methods. (2) Clear and intuitive feedback has to be provided to allow the players to evaluate the outcome of their actions. (3) A well-defined task is needed in order to provide the learners with a clear goal and to challenge them to apply their AT knowledge.

We adopted the idea to use a manipulable object as a common game mechanic of many computer games. In the case of GEtiT, the use case of this game mechanic is twofold: On the one hand, the object

---

[*] e-mail:sebastian.oberdoerfer@uni-wuerzburg.de
[†] e-mail:marc.latoschik@uni-wuerzburg.de

VRST '16, November 02-04, 2016, Garching bei München, Germany
ISBN: 978-1-4503-4491-3/16/11
DOI: http://dx.doi.org/10.1145/2993369.2996314

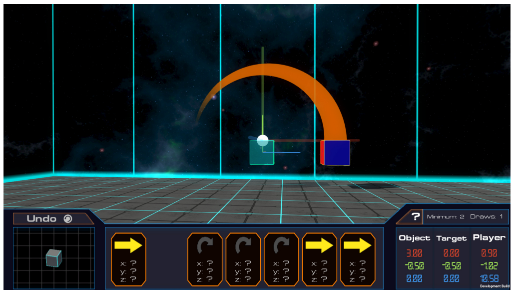


Figure 2: *Executing a rotation transformation in GEtiT.*

gets transformed based on the players' inputs thus giving them a clear feedback on the correctness of their approach. On the other hand, the object game mechanic internally stores the object's current status which can be used as a goal. The learners are then required to transform the object in such a way that it matches the victory conditions, which are displayed in form of a half-transparent object, for a particular training task (see Fig. 2).

Figure 3: *GEtiT's UI demands the application of AT.*

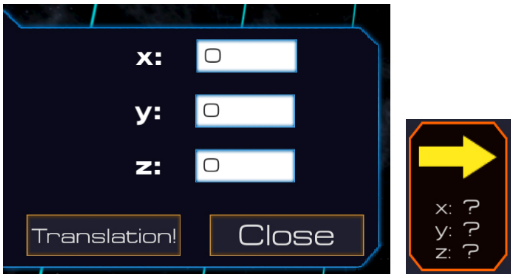


Figure 4: *Users are required to use their computational results.*

We developed a special user interface (UI) that gives the players access to AT types (properties and effects) and informs them about the object's, target's and player's position. The AT types are symbolized by cards that display a symbol indicating the type of the transformation as well as the predefined values (see Fig. 1). Depending on the game's setting, activation immediately transforms the object according to the predefined values or opens a direct value configuration screen (see Fig. 3) in order to accept self-determined computational results. In addition, the first two difficulty settings use a vector representation (see Fig. 4) of the transformations whereas the last two difficulty settings utilize a matrix representation. Both methods are used as one way to increase the level of abstraction as well as the difficulty of the learning content.

The learning tasks are created with the general game mechanic of the level design, the selection of available AT types, as well as the victory conditions. The level design determines the initial position of the object, the level's origin, and the target's position. Also, the level design is used to place obstacles between the object's initial position and the target thus requiring the learners to translate the object around the obstacles.

In addition, for the purpose of providing the players with a clear goal, a fourth game mechanic—an exit portal to escape a particular level—was added to GEtiT. The portal is, however, deactivated at the start of a level. Hence, the players are challenged to activate the portal by transforming the object in such a way that it matches the victory conditions. This way, GEtiT's gameplay becomes meaningful [McGonigal 2011] to the players and increases their motivation to tackle the learning tasks.

GEtiT players start trapped in a sealed room from which they can only escape when they open the portal. In order to do so, they need to transform the object using their transformation types in such a way that it matches the victory conditions. However, they have to pay attention to the environment as the object can not translate through obstacles that are placed inside a particular level. Once the object matches the victory conditions, the portal gets activated and the players can proceed to the next level.

3 Results and Conclusion

We have evaluated the learning effects of playing GEtiT during the summer term of 2016 by inviting students who visited a lecture on Interactive Computer Graphics to participate in our study. After being randomly assigned to a game group or a control group, the participants trained their AT knowledge with GEtiT or alternatively with traditional assignments as a control group. Finally, all completed an exam in order to assess their learning outcome.

During our study, GEtiT achieved a learning effect that is equal to the learning effect of a traditional training method. Furthermore, GEtiT achieved a higher enjoyment of use than the traditional training method indicating that the learning quality was superior to the traditional training method.

Acknowledgements

We would like to thank David Heidrich for his contributions to GEtiT.

References

ADAMS, E., AND DORMANS, J. 2012. *Game Mechanics*. Advanced Game Design. New Riders, Berkeley.

CSIKSZENTMIHALYI, M. 2010. *Flow : Das Geheimnis des Glücks*, 15 ed. Klett-Cotta, Stuttgart.

GEE, J. P. 2007. *What video games have to teach us about learning and literacy*, 1 ed. Palgrave Macmillan, New York.

MCGONIGAL, J. 2011. *Reality is broken : why games make us better and how they can change the world*, 1 ed. Penguin Press, New York.

OBERDÖRFER, S., AND LATOSCHIK, M. E. 2013. Develop your strengths by gaming. *Informatik 2013 - Proceedings of 43rd annual German conference on informatics P-220*, 2346–2357.

SICART, M. 2008. Defining game mechanics. *Game Studies 8*, 2.

5.2 GEtiT VR

After the successful application of the Gamified Knowledge Encoding to develop a desktop-3D serious game, i.e., *GEtiT*, it was important to test the model's applicability for the design of serious games being visualized with other technologies. For comprehensively analyzing the educational potential of using game mechanics, it was also important to analyze whether the visualization technology used has an effect on the learning outcome. To complete these two intermediate research goals, this thesis discusses and evaluates the effects of visualizing *GEtiT*'s gameplay using HMD-VR. This technology was selected because of its high potential to increase the effectiveness of using game mechanics for a knowledge learning.

The functionality of HMD-VR allows users to easily change their perspectives which facilitates the analysis of complex learning contents like 3D geometry (Dede, 2009). As an audiovisual presentation supports the compilation of mental models (Weidenmann, 2009), a full visual immersion in an VE which demonstrates a specific learning content should further enhance the learning outcome. A higher visual immersion and presence leads to a higher performance in the case of a training scenario (Stevens and Kincaid, 2015). By providing an accurate and intuitive simulation as well as an audiovisual presentation of the learning content, e.g., by simulating complex machinery (Rogers, El-Mounaryi, Wasfy, and Satterwhite, 2017) or by using avatars that directly demonstrate the application, implicit learning is achieved in VR (Slater, 2017; Reber, 1989). As game mechanics can provide such an accurate simulation of specific learning contents, visualizing them in VR might enhance their educational effects. Also, presence has a mediating effect on the learning outcome as it affects a student's intrinsic motivation and enjoyment, thus increasing the perceived learning quality and satisfaction (Makransky and Lilleholt, 2018). Overall, immersive VR achieves an immersive and natural experience (Salomoni, Prandi, Roccetti, Casanova, and Marchetti, 2016), provides the advantages of increasing a student's motivation as well as engagement, and allows for a constructivist approach of learning (Freina and Ott, 2015; Martín-Gutiérrez, Mora, Añorbe-Díaz, and González-Marrero, 2017).

The effectiveness of implementing VR technology for realizing effective learning environments was evaluated using an immersive VR-based classroom simulation: *Breaking Bad Behaviours* (Lugrin, Latoschik, Habel, Roth, Seufert, and Grafe, 2016). The collaborative system allows pre-service and in-service teachers to practice their classroom management skills in the safe environment of a virtual simulation. In a user study, *Breaking Bad Behaviours* was compared to a traditional video-based approach in respect to the achieved learning outcome (Lugrin, Oberdörfer, Latoschik, Wittmann, Seufert, and Grafe, 2018b). By revealing a better learning outcome when using the VR simulation for practicing classroom management skills, the study supports the beneficial effects of using immersive VR for realizing effective learning environments, e.g., serious games. Subsequently, *Breaking Bad Behaviours* received an atmosphere plugin system, i.e., a game-bound game mechanic, to generate more believable classroom atmospheres (Lugrin, Charles, Habel, Dudaczy, Oberdörfer, Matthews, Porteous, Wittmann, Seufert, Grafe, and Latoschik, 2018a). Depending on the setting, e.g., highly disciplined or very agitated, virtual students automatically react to activated disturbances, thus creating new challenges for the learner. In this way, the classroom atmosphere game mechanic further requires the application of classroom management skills.

Based on these theoretical considerations, designing a specific *GEtiT VR* version leads to a visualization of the gameplay in an immersive as well as more natural way. This should allow for an easier compilation of mental models and hence a better learning outcome. Also, it should increase a learner's motivation and satisfaction when practicing the application of affine transformations. *GEtiT VR* implements the same gamification metaphor as *GEtiT* but realizes it in a diegetic way to increase the overall sense of presence and usability (Galloway, 2006; Bowman, McMahan, and Ragan, 2012; Salomoni et al., 2016).

Table 7: Interactive Gamified Virtual Reality Training of Affine Transformations

Author	**Contribution**
Oberdörfer, S.	Literature review, conceptual design, manuscript preparation and revision
Heidrich, D.	Conceptual design
Latoschik, M. E.	Manuscript revision

Oberdörfer, S., Heidrich, D., and Latoschik, M. E. Interactive Gamified Virtual Reality Training of Affine Transformations. In Ullrich, C. and Wessner, M., editors, *Proceedings of DeLFI and GMW Workshops 2017*, Chemnitz, Germany, 2017

Interactive Gamified Virtual Reality Training of Affine Transformations

Sebastian Oberdörfer[1], David Heidrich[1], Marc Erich Latoschik[1]

Abstract: Affine transformations which are used in many engineering areas often escape an intuitive approach due to their high level of complexity and abstractness. Learners not only need to understand the basic rules of matrix algebra but are also challenged to understand how the theoretically grounded aspects result in object transformations. Therefore, we developed the Gamified Training Environment for Affine Transformation that directly encodes this abstract learning content in its game mechanics. By intuitively presenting and demanding the application of affine transformations in a virtual gamified training environment, learners train the application of the knowledge due to repetition while receiving immediate and highly immersive visual feedback about the outcomes of their inputs. Also, by providing a flow-inducing gameplay, users are highly motivated to practice their knowledge thus experiencing a higher learning quality. As the immersion, presence and spatial knowledge presentation can have a positive effect on the training outcome, GEtiT explores the effectivity of different visual immersion levels by providing a desktop and a VR version. This article presents our approach of directly encoding the abstract learning content in game mechanics, describes the conceptual design as well as technical implementation and discusses the design differences between the two GEtiT versions.

Keywords: Gamification; Virtual Reality; Education; Knowledge Training

1 Introduction

In-depth understanding of affine transformation (AT) is critical for many engineering areas including robotics, 3D computer graphics, or Virtual and Augmented Reality (AR, VR). However, due to the complexity of the learning content, e.g., ATs for operations in $\mathbb{R}^3$ are commonly expressed as 4×4 matrices, developing an in-depth understanding often escapes an intuitive approach as students are challenged to learn how the theoretically grounded mathematical aspects achieve a transformation of an object thus resulting in a high degree of frustration. Furthermore, ATs are order dependent and hence different sequences of the same transformation operations can result in different outcomes. Finally, students have to understand the basic rules of matrix algebra as mappings between affine spaces are executed via matrix multiplications.

---

[1] University of Würzburg, Human-Computer Interaction, Am Hubland, 97074 Würzburg, Germany,
sebastian.oberdoerfer@uni-wuerzburg.de, david.heidrich@stud-mail.uni-wuerzburg.de,
marc.latoschik@uni-wuerzburg.de

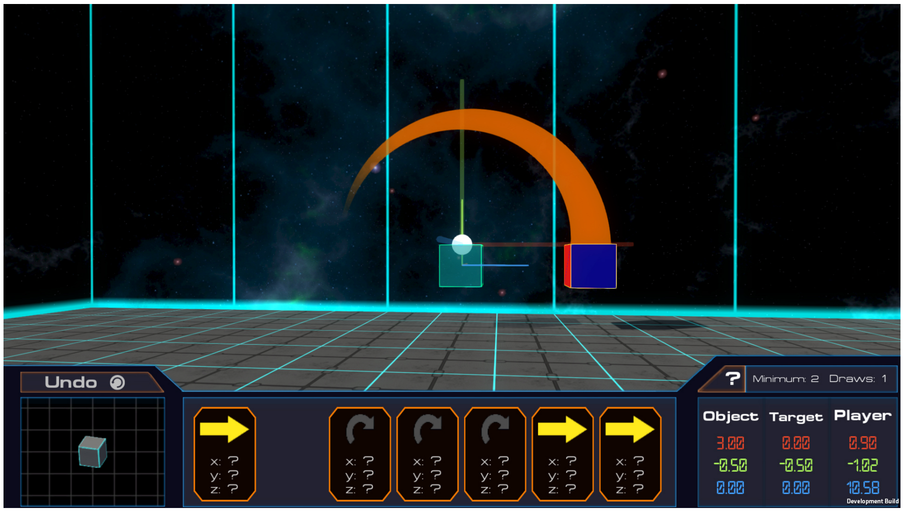


Fig. 1: *GEtiT* intuitively demonstrates the effects of the AT and challenges learners to apply their knowledge to solve puzzle exercises.

Therefore, we developed a virtual gamified training environment–the *Gamified Training Environment for Affine Transformation (GEtiT)* –to intuitively train and master the application of ATs, i.e., application of transformations allowing for object translation, rotation, scaling, reflection, and shearing [OL16]. In order to do so, we developed a model to directly encode the AT knowledge in game mechanics that periodically demand the knowledge's application, provide visual feedback about the correctness and hence lead to a knowledge training due to repetition (see Figure 1). Also, as a higher visual immersion can lead to a higher presence and performance [Sl96] in the case of a virtual training simulation [SK15], we developed a specific VR version to potentially increase GEtiT's training effects by achieving a higher presence as well as a higher and more intuitive spatial knowledge presentation. For this purpose, *GEtiT-VR* implements the same core game mechanics but utilizes a higher immersive visual presentation to allow for a direct experience of an AT operation's effects. Ultimately, GEtiT is intended to demonstrate the effectivity of our knowledge encoding model which we currently prepare for publication.

This paper describes the conceptual design and technical implementation of both GEtiT versions which are based on our direct gamified knowledge encoding model, discusses their differences and presents our expectations towards their individual training effects. The paper begins with a brief description of our model we developed in order to directly encode the AT knowledge in GEtiT using game mechanics. Subsequently, we present the concept as well as technical implementation of the two GEtiT versions. Finally, this paper discusses

---

http://www.hci.uni-wuerzburg.de/projects/getit.html the similarities and differences between GEtiT's desktop as well as the VR version and concludes with our expectations towards the individual training effects.

2 Direct Knowledge Encoding

Game mechanics are the rules of a computer game that define what is possible, create the virtual game world [AD12] and allow players to interact [Si08] with the game. Furthermore, utilizing game mechanics demands and hence trains a specific set of human skills [OL13]. By periodically executing game mechanics, players train the encoded knowledge due to repetition [Ge07]. Learning due to repetition, or practicing, is a very important aspect of learning new knowledge as it helps learners to achieve an automatization or deepening of the learning content which facilitates a knowledge transfer to a different domain or unknown problem [Br00, Me04]. Hence, game mechanics have the potential to directly encode even abstract knowledge as their rules thus creating intuitive training environments for complex learning contents. That way, the game mechanics create a gamification metaphor for the learning content that acts as a learning affordance [DL10, KN12]. Learning affordances achieve a periodic knowledge training by demanding the application of the encoded knowledge and informing about the underlying principles.

Moreover, GEtiT moderates the knowledge's level of abstractness to facilitate the training process by intuitively presenting and demanding the learning content. For this purpose, the game mechanics were designed to scale in the complexity and level of abstractness thus resulting in a gradual increase in the learning content's as well as game's difficulty. Also, the gradual difficulty increase in combination with an immediate feedback as well as a constant stream of new challenges creates the potential for game flow [Cs10, Mc11] that keeps learners motivated and engaged.

3 Conceptual Design

Aside from encoding the AT knowledge rules in its game mechanics, GEtiT, in order to ensure an effective AT training, needs to fulfill three additional requirements: (1) The moderation of the level of abstractness requires a tailored gamification metaphor that scales the learning content's complexity. (2) A clear, intuitive and immediate feedback has to be provided to allow learners to analyze and visualize the effects of an AT operation and to learn from their potential mistakes. (3) Finally, a well-defined game goal is needed to challenge and motivate the learners to apply their AT knowledge.

As, in case of 3D computer graphics and VR/AR applications, the AT is used to transform and display objects, we adopted a frequently used manipulable object game mechanic in order to achieve similarities between the gamified training environment and a potential real world application of the learning content to facilitate a knowledge transfer process

Fig. 2: The symbols displayed on the AT cards indicate the transformation type.

[DL10, OP13]. However, instead of allowing for a direct manipulation which is commonly used in many computer games, GEtiT requires the application of an AT operation to manipulate, or transform, the object. That way, as the object immediately gets transformed based on the learners' inputs (see Figure 1), the game mechanic provides them with a visual feedback about the effects and correctness of their chosen approaches. For the purpose of enhancing the feedback, the object also casts a trail each time it gets transformed thus visualizing the effects of an individual AT and helping the learners to intuitively develop a spatial understanding for the AT knowledge. Furthermore, as the object internally stores its status, the object game mechanic also is used to provide the players with a clear goal. Each training exercise challenges them to transform the object in such a way that it matches specific victory conditions which are displayed in form of a half-transparent object ultimately representing the players' goal.

1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1

Fig. 3: On hard difficulty, learners see the matrix representation for the first time, but are only required to enter the matrix elements relevant for the chosen transformation type using the direct value configuration screen.

For the purpose of using AT operations as game inputs and achieving a moderation of the level of abstractness, we developed a special UI that provides users with access to AT operations and simultaneously informs them about the object's, target's and player's position. The AT operations are represented by AT cards of which each represents an individual mathematical operation. The AT cards display a symbol indicating the AT type (see Figure 2) and a symbolized vector or matrix representation showing predefined and undefined elements. Hence, the AT cards scale the complexity of the learning content thus achieving a moderation of the level of abstractness. GEtiT features four difficulty levels that gradually increase the learning content's abstractness. On easy difficulty, the gamified training environment only provides predefined vector AT cards that, upon activation, automatically perform the displayed transformation, and, as a result of this, learners merely need to select the correct cards to solve a level. The remaining three difficulty levels feature undefined AT cards that open a direct value configuration screen (see Figure 3) on activation allowing for the use of self-obtained computational results as inputs to the game. On medium difficulty, GEtiT still utilizes the vector representation but challenges the users to enter the vector elements. Once students move on to hard difficulty, GEtiT starts to use the 4×4 matrix representation but only requires the learners to configure those of the matrix elements that are relevant for the AT type displayed on the selected card. Finally, on expert difficulty, the moderation of the level of abstractness is scaled back completely as learners are challenged with a full transformation matrix demanding them to enter every element. At this point, the expert difficulty simulates the AT knowledge as it implements the complete set of AT knowledge rules that are directly encoded in the gamification metaphor.

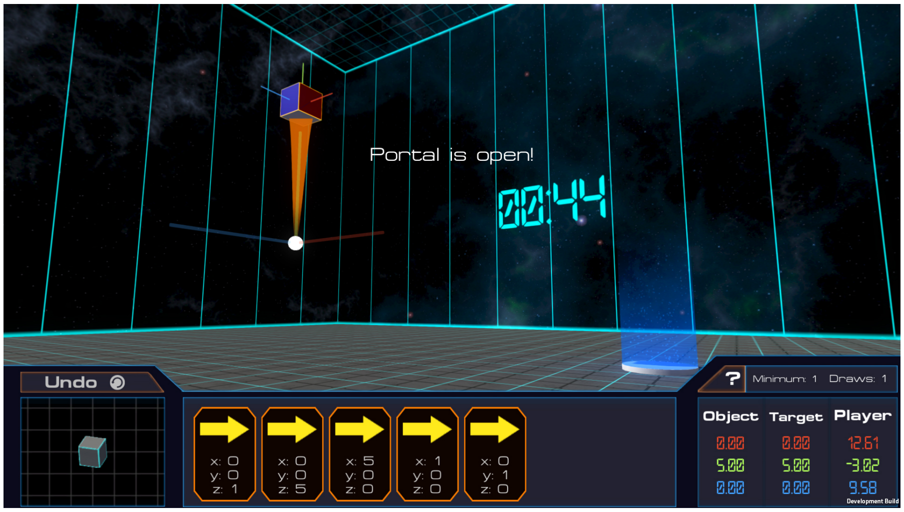


Fig. 4: After having matched the victory conditions with the object, a portal gets activated and allows players to exit the level.

The gamified training exercises are created by the level design, a selection of available AT cards, and the level-specific victory conditions. The level design determines the object's initial position, the origin's position and the position of potential obstacles that can block the object thus adding another challenge to the gameplay as players are required to translate the object around them. Also, in order to give the puzzle exercises an important meaning [Mc11], they were embedded in an escape scenario being inspired by the gameplay of Portal which puts players in sealed rooms and challenges them to open the levels' exits by solving spatial puzzles. Similar to Portal, each of GEtiT's levels represents a sealed room players have to escape from by opening the level's exit–a portal (see Figure 4)–and walking through it. This, however, can only be done by solving spatial puzzles, i.e. transforming the object in such a way that it matches a level's victory conditions which subsequently opens the exit thus allowing the player to proceed to the next level (see Table 1). In addition, some levels challenge the learners to use the object as a stepping stone in order to reach the top of an obstacle or to cross a bottomless gap. As a result of this, not only the gameplay but also the AT knowledge itself becomes meaningful to the players as GEtiT turns it into a tool that allows them to exhaust the challenges.

Tab. 1: Overview of GEtiT's gameplay

Step	Task	Game mechanics
1	Enter a level	-
2	Analyze the level's spatial puzzle	Level design Object start position Victory conditions
3	Transform the object to match victory conditions using the available AT cards	AT cards Manipulable object Victory conditions
4	Leave the level	Portal

Finally, GEtiT implements additional game mechanics to keep the learners engaged and to avoid breaking the immersion. On the one hand, the gamified training environment challenges players with the indication of the minimum of cards that are needed to solve a particular level. Solving a level with the minimum or a small deviation from the minimum rewards players with points that represent their progression towards the completion of the game. That way, learners simultaneously receive feedback about their efficiency applying their AT knowledge and are challenged to retry a level when they exceeded the minimum. Moreover, users can unlock achievements for efficiently solving a level, completing the game or finding a special easter-egg hidden in one of the levels. On the other hand, GEtiT also provides a small built-in wiki that summarizes the AT knowledge for the purpose of keeping players immersed as they can look up the theoretically grounded aspects directly inside of the game.

---

http://www.thinkwithportals.com

4 Technical Implementation

GEtiT was developed in Unity 3D for PC and Mac to make the game available for most systems used by students as well as in classrooms without requiring additional powerful hardware. In addition, using Unity 3D facilitates the implementation of further game mechanics and other improvements of the game. This decision also made it easy to develop a VR-version as Unity 3D provides a good support for current VR devices of which we chose the HTC Vive as it offers room-scale VR and hence a potentially higher presence. However, in order to play GEtiT-VR, a more powerful computer setup as well as the VR device are needed.

Fig. 5: Playing *GEtiT-VR* in the lab.

5 Similarities and Differences

GEtiT-VR provides a similar gameplay to GEtiT's desktop version as it utilizes the same gamification metaphor, additional game mechanics as well as training exercises, but, instead of being played on a desktop computer setup, it is played using the HTC Vive to achieve a higher level of visual immersion, presence and spatial knowledge presentation. However, despite implementing the same game mechanics, the VR port required some UI as well as interaction adjustments to ensure a good usability as well as a believable and immersive environment.

---

https://unity3d.com
https://www.vive.com

5.1 Game Controls

The interaction adjustments [un17a] were required to implement the HTC Vive controllers as the input devices used to interact with the GEtiT-VR and to successfully utilize the HTC Vive's room-scale function. For this purpose, all movement controls were mapped to the system's tracking function that tracks the position of the HTC Vive Head-Mounted Display (HMD) thus allowing users to look and walk around (see Figure 5) as long as they stay within the boundaries of the tracking area. However, as the levels are larger than the tracking area, the gamified training environment also provides the option to teleport within a level by pressing the trackpad on one of the controllers and subsequently selecting a new location by pointing at it with a target selection marker (see Figure 6). On release of the trackpad, the player is teleported to the selected location inside of the level thus providing the option to move over larger distances, to get on top of the object and to enter the portal to escape a room.

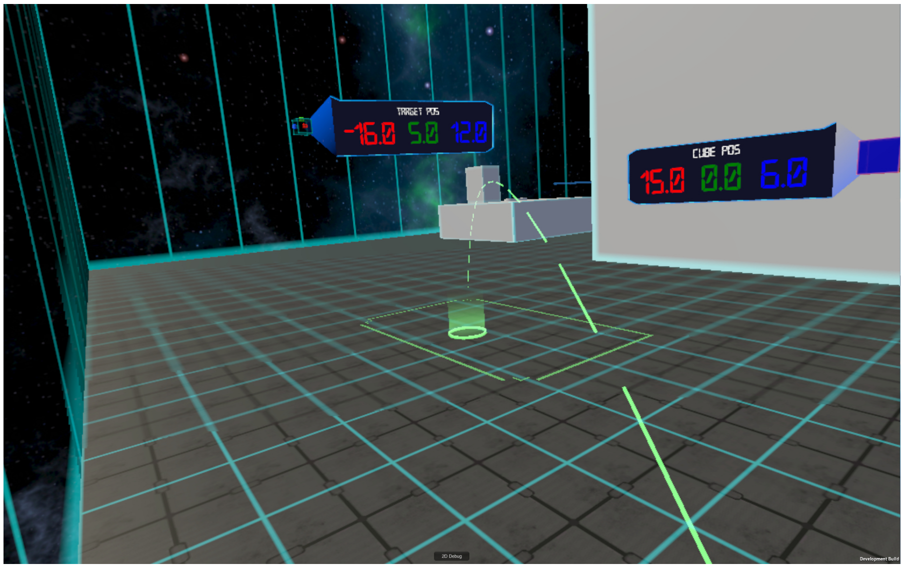


Fig. 6: Players can teleport in *GEtiT-VR* to cross larger distances, to get on top of the object and to enter the portal.

In addition to the teleport feature, the controllers are used to allow a user to select one of the AT cards, to configure a card's elements and, finally, to activate a card to apply a transformation to the object inside of GEtiT-VR. In order to select and grab a card, a player merely has to touch the desired card–they are placed on a floating console (see Figure 7) to avoid static UI elements–with one of the controllers. Afterwards, the selected card is attached to the player's controller and can be played by pulling the controller's trigger button, configured by using the controller's trackpad or placed again on the console by touching it

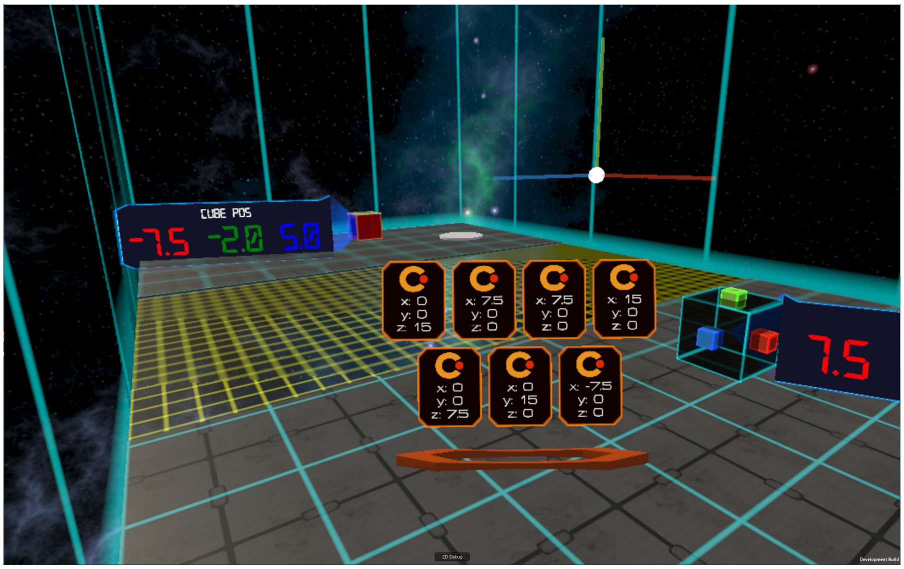


Fig. 7: All available AT cards are placed on a floating console in *GEtiT-VR*.

with the controller that holds the card. In contrast to the desktop version, GEtiT-VR provides no direct value configuration screen in order to allow for a change of a card's transformation values. Instead, by using the trackpad, a user can select the element to be changed and subsequently use an input matrix that is shown on the opposite controller (see Figure 8) to enter the desired value. For this purpose, the opposite controller itself is used for the selection and the confirmation of the values. That way, GEtiT-VR can intuitively be played independent of the player's handedness.

5.2 User Interface

As a static UI often breaks the immersion of a VR application, GEtiT's UI got adapted to fulfill the technical requirements for a good VR interface [un17b]. Instead of using a fixed bar in the UI displaying the available AT cards, GEtiT-VR follows the idea of a spatial UI and implements a floating console to provide access to them. The console can be grabbed and moved around using one of the controllers to allow players to place the console at a spot from where they can simultaneously see the available cards as well as the object thus facilitating the process of selecting the correct card. The cards itself also received a physical property and hence can be carried around. This decision was mainly made to make the virtual environment more believable and immersive.

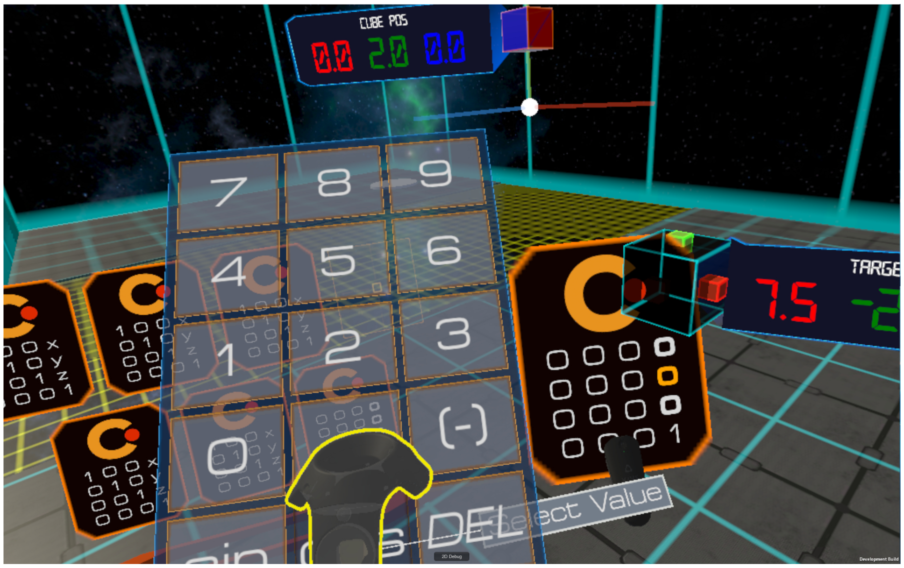


Fig. 8: *GEtiT-VR* allows for a direct value input via a special input matrix UI.

Additionally, instead of tying the indication of the object's and target's position to the player's view, both game mechanics, following again the idea of a spatial UI, received a label that displays the position information. The labels, despite being attached to their relevant object, have no fixed position or orientation. Instead they always face to the player, and, in case of one of the labels is relative to the player behind one of the level's obstacles, the label starts to shine through the obstacle thus ensuring a good visibility from any position inside of a particular level.

5.3 Walk-In Game Menu

The final challenge of the VR port was to avoid breaking the immersion when a player accesses one of the game menus, such as the level selection screen, the game options, and the wiki. This challenge was solved by turning the individual menus of the desktop version into control consoles that are placed inside of the player's futuristic playing room that provides a connection between GEtiT-VR's training exercises and the real world. Aside from the control consoles and relevant displays for the various menus, the playing room also features a fictive game console that loads and previews the available training levels–they are provided in form of cubes in a shelf–by placing one of the level cubes on top of it. In order to play a loaded level, a player has to wear a virtual in-game HMD that is connected to the game console (see Figure 9) by grabbing it with one of the controllers and putting it on with

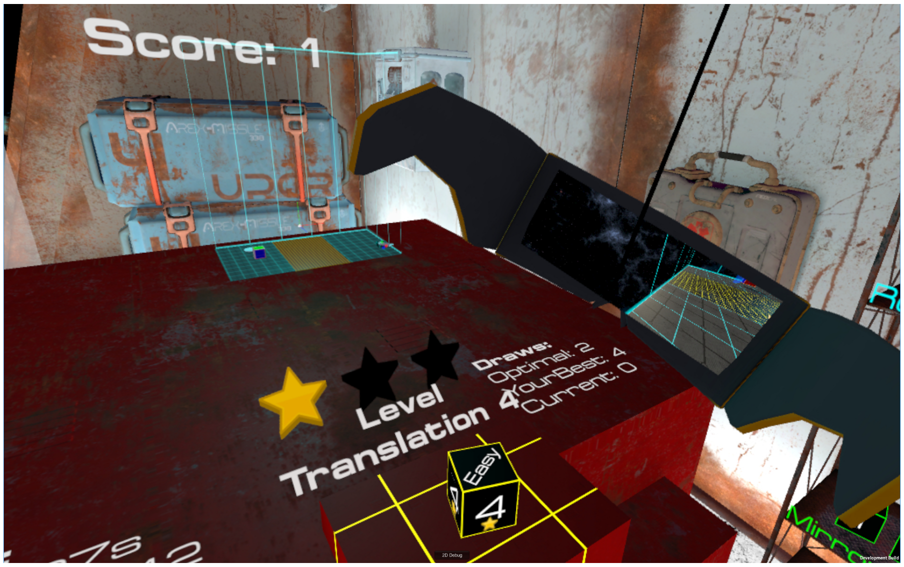


Fig. 9: *GEtiT-VR* implements the functionality of VR Head-Mounted Display devices to allow for a transition between menus and the normal gameplay.

a similar gesture one would perform to wear normal glasses. Similarly, a user can return to the playing room from one of the training exercise levels by simply taking off the virtual HMD. That way, GEtiT-VR implements the VR technology itself as a method to transition between the game and the menus in a believable and immersive way.

6 Conclusion

We described the conceptual design and technical implementation of GEtiT which is used as a demonstrator for our model describing a direct knowledge encoding using game mechanics. The virtual gamified training environment achieves an intuitive presentation and demand of the abstract AT knowledge by moderating the learning content's level of abstractness. GEtiT comes in two versions which are distinguished by their level of visual immersion and is, to our knowledge, the first gamified training environment that is based on a general knowledge encoding model.

GEtiT's desktop version was already used in three AT training modules associated with an interactive computer graphics lecture and achieved a training outcome equal to a traditional paper-based training method. In addition, GEtiT achieved a significantly higher intuitive training and a higher enjoyment of use in general. The results of the completed studies are currently in preparation for publication. Therefore, we expect GEtiT-VR, due to a higher visual immersion, presence and spatial knowledge presentation, to yield a similar or even better training outcome in a forthcoming evaluation that compares the efficiency of the two different versions.

References

[AD12] Adams, Ernest; Dormans, Joris: Game Mechanics. Advanced Game Design. New Riders, Berkeley, 2012.

[Br00] Brophy, Jere: Teaching, volume 1 of Educational Practices Series. International Academy of Education & International Bureau of Education, Brussels, 2000.

[Cs10] Csikszentmihalyi, Mihaly: Flow : Das Geheimnis des Glücks. Klett-Cotta, Stuttgart, 15 edition, 2010.

[DL10] Dalgarno, Barney; Lee, Mark J. W.: What are the learning affordances of 3-D virtual environments? British Journal of Educational Technology, 41(1):10–32, 2010.

[Ge07] Gee, James Paul: What video games have to teach us about learning and literacy. Palgrave Macmillan, New York, 1 edition, 2007.

[KN12] Kaptelinin, Victor; Nardi, Bonnie A: Affordances in HCI: Toward a Mediated Action Perspective. CHI 2012, pp. 967–976, 2012.

[Mc11] McGonigal, Jane: Reality is broken : why games make us better and how they can change the world. Penguin Press, New York, 1 edition, 2011.

[Me04] Meyer, Hilbert: Was ist guter Unterricht? Cornelsen, 2004.

[OL13] Oberdörfer, Sebastian; Latoschik, Marc Erich: Develop your strengths by gaming. Informatik 2013 - Proceedings of 43rd annual German conference on informatics, P-220:2346–2357, 2013.

[OL16] Oberdörfer, Sebastian; Latoschik, Marc Erich: Interactive gamified 3D-training of affine transformations. In: Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16). ACM Press, Garching, Germany, pp. 343–344, 2016.

[OP13] Oei, Adam C; Patterson, Michael D: Enhancing Cognition with Video Games: A Multiple Game Training Study. PLoS ONE, 8(3):e58546, February 2013.

[Si08] Sicart, Miguel: Defining game mechanics. Game Studies, 8(2), 2008.

[SK15] Stevens, Jonathan A.; Kincaid, J. Peter: The Relationship between Presence and Performance in Virtual Simulation Training. Open Journal of Modelling and Simulation, 3:41–48, 2015.

[Sl96] Slater, Mel; Linakis, Vasilis; Usoh, Martin; Kooper, Rob: Immersion, Presence, and Performance in Virtual Environments: An Experiment with Tri-Dimensional Chess. In: ACM Virtual Reality Software and Technology (VRST). pp. 163–172, 1996.

[un17a] unity3d.com: , Interaction in VR. https://unity3d.com/learn/tutorials/topics/virtual-reality/interaction-vr, last checked 31.05.2017.

[un17b] unity3d.com: , User Interfaces for VR. https://unity3d.com/learn/tutorials/topics/virtual-reality/user-interfaces-vr, last checked 31.05.2017.

5.3 Discussion

The development of *GEtiT* expands the answers to following RQs provided by the definition of the Gamified Knowledge Encoding model:

RQ2: How do game mechanics demonstrate and require the application of knowledge during the gameplay?

RQ3: How can (abstract) knowledge be directly encoded in computer games using game mechanics?

The development of *GEtiT* demonstrated the effectiveness of the Gamified Knowledge Encoding as a guideline for the development of serious games. Working with this model, the affine transformations knowledge was transformed into sets of game rules. These game rules were then encoded in game mechanics requiring and demonstrating the application of the knowledge. The interaction between the game mechanics creates learning affordances for this learning content during the gameplay. The selection and the realization of the game mechanics demonstrated the knowledge mediation. The development process also demonstrated the moderation of the knowledge's level of abstraction by realizing four different difficulty levels. Learners may start the learning process with a very intuitive way of transforming an object, i.e., by merely selecting the correct card, and master the affine transformations by playing the game on expert difficulty. Thus, the resulting gameplay should result in an effective and an intuitive knowledge learning. This chapter also demonstrated the applicability of the Gamified Knowledge Encoding for different visualization technologies, i.e., desktop-3D and immersive VR. In conclusion, the successful development of *GEtiT* represents a first step towards validating the Gamified Knowledge Encoding's applicability to act as a guideline for the design of effective serious games.

6 Validating the Gamified Knowledge Encoding-Driven Design

If you want to do a good job, the quickest and most effective way is with excellence. – Lewis Pugh (2013)

After the successful development of *GEtiT*, it is important to evaluate the serious game's usability, i.e., its effectiveness, efficiency and satisfaction, as well as its capability to induce flow during the gameplay. This evaluation validates the Gamified Knowledge Encoding model's effectiveness for the design of good serious games. This chapter reports on two user studies that aim at the overall validation of *GEtiT*'s design and hence of the Gamified Knowledge Encoding.

6.1 Transitioning Into the Unknown

For providing a diegetic user interface in *GEtiT VR*, a Virtual HMD metaphor was realized to allow for a transition between the game's main menu and the spatial puzzle levels. Thus, the Virtual HMD transition technique connects the central gameplay phase of requiring the actual knowledge application with a reflection phase during which learners can access the built-in wiki to learn more about the underlying principles. As the process of transitioning between the two individual VEs might have an impact on the user experience and hence on the overall learning outcome, it was critical to specifically analyze this transition technique's effects and to compare it to other metaphors.

Table 8: Effects of VE Transition Techniques on Presence, Illusion of Virtual Body Ownership, Efficiency, and Naturalness

Author	Contribution
Oberdörfer, S.	Literature review, conceptual design, experimental design, data analysis, discussion, manuscript preparation and revision
Fischbach, M.	Literature review, conceptual design, experimental design, discussion, manuscript preparation and revision
Latoschik, M. E.	Experimental design, manuscript revision

Oberdörfer, S., Fischbach, M., and Latoschik, M. E. Effects of VE Transition Techniques on Presence, IVBO, Efficiency, and Naturalness. In *Proceedings of the 6th Symposium on Spatial User Interaction (SUI '18)*, pages 89–99, Berlin, Germany, October 2018. ACM. doi: 10.1145/3267782.3267787

Effects of VE Transition Techniques on Presence, Illusion of Virtual Body Ownership, Efficiency, and Naturalness

Sebastian Oberdörfer
University of Würzburg

Martin Fischbach
University of Würzburg

Marc Erich Latoschik
University of Würzburg

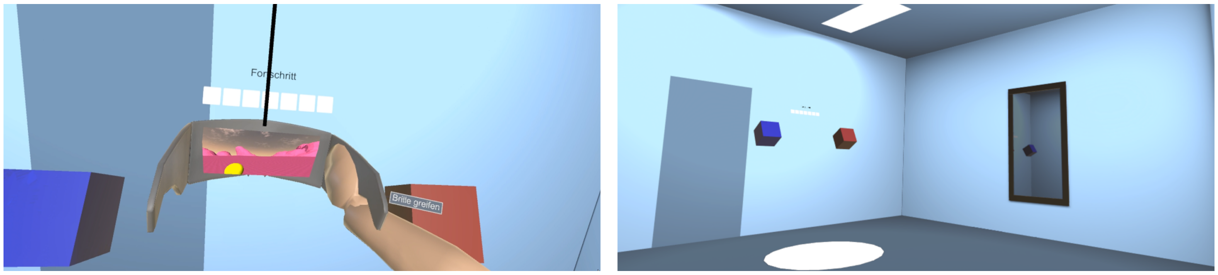


Figure 1: The VMD metaphor mimics a real world HMD that permits transitions between VEs (left). An acclimatization environment is a starting location for such transitions in which users are given time to accustom themselves to VR (right).

ABSTRACT

Several transition techniques (TTs) exist for Virtual Reality (VR) that allow users to travel to a new target location in the vicinity of their current position. To overcome a greater distance or even move to a different Virtual Environment (VE) other TTs are required that allow for an immediate, quick, and believable change of location. Such TTs are especially relevant for VR user studies and storytelling in VR, yet their effect on the experienced presence, illusion of virtual body ownership (IVBO), and naturalness as well as their efficiency is largely unexplored. In this paper we thus identify and compare three metaphors for transitioning between VEs with respect to those qualities: an in-VR head-mounted display metaphor, a turn around metaphor, and a simulated blink metaphor. Surprisingly, the results show that the tested metaphors did not affect the experienced presence and IVBO. This is especially important for researchers and game designers who want to build more natural VEs.

CCS CONCEPTS

• **Human-centered computing** → **HCI design and evaluation methods**; **Virtual reality**; **Interaction techniques**;

KEYWORDS

Transition Techniques, Interaction Design, Illusion of Virtual Body Ownership, Presence

ACM Reference Format:
Sebastian Oberdörfer, Martin Fischbach, and Marc Erich Latoschik. 2018. Effects of VE Transition Techniques on Presence, Illusion of Virtual Body Ownership, Efficiency, and Naturalness. In *Symposium on Spatial User Interaction (SUI '18), October 13–14, 2018, Berlin, Germany*. ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3267782.3267787

1 INTRODUCTION

Moving from the current location to a new one is an integral task in most Virtual Reality (VR) applications. It is commonly categorized as an aspect of spatial navigation, one of the three fundamental 3D interaction tasks [34]. Several well-understood locomotion techniques exist that allow users to continuously travel to a new target location in the vicinity of their current location, e.g., real-walking [13, 21], walking-in-place [44, 58], and redirected walking [12] as well as many controller-based and gesture-based locomotion methods [10, 15]. When it comes to overcoming greater distances or to transitioning to a different Virtual Environment (VE), other techniques are required that allow for a quick as well as believable change of location, called *transition techniques* (TTs) in the remainder of this paper. These often artificial, teleportation-based techniques are less-researched and their effect on the experienced presence, illusion of virtual body ownership (IVBO), and naturalness as well as their efficiency is largely unexplored [4, 11]. Naturalness in this specific context refers to a TT's intuitiveness as well as ease of use regarding its interaction technique and interface elements.

Still, TTs are highly relevant for VR user studies and storytelling in VR: In VR user studies, participants are commonly given time to accustom themselves to VR within an initial acclimatization environment, called *training room* [37], *VR acclimatization* [48, 49], *VR accustomization* [3], *embodiment phase* [47], *orientation phase* [2], or *familiarization phase* [43], before being exposed to certain stimuli (in another VE) that are to be evaluated. Using a virtual replica of the physical laboratory as acclimatization environment increases the

---

SUI '18, October 13–14, 2018, Berlin, Germany

ACM ISBN 978-1-4503-5708-1/18/10…$15.00
https://doi.org/10.1145/3267782.3267787

users' sense of presence [62] and improves their distance estimation skills [61] as well as their spatial and situational awareness [65]. Thus, this procedure is particularly common for studies including virtual embodiment. In VR-storytelling, TTs are required as an equivalent to scene transitions in films [31, 38]. VR computer games, for instance, require such design elements to navigate the player between levels or to a *home* environment for system control, just as their non-VR counterparts. In both cases, a high presence, IVBO, naturalness, and efficiency as well as no occasion of simulator sickness is desired. In addition, it is especially important for VR user studies to know if the use of different TTs has the potential to confound the actual measurements.

Our contribution: Given the lack of user-centric, empirical, and comparative evaluation of TTs between VEs targeting head-mounted display (HMD) setups, this paper identifies three metaphors and compares them with regard to their effect on the experienced *presence*, *IVBO*, *efficiency*, and *naturalness*.

Simulated Blink (SB) fades a user's view to black, changes the location or environment, and fades in again.

Turn Around (TA) requires the user to turn around and changes the environment out of her field of view (see Figure 2).

Virtual-head Mounted Display (VMD) mimics the functionality of a real world HMD (see Figure 1 left).

The results presented in this paper show that the tested metaphors did not affect the experienced presence and IVBO and that the perceived naturalness can be increased by realizing TTs in a continuous and physical way.

The remainder of this paper is structured as follows: The next section presents an analysis of the state of research concerning VE TTs, presence in VR, and IVBO. Subsequently, the TT metaphors are presented conceptually, followed by an overview of their technical implementations. The applied methodology is then described together with a specification of the conducted user study procedure. Finally, the results of this evaluation are presented and discussed, followed by a conclusion and outlook.

2 RELATED WORK

LaViola et al. [34] categorize the task of travel to be an aspect of navigation that supports another task rather than being the user's primary goal in most VR applications. TTs are interaction techniques to fulfill travel tasks that are distinguished from other commonly used TTs in the distance to be travelled, which is high or undefined (if the target is another VE), and the degree to which the target is visible from the starting location. They are related to travel or rather TTs between physical and virtual locations, like [16]. However, transitioning from or to a physical location implies constraints that are out of this paper's scope.

The following terminology is used throughout this paper for classifying TTs and for discussing their relevant distinctions: Firstly, the *interaction type* of the technique characterizes the manner of triggering the navigation. It can be *physical*, i.e., "exploiting physical motion cues for navigation and translating natural movement to VR motion through some kind of body tracking", or it can be *artificial*, i.e., "utilizing input devices to direct VR motion and navigation" [4]. Secondly, the *motion type* of the technique describes the user's motions during the navigation. It can be *continuous*, "supporting smooth, uninterrupted movement in the virtual environment" or *non-continuous*, "providing instantaneous, non-continuous movement transitions" [4]. Finally, the *diegesis* of the interface elements utilized for the concrete realization of a TT metaphor, e.g., of the elements used to trigger the transition. They can be *diegetic*, i.e., part of the VE, or *non-diegetic*, like classical user interfaces in computer games [19]. With respect to HMD-VR applications, there is evidence that diegetic interfaces perform better than a non-diegetic ones, in terms of immersion, sense of presence, usability and cybersickness avoidance [51]. In addition, there is no need to use non-diegetic realizations for triggering actions, since using a button of a controller is a common diegetic realization for HMD-VR. HMD-VR setups normally display the position of the game controllers using 3D assets thus making them to a part of a VE. Hence, pressing a button in them is a diegetic realization for triggering actions. Altogether this explains why non-diegetic alternatives are rarely used in HMD-VR.

TTs between VEs utilized in research projects are oftentimes very simple, e.g., artificial, non-continuous, non-diegetic approaches like asking the user to close her eyes and loading a new scene [1, 29], or they are not concretely reported as part of the study design at all. Yet, there are some elaborated approaches: A physical, continuous, diegetic technique targeting CAVE setups is proposed by [32] that allows the user to grab and manipulate so-called *photoportals*, 2D windows showing a 3D view of another perspective of the VE. Users can "enter" a photoportal by putting their head into the portal thus using it to navigate within the VE. Static connections between head-high portals and remote locations within the VE constitute a similar technique that has been realized for CAVE setups [18] and HMD setups [14]. A different physical, non-continuous, diegetic approach targeting HMD setups is suggested by [31]. It allows users to teleport to remote locations by turning around by 180 degrees within a specific area.

A similar situation is found in the area of VR games. Most of them rely on artificial, non-continuous approaches, basing on a simulated blink metaphor for navigating the player between VEs or rather levels [27, 46]. Analogously, there are some elaborated approaches: *Budget Cuts* [42], *Accounting* [17], and *SuperHot VR* [63] utilize a physical, continuous, diegetic technique targeting HMD setups. In these games, grabable portals similar to the photoportals can be moved near the player's head to transition to a remote location or another VE. During this movement the portal is continuously enlarged (since it is getting nearer) until it fills the user's field of view completely.

In total, TTs for navigating between VEs are often artificial and teleportation-based. They are part of many VR research systems and computer games allowing the user to travel. As a central part of these applications, TTs also effect the overall VR experience. One fundamental aspect of this experience is the sensation of *presence*. Presence, *telepresence*, or *place illusion* is the qualia of having a sensation of being in a real place [53]. It distinguishes from *visual immersion*, an objective description of system properties [60] or rather of the sensorimotor contingencies that it supports [53], e.g., allowing the user to move her head to change the perspective onto an object or to walk to change location. Presence also distinguishes from *plausibility illusion* [53]. Plausibility illusion describes a user's illusion to perceive events happening in a VE as actually occurring events. These events are outside of the user's direct control but refer directly her. As an analysis of a TT's effect on the plausibility illusion requires the simulation of external events potentially confounding the targeted measurements, it is out this paper's scope.

High presence can be a goal in itself, especially in the field of VR storytelling [52]. It may also contribute to higher task performance [30], although it seems more evident that the achieved immersion is more important for this correlation [54]. When it comes to achieving or maintaining high presence, previous findings indicate that the interaction type, motion type, and diegesis of a TT is relevant [39]. Maintaining presence requires a *continuous* stream of stimuli and experiences [69]. Using TTs that interrupt this stream can lead to a break in presence and immersion which negatively affects the overall experience of the simulation. Moreover, presence will be increased if interactions involve whole-body movement [55]. Such a more *physical* form of interaction is also more engaging [31], i.e., the degree to which its execution is fascinating to a user, which is related to naturalness [9, 20]. Thus, naturalness is important for presence [36], indicating that *diegetic* interfaces are beneficial.

Naturalness, usability, and a user's performance depend on the degree to which an interaction technique matches the task context [9]. This includes a technique's concrete interactions and the relevant interface elements inside of a VE. For instance, a steering wheel might achieve a high degree of naturalism in case of a racing simulation, but cease to be effective for first-person shooter gamers. Hence, natural interaction techniques are most effective when they achieve a high level of fidelity and a familiar interface for users.

Finally, a poorly designed TT may introduce cybersickness [11, 36]. Early findings suggested that quick, non-continuous, teleportation-based TTs are correlated with increased user disorientation [8]. More recent implementations showcased their potential with only minor effects on space cognition and disorientation [5, 11].

Besides the characteristics of the interactions itself, the representation of the user in the VE is of central importance for the overall VR experience. Apart from not representing the user at all, the utilization of artificial virtual bodies as a proxy for the user's real physical body [26] is a commonly applied approach that creates the so-called IVBO [56]. The existence of a virtual body while interacting in VR is found to be related to a higher sense of presence, compared to interacting through a traditional user interface [57]. Other studies, however, do not suggest IVBO as a cause of presence [52] or do not find an increase in presence owed to IVBO [35].

Altogether, these findings with respect to presence, immersion and cybersickness theoretically suggest physical techniques to be better than artificial ones, continuous ones to be better than non-continuous ones, and diegetic ones to be better than non-diegetic ones. Concrete investigations targeting such correlations for TTs, however, are pending and thus raising the necessity of comparative, user-centric, empirical evaluations [4, 11]. This paper thus identifies and compares three TT metaphors with regard to their effect on the experienced presence. Due to the central role of IVBO for presence [67], the evaluation investigates the TTs' effects in two separate conditions, with a full and a minimal virtual body in a HMD setup. This is additionally important, since studies involving IVBO often use an initial acclimatization environment that should necessitate a TT to navigate the user into the actual stimulus environment [2, 3, 37, 43, 47–49]. In those cases, the impact of the chosen TT on the evaluated qualities is paramount. Additionally, the presented evaluation covers the techniques' efficiency and naturalness, to assess their suitability for VR storytelling.

3 TRANSITION TECHNIQUES

Three TT metaphors were selected to margin the design space of interaction type and motion type in terms of the theoretically best and theoretically worst characteristics with respect to presence, naturalness, and cybersickness. SB represents a commonly used TT metaphor that represents the lower margin, while TA and VDM represent the upper one. TA was chosen in addition to VMD due to its inclusion of whole-body movements. All three metaphors were chosen to be realized in a diegetic way due to the strong disadvantages and rare use of non-diegetic interface elements in HMD-VR.

3.1 Simulated Blink

A commonly used, artificial and non-continuous metaphor for achieving a transition between two VEs is by simulating a blink of an eye. This metaphor fades the user's view to black, changes the scene or teleports the player to a different location, and finally fades the view in again. Depending on the trigger method it can be diegetic or non-diegetic. For our comparison we used a button press to trigger the transition, making it diegetic.

3.2 Turn Around

The TA metaphor represents a physical and continuous transition. It is following the idea of [31]. This metaphor requires a user to turn around by 180 degrees after the intention to transition is given. The performance of the turn around is completely up to the user to allow for a high degree of self-control and simulator sickness avoidance. The environment behind the player is then replaced with the target VE (see Figure 2). As a result of this, the user sees the VE she is transitioning to, when she turns around. As soon as the first VE is outside of the user's view, it also gets exchanged with the new VE, thus completing the transition to the other environment. TA requires the user to physically perform the transition, turning it into a process that involves whole-body movement. Depending on the trigger method it can be diegetic or non-diegetic. For our comparison we used a button press to trigger the transition, making it diegetic. Despite implementing a mere button press to initiate the transition, the requirement to turn around makes it more complex in comparison to SB.

3.3 Virtual-head Mounted Display

A physical, continuous, and diegetic metaphor that mimics the functionality of a real world HMD, following the ideas of [17, 45, 59, 63] (see Figure 1 left). The VMD metaphor requires the user to grab a virtual HMD and to put it on using a gesture one would perform to wear normal glasses. By reversing this gesture, users can return to the initial VE. Just like real world HMDs, VMDs provide a live preview of the position where the user would enter the new VE after the transition. That way, users can already take a sneak peak of the navigation target and prepare for the transition by slowly putting on the VMD. During this process, the scenery gets continuously larger until it visually immerses the user into the target VE. Vice versa, by slowly removing the VMD, the visual immersion gets

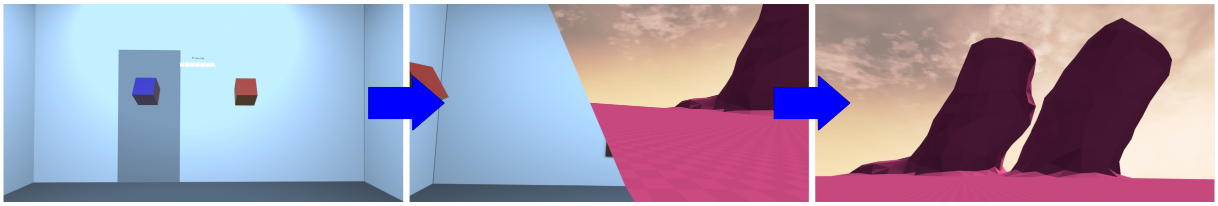


Figure 2: The TA metaphor requires users to physically turn around to change from one VE to another.

broken and the initial VE is revealed again. Thus, this metaphor combines a natural interaction with familiar and diegetic interface elements to match the task of immersing oneself in a different VE [9]. This, however, makes this metaphor more complex in contrast to a mere button press of SB.

4 DESIGN

In this paper, we compare the three TT metaphors *TA*, *VMD*, and *SB* with regard to their effect on the experienced presence, IVBO, naturalness as well as their efficiency.

4.1 Study

Due to the classification of the metaphors and indications discussed in section 2, suggesting that with respect to presence, IVBO, and naturalism, physical techniques theoretically should be better than artificial ones and continuous ones better than non-continuous ones, we assume the following hypotheses (H):

H_{pre} VMD and TA elicit a higher self-reported presence
H_{ivbo} VMD and TA elicit a higher self-reported IVBO
H_{eff} VMD and TA are less efficient
H_{nat} VMD and TA are more natural

To validate the four presented hypotheses, the study is designed to require users to transition between two individual VEs thus allowing them to evaluate the naturalness and efficiency of the three discussed TTs. Furthermore, to assess the TTs' effects on the experienced presence and IVBO, a simple task including a rudimentary interaction is required that simultaneously directs the users' attention to their virtual body parts. Due to the potentially central role of IVBO for presence, the evaluation investigates the TTs' effects with an between groups design by implementing a minimal virtual embodiment (**min-VB**), i.e., simply showing the devices' 3D assets, and a full virtual embodiment (**full-VB**), i.e., using an avatar as a proxy for a user's body, condition (see Figure 3). By providing these two conditions, an analysis of the moderating effects of IVBO is achieved. Internally, the groups follow a within subjects design as every group is required to use all of the TTs. The TTs appear in an randomized order to allow for an evaluation of the potential moderating effects.

4.2 System

A system design featuring two separate VEs is required for evaluating the three presented TTs. It should be simple to avoid confounds induced by distracting context. The first VE we chose represents the acclimatization environment found in many VR studies or alternatively the *home* environment found in many computer games (called *AE* in the remainder of this paper). It is designed to have simplified but still major similarities with the layout of the Real Room (RRm) where the experiment was conducted. For instance, the AE (see Figure 1 right) has the same size and major features (e.g. position of doors and windows) as the RRm. The RRm and the AE feature a mirror to allow the participants to inspect their virtual appearance and to induce IVBO.

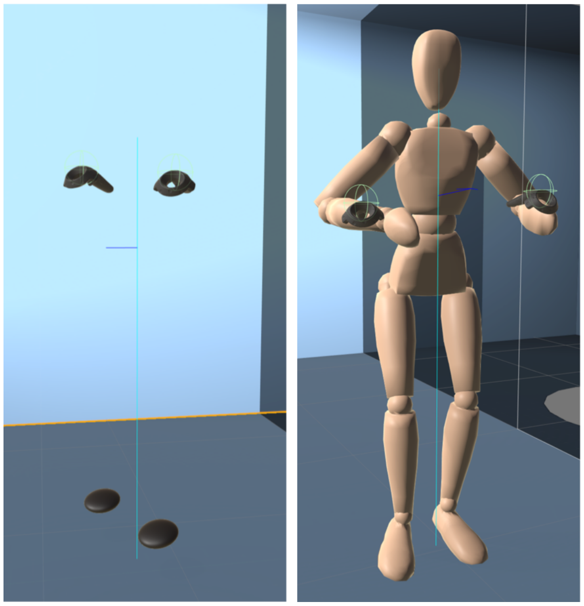


Figure 3: Realization of the two VB conditions. Min-VB (left) uses 3D assets of the controllers and clinched black cylinders for the feet tracker. Full-VB utilizes a wooden manikin as the avatar of the users.

The second VE represents the environment in which a stimuli to be measured would be applied in a VR study or alternatively a computer game level (called *SE* in the remainder of this paper). The SE is designed with a strong contrast to the AE to achieve an obvious difference between both VEs, thus increasing the experience of transitioning to a completely different VE. The SE is an open-world environment featuring pink terrain and some abstract mountains. These features provide users with a sense of direction and allow them to orientate themselves in the SE.

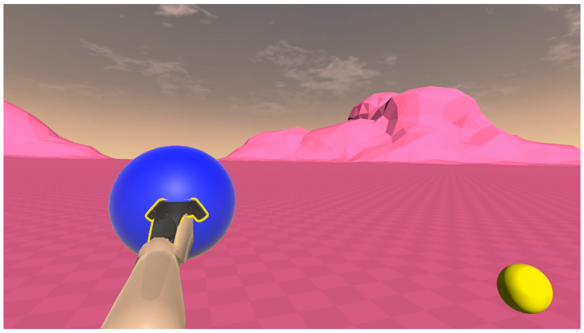


Figure 4: Yellow spheres that reveal their true color upon touch are spawned inside of the SE.

Finally, participants were given a game-like task that involved touching floating spheres in SE and memorizing one color (red or blue) to create an incentive to repetitively transition back and forth between the AE and SE. A color-selection console allowing for the input of either one of two colors is placed in the center of the AE (see Figure 2 left). The console features a progress bar that displays the number of times a user has to enter a color into the system to complete an experimental condition. Each time a user enters a color, a visual feedback indicating the correctness of the entered solution is provided and the progress bar is updated. As the correct color can only be determined by transitioning to the SE, an overall goal is created for the participants. Inside of the SE, three yellow spheres are randomly spawned within a radius of $1.5m$ after each transition. All spheres are programmed to change their color when touched with either the virtual hands or feet (see Figure 4). In addition, each sphere has a fixed height relative to the participant’s body height to challenge the participants to perform some extensive movements, e.g., stretch out an arm or touch a sphere with a foot, and thus to redirect a user’s attention towards the virtual body ($0.3m$ above the HMD, at the height of the upper body tracker, and $0.3m$ above ground level).

Min-VB is realized by virtually representing the position of the input devices, using 3D models of the controllers as well as clinched black cylinders for the additional trackers. Full-VB is realized using an avatar with the appearance of a wooden manikin called *Woody* [49]. Woody was chosen due to its gender-neutrality and its verified high IVBO rating [33]. Besides the HMD and the two controllers for each hand, three additional trackers are used to detect the user’s upper body and feet position and orientation. Jointly, this information is utilized as input for an inverse kinematic algorithm that determines the overall avatar pose.

5 IMPLEMENTATION

The VR TT experiment system was developed with *unity* in the version 2017.3.1f1 [64] for PC using the *SteamVR Plugin* [66] in the version 1.2.2 to implement the controller-based interaction system and the overall player controller. The gameplay is rendered to the HTC Vive HMD [24]. The glasses used for the virtual HMD are part of the *Unity Standard Assets* and the virtual mirror is part of the *Vive Stereo Rendering Toolkit* [25].

Figure 5: Virtual bodies are implemented by tracking the positions and orientations of feet, back, head and hands.

The HTC Vive HMD (resolution: 2160×1200, 1080×1200 per eye; refresh rate: 90 Hz) was connected to the computer (CPU: Intel(R) Xeon(R) CPU E3-1230 v5 @ 3.40GHz, RAM: 16GB, Graphics card: MSI NVIDIA GeForce GTX 980 Ti) and the HTC Vive’s tracking area had a size of $4.8m \times 4.5m$. The HMD and the controllers were cleaned after a participant has finished the experiment using a cleansing and disinfectant product.

The tracking of a user’s body is achieved by using three additional Vive Trackers to determine the position of the upper body and the feet (see Figure 5). The upper body tracker is attached to a belt which is adjusted to position the device at the participant’s back just above the hip bone. The two trackers for the feet are attached to a non-slip over shoe system which can be worn over the participants’ shoes, keeping them in a fixed position right above the toes. The additional trackers are also worn by participants of the min-VB group to avoid causing a confound of the experiment.

5.1 Simulated Blink

SB and TA use the HTC Vive controllers’ trigger buttons to initiate a transition. While being in the AE, the transition can only be initiated by standing on top of a transition platform placed adjacent to the color-selection console (see Figure 1 right). Also, while being in the SE, the transition can only be initiated after revealing all the three balls. This decision was made to prevent participants who use the controllers for the very first time to frequently transitioning back and forth as they subconsciously might use the trigger button to reveal the colors. The transition platform is used to reduce potential room-space-related issues, e.g., risk of a collision with the RRm’s walls after the completion of some experimental task cycles, by positioning the player at a defined position inside of the RRm at the start of the experiment. SB is implemented by fading the players' view to black for 1*s*, subsequently teleporting them between the two VEs, and finally fading the view in again. The transition duration time was selected based on a quick internal evaluation that revealed 1*s* to be the most comfortable time. When returning back from the SE, the players find themselves back on the transition platform, thus allowing them to enter a color into the console without any additional movement.

5.2 Turn Around

For the TA technique, the AE and the SE are internally represented by means of two different layers that can be filtered out with transparent game objects. This permits to create the illusion that parts of a VE are missing. Two transparent filter cubes are used to either filter out parts of the AE to achieve a transition to the SE or, vice versa, to filter out parts of the SE to achieve a transition back to the AE. While the former cube is placed behind the user after the transition was initiated, the latter cube is spawned directly in the field of view to hide parts of the AE. After the user has turned around by 180 degrees and the previous VE is no longer in her field of view, it gets disabled. To increase the usability, the AE is rotated in such a way that the color-selection console is always positioned directly behind the user. That way, the user merely needs to turn around to complete the transition and to stand in front of the console thus allowing for an easy input of the determined color.

5.3 Virtual-head Mounted Display

The VMD's 3D asset can be grabbed by the user with one of the controllers (intersecting virtual controller and VMD asset, holding down the trigger button). VMD is implemented using a video texture that displays the view of a camera located at the user's spawn position inside of the SE. This texture is added to the inside of the VMD 3D asset. As soon as the grabbed VMD falls below a certain distance to the user's virtual head, the user gets teleported to the SE. Vice versa, as soon as she grabs the VMD asset from her virtual head, again exceeding the distance threshold, the player gets teleported back to the AE. For the purpose of achieving consistency between the two virtual environments and the other TTs, the user always returns to the position in the AE where the VMD was put on. Similarly, the transition returns the player to the last position inside of the SE before the VMD was removed. The VMD asset is connected to a spring-like force in the AE that achieves the functionality of a rubber band. That way, the glasses hang from the virtual ceiling and are always in easy reach for the users. Moreover, they swing back to their initial position after returning to the AE.

All realizations of the TT metaphors feature tooltips that are shown on the controllers to inform users about the possible interactions with the system.

6 MEASURES

All questionnaires used were translated to the common language of the study's location. The language proficiency of each participant was assessed to ensure that the questions were understood properly.

6.1 Simulator Sickness

The simulator sickness was measured for all participants before and after the experiment using the *simulator sickness questionnaire* (*SSQ*) [28]. This questionnaire was used to measure the overall quality of the VR simulation and to identify potential negative effects that could have affected the study's results.

6.2 Presence and Immersion

The study included the *immersive tendency questionnaire* (*ITQ*) [69] and the *presence questionnaire - version 3.0* (*PQ*) consisting of the 19 core items [68]. Also, a single-question mid-immersion oral presence assessment [6, 7] was conducted as presence is quickly lost after the end of the immersion. The questionnaires were used to evaluate immersive as well as believable aspects of the simulation and, more importantly, of the TTs. While the ITQ was only filled out before the start of the experiment, the PQ was completed after each experimental simulation session. The mid-immersion assessment was conducted after a participant's fourth transition to the SE.

6.3 Illusion of Virtual Body Ownership

The IVBO was measured using the *Alpha IVBO* questionnaire [50]. It was completed after each experimental simulation session to determine if the used TT affects the experienced IVBO.

6.4 Efficiency

The efficiency of the TTs, as a measure of the resources expended, was assessed by measuring a participant's *completion time* needed to complete an experimental condition. In addition, the *NASA-TLX* [23] was implemented to measures the users' perceived task load after the completion of each condition. To facilitate the evaluation process, the NASA-TLX was used in the modified *Raw NASA-TLX* (*RTLX*) [22] version, i.e., the RTLX eliminates the weighting process and only implements the six subscales [40].

6.5 Naturalness

The naturalness of the TTs was assessed by evaluating their intuitiveness, the most fundamental quality of natural user interfaces [20], as well as by asking for the users preference. Intuitiveness was assessed by implementing the *QUESI* [41] after the completion of each condition. At the end of the experiment, participants were asked to express their *preference* for one of the three TTs and to reason their selection.

7 PROCEDURE

The experiment consisted of eight stages:
(1.) *Introduction:* The participant is welcomed and receives a short introduction into the experimental design. The participant signs the informed consent form.
(2.) *Pre-questionnaire:* The participant fills out pre-questionnaire consisting of demography questionnaire, ITQ, and pre-test SSQ.
(3.) *Preparation:* The participant dons the tracking system, HMD and controllers. Subsequently, a brief explanation of the controls is given. The real world mirror is covered to avoid tracking issues.
(4.) *Acclimatization:* In the *full-VB* condition, Woody is adjusted to the participant's body height. Subsequently, the participant is

given the opportunity to explore the AE for 1 minute. In the *min-VB* condition, the participant is given the opportunity to explore the AE for 1 minute. Both conditions include a brief tutorial explaining the mechanic to reveal a sphere’s color.

(5.) *Simulation:* The participant utilizes a TT to determine the correct color and enters the solution into the color-console. After the 4th transition to the SE, the mid-immersion presence gets assessed. (Repeated 7 times).

(6.) *Evaluation:* The participant fills out the post-questionnaire consisting of PQ, NASA-TLX, QUESI, and IVBO.

(7.) *Repetition:* Back to *Step 5* until all three TTs are completed. The TTs are presented in a randomized order.

(8.) *Conclusion:* The participant fills out the post-test SSQ and is asked which of the TTs would be the participant’s choice for a frequent use in VR. Also, the participant is asked to provide an optional explanation for the choice.

8 PARTICIPANTS

In total, 49 participants (33 females, 16 males) were recruited from the undergraduate students who were enrolled at the University of Würzburg. They had a mean age of 21.18 (SD_{age} = 1.98) and were native speakers. 15 participants reported to be frequent computer game players and 40 participants reported to have used an HMD before. The participants first were sorted by their gaming experience to ensure an equal distribution of well experienced gamers among the two groups. Then, the participants were randomly assigned to either the full virtual embodiment *full-VB group* (n = 23, 7 females, 6 males; 7 regular computer game players) or the minimal embodiment *min-VB group* (n = 26, 16 females, 10 males; 8 regular computer game players).

9 RESULTS

The results were analyzed by either computing *Wilks’ Lambda repeated measurements ANOVA* and *paired t-tests* for comparisons of the measured effects inside of the within subjects design evaluations, i.e., full-VB and min-VB group, or computing *two sample t-tests* to compare the results between the full-VB and min-VB group. The effect size was determined by computing the *Cohen’s D.* A correlation was analyzed by using *Pearson’s product-moment correlation.*

9.1 Simulator Sickness

The total score of the SSQ was computed for the measurements that took place at the beginning ($M_{\text{full-VB}} = 13.98$, $SD_{\text{full-VB}} = 12.87$, $M_{\text{min-VB}} = 17.26$, $SD_{\text{min-VB}} = 14.96$) and the end ($M_{\text{full-VB}} = 17.07$, $SD_{\text{full-VB}} = 19.00$, $M_{\text{min-VB}} = 15.68$, $SD_{\text{min-VB}} = 16.22$) of the experiment. No significant difference was found between the two groups before ($t_{\text{pre}}(47) = 0.82$, $p_{\text{pre}} = 0.42$) and after ($t_{\text{post}}(47) = 0.28$, $p_{\text{post}} = 0.78$) the experiment. Also, no significant change in the SSQ total score between the two measurements was found in the two groups ($t_{\text{full-VB}}(22) = 0.75$, $p_{\text{full-VB}} = 0.46$, $t_{\text{min-VB}}(25) = 0.68$, $p_{\text{min-VB}} = 0.50$).

9.2 Presence

9.2.1 Immersive Tendency. The participants showed a mean immersive tendency ($M_{\text{IT}} = 4.34$, $SD_{\text{IT}} = 0.53$) which was above the neutral mid-point (1 = low tendency, 7 = high tendency) on the ITQ. The participants who were randomly assigned to the full-VB group ($M_{\text{full-VB}} = 4.43$, $SD_{\text{full-VB}} = 0.56$) and to the the min-VB group ($M_{\text{min-VB}} = 4.26$, $SD_{\text{min-VB}} = 0.49$) were not significantly different ($t(47) = 1.08$, $p = 0.29$) in their immersive tendency.

Table 1: Mean Presence (PQ).

Group	M_{VMD}	SD_{VMD}	M_{SB}	SD_{SB}	M_{TA}	SD_{TA}	p
Full-VB	5.42	0.70	5.50	0.69	5.13	1.01	0.07
Min-VB	5.57	0.74	5.76	0.60	5.45	0.61	0.01*

Table 2: Mean Mid-Immersion Presence.

Group	M_{VMD}	SD_{VMD}	M_{SB}	SD_{SB}	M_{TA}	SD_{TA}	p
Full-VB	7.17	1.67	7.30	1.29	6.91	1.68	0.46
Min-VB	7.42	1.96	7.50	1.84	7.08	2.00	0.18

9.2.2 Presence Questionnaire. The full-VB group and the min-VB group (see Table 1) gave an above neutral mid-point rating (1 = low presence, 7 = high presence) on the PQ for the VR TT system independent of the used TT. A significant difference was only found in the min-VB group ($F_{\text{full-VB}}(21) = 3.12$, $p_{\text{full-VB}} = 0.07$, $F_{\text{min-VB}}(24) = 5.36$, $p_{\text{min-VB}} = 0.01$) between SB and TA ($t(25) = 3.30$, $p = 0.003$, *cohensD* $= 0.65$). No significant difference was found in the min-VB group between VMD and SB ($t(25) = 1.53$, $p = 0.14$) as well as between VMD and TA ($t(25) = 0.95$, $p = 0.35$). Also, no significant difference was found between the two groups ($t_{\text{VMD}}(47) = 0.77$, $p_{\text{VMD}} = 0.45$, $t_{\text{SB}}(47) = 1.42$, $p_{\text{SB}} = 0.16$, $t_{\text{TA}}(47) = 1.37$, $p_{\text{TA}} = 0.16$).

9.2.3 Mid-Immersion Presence. The full-VB group and the min-VB group (see Table 2) gave an above neutral mid-point rating (1 = low presence, 10 = high presence) on the mid-immersion presence assessment for the VR TT system independent of the used TT. No significant difference was found in both groups ($F_{\text{full-VB}}(21) = 0.80$, $p_{\text{full-VB}} = 0.46$, $F_{\text{min-VB}}(24) = 1.85$, $p_{\text{min-VB}} = 0.18$). Moreover, no significant difference was found between the two groups ($t_{\text{VMD}}(47) = 0.48$, $p_{\text{VMD}} = 0.63$, $t_{\text{SB}}(47) = 0.43$, $p_{\text{SB}} = 0.67$, $t_{\text{TA}}(47) = 0.31$, $p_{\text{TA}} = 0.76$).

Lastly, a significant correlations was between both presence assessment tools in the full-VB group (Pearson’s cor: $t_{\text{VMD}}(21) = 3.17$, $p_{\text{VMD}} = 0.005$, $t_{\text{SB}}(21) = 2.19$, $p_{\text{SB}} = 0.04$, $t_{\text{TA}}(21) = 2.11$, $p_{\text{TA}} = 0.04$) and the min-VB group (Pearson’s cor: $t_{\text{VMD}}(24) = 5.51$, $p_{\text{VMD}} < 0.001$, $t_{\text{SB}}(24) = 6.44$, $p_{\text{SB}} < 0.001$, $t_{\text{TA}}(24) = 5.06$, $p_{\text{TA}} < 0.001$).

9.3 IVBO

As Table 3 depicts, all three tested TTs had no effect on the participants’ IVBO. The Alpha IVBO is a three factor questionnaire measuring a user’s acceptance of the own virtual body (*acceptance*), the agency and visual representation of motion (*control*) and the perceived change of the own body (*change*). The implementation of Woody using inverse kinematic resulted in a rating above the neutral mid-point (1 = low effect, 7 = high effect) of the acceptance as well as control subscales and a below neutral mid-point rating

Table 3: Overview of the IVBO subscales.

Scale	M_{VMD}	SD_{VMD}	M_{SB}	SD_{SB}	M_{TA}	SD_{TA}	p
Full-VB							
Acceptance	4.23	1.12	4.23	0.85	4.16	0.78	0.88
Control	5.89	1.22	5.89	0.96	5.84	1.29	0.71
Change	2.33	1.18	2.46	1.26	2.32	1.26	0.89
Min-VB							
Acceptance	5.24	1.32	5.04	1.45	4.99	1.32	0.32
Control	6.07	0.84	6.25	0.69	5.99	0.91	0.34
Change	2.09	1.28	1.88	1.12	1.71	0.97	0.08

Table 4: Mean Completion Time in seconds.

Group	M_{VMD}	SD_{VMD}	M_{SB}	SD_{SB}	M_{TA}	SD_{TA}	p
Full-VB	131.94	31.42	123.74	24.60	139.54	29.81	0.16
Min-VB	131.02	30.15	114.50	21.40	134.66	28.44	0.02*

Table 5: Mean NASA-TLX score.

Condition	M_{VMD}	SD_{VMD}	M_{SB}	SD_{SB}	M_{TA}	SD_{TA}	p
Full-VB	27.50	17.76	19.38	10.07	28.19	15.21	0.007*
Min-VB	21.92	15.05	16.63	9.80	21.47	14.00	0.02*

Table 6: Mean QUESI rating.

Group	M_{VMD}	SD_{VMD}	M_{SB}	SD_{SB}	M_{TA}	SD_{TA}	p
Full-VB	4.05	0.79	4.37	0.63	3.99	0.86	< 0.001*
Min-VB	4.20	0.64	4.48	0.57	4.12	0.49	0.01*

of the change subcomponent. Similarly, the min-VB condition resulted in a rating above the neutral mid-point of the acceptance as well as control subscales and a below neutral mid-point rating of the change subcomponent. The acceptance subcategory was rated significantly higher in the min-VB group than in the full-VB group ($t_{\text{VMD}}(47) = 2.88$, $p_{\text{VMD}} = 0.006$, $cohensD_{\text{VMD}} = 0.82$, $t_{\text{SB}}(47) = 2.33$, $p_{\text{SB}} = 0.02$, $cohensD_{\text{SB}} = 0.67$, $t_{\text{TA}}(47) = 2.63$, $p_{\text{TA}} = 0.01$, $cohensD_{\text{TA}} = 0.85$) for all of the used TTs.

9.4 Efficiency

9.4.1 Completion Time. As Table 4 displays, a significant difference in the total completion time for an experimental condition was only found in the min-VB group ($F_{\text{full-VB}}(21) = 2.03$, $p_{\text{full-VB}} = 0.16$, $F_{\text{min-VB}}(24) = 4.61$, $p_{\text{min-VB}} = 0.02$). A further analysis of the results revealed a significant difference between VMD and SB ($t(25) = 2.30$, $p = 0.03$, $cohensD = 0.45$) as well as SB and TA ($t(25) = 3.00$, $p = 0.006$, $cohensD = 0.59$) but not between VMD and TA ($t(25) = 0.56$, $p = 0.58$). No significant difference was found for each of the used TTs between the two groups ($t_{VMD}(47) = 0.10$, $p_{VMD} = 0.92$, $t_{SB}(47) = 1.41$, $p_{SB} = 0.17$, $t_{TA}(47) = 0.59$, $p_{TA} = 0.56$).

9.4.2 NASA-TLX. For evaluating the NASA-TLX and comparing the perceived task load of the three tested TTs, the mean score across all six subscales of the assessment tool was computed. As Table 5 displays, a significant difference in the perceived task load was found between the TTs in both groups ($F_{\text{full-VB}}(21) = 6.34$, $p_{\text{full-VB}} = 0.007$, $F_{\text{min-VB}}(24) = 4.80$, $p_{\text{min-VB}} = 0.02$). Further analyses revealed a significant difference in the full-VB group between VMD and SB ($t(22) = 2.97$, $p = 0.007$, $cohensD = 0.62$) as well as SB and TA ($t(22) = 2.55$, $p = 0.02$, $cohensD = 0.53$) but not between VMD and TA ($t(22) = 0.17$, $p = 0.87$). The min-VB group showed a significant difference between VMD and SB ($t(25) = 2.67$, $p = 0.01$, $cohensD = 0.52$) as well as SB and TA ($t(25) = 2.70$, $p = 0.01$, $cohensD = 0.53$) but not between VMD and TA ($t(25) = 0.22$, $p = 0.82$). No significant difference was found between the two groups for any of the tested TTs ($t_{\text{VMD}}(47) = 1.19$, $p_{\text{VMD}} = 0.24$, $t_{\text{SB}}(47) = 0.97$, $p_{\text{SB}} = 0.34$, $t_{\text{TA}}(47) = 1.61$, $p_{\text{TA}} = 0.11$).

9.5 Naturalness

9.5.1 Preference. At the end of the experiment, the participants were asked to choose their preferred TT: 18 participants chose VMD (full-VB = 9, min-VB = 9), 20 participants voted for SB (full-VB = 9, min-VB = 11) and 11 participants selected TA (full-VB = 5, min-VB = 6). The participants were also given the opportunity to provide an explanation for their choice. They praised the high naturalness, believability and degree of self-control of VMD, the simplicity and efficiency of SB, and the high physical involvement in the transition process as well as naturalness of TA. However, they also reasoned a selection of SB with a high degree of familiarity which made this TT seem natural to them.

9.5.2 Intuitive Use. All three TTs scored above the neutral mid-point (1 = negative perception, 5 = positive perception) on the QUESI questionnaire (see Table 6). A significant difference in the perceived intuitive use was found between the TTs in both groups ($F_{\text{VBO}}(21) = 11.23$, $p_{\text{VBO}} < 0.001$, $F_{\text{min-VB}}(24) = 5.19$, $p_{\text{min-VB}} = 0.01$). Further analyses revealed a significant difference in the full-VB group between VMD and SB ($t(22) = 3.17$, $p = 0.004$, $cohensD = 0.66$) as well as SB and TA ($t(22) = 3.39$, $p = 0.003$, $cohensD = 0.71$) but not between VMD and TA ($t(22) = 0.37$, $p = 0.72$). The min-VB group showed a significant difference between VMD and SB ($t(25) = 2.44$, $p = 0.02$, $cohensD = 0.48$) as well as SB and TA ($t(25) = 3.07$, $p = 0.005$, $cohensD = 0.60$) but not between VMD and TA ($t(25) = 0.66$, $p = 0.52$). No significant difference was found between the two groups for any of the tested TTs ($t_{\text{VMD}}(47) = 0.73$, $p_{\text{VMD}} = 0.47$, $t_{\text{SB}}(47) = 0.62$, $p_{\text{SB}} = 0.54$, $t_{\text{TA}}(47) = 0.64$, $p_{\text{TA}} = 0.52$).

10 DISCUSSION

The study was designed to identify and compare potential effects of TTs on the experienced presence and IVBO that not only would affect the overall experience of VR applications but also potentially confound user studies.

10.1 Presence

The analysis of the experienced presence only revealed a significant difference in the min-VB group between SB and TA when measured using the PQ. In contrast, the mid-immersion presence assessment revealed no significant difference. Presence is quickly lost when the visual immersion has ended. Also, users quickly recover from a break in place illusion [53]. Thus, the mid-immersion presence assessment right after a transition potentially is more accurate than the PQ filled in at the end of an experimental cycle. Consequently, the three tested TTs have only a limited moderating effect on the experienced presence. Hence, all of them are interchangable in VR applications without breaking a user's presence. A potential explanation for this finding could be the fact that transitions are used in all visual media, such as movies, animations and computer games. Hence, a change of environment potentially is a habituated occurrence that is not perceived as a disturbance.

No significant difference was found between the full-VB group and the min-VB group in the experienced presence independent of the used assessment tool. This can by explained by the fact that the participants of both groups were (partly) visually represented by the virtual replicas of the controllers that induced a certain level of IVBO. Thus, it is possible to assume that aspects of IVBO relevant for presence were similarly induced by the min-VB as well as by the full-VB conditions. This can be a valuable insight for designers of immersive VR applications as creating believable avatars is currently still a complex and expensive process.

The study also demonstrated by analyzing the results of the PQ and the mid-immersion presence assessment that both approaches yield a valid indication of presence. Hence, by merely implementing the mid-immersion single question presence assessment, a study can be streamlined and still provide insights into the tested system's presence.

H_{pre} The results of the study led to the rejection of H_{pre} as all three TTs showed a similar effect on the self-reported presence.

10.2 IVBO

The results revealed no significant difference in the perceived acceptance, control, and change related to IVBO caused by the utilization of the three tested TTs. Therefore, it can be assumed that all of the three techniques are causing no interference with the IVBO. Hence, they can be used in user studies to allow participants to change between to independent VEs.

However, the study revealed a significantly higher acceptance rating in the min-VB condition. This could be an effect of the experimental design. Instead of mainly focussing on their virtual embodiments, participants were challenged to transition between two different VE to determine a color. Despite the chosen simple task including a rudimentary interaction, the experimental procedure accidentally yielded game flow. This game flow could have redirected a participant's awareness from her virtual body to the activities required to complete the task. The result also aligns with the finding [35] that game flow resulting from a game's gameplay can result in a player's loss of awareness for herself and for her virtual body, respectively. This could also have happened with any other task that provides a clear goal and immediate feedback. Implementing such a task, however, was necessary. It gave the participants an incentive to repetitively transition between the two VEs, provided them with immediate feedback, and hid the core research goal. In the end, the conclusions drawn from this study are still very relevant as they indicate a TT's effects when used in a game-like or task-oriented context.

H_{ivbo} As a result, the study also led to the rejection of H_{ivbo} as the self-reported IVBO was not affected by the tested TTs.

10.3 Efficiency

The efficiency evaluation consisted of the measured completion time and perceived task load. It revealed that VMD and TA are, as expected, slower and cause a higher task load. This can be explained by the additional actions a user has to perform to achieve a transition using VMD and TA. SB, in contrast to the other two tested TTs, merely requires a user to press a button to complete a transition. The other two TTs require a user to perform the gesture of putting on glasses or to physically turn around by 180 degrees, respectively.

Still, despite the significant difference, all TTs yielded low task load ratings that indicate their efficiency for achieving a transition from one VE to another. This outcome is important for game designers who like to realize transitions in a more natural and engaging way.

H_{eff} The study's results confirm H_{eff}. SB achieved a significantly lower total task load and significantly faster completion time.

10.4 Naturalness

Finally, the naturalness evaluation consisted of the users' preference and perceived intuitive use. The evaluation revealed that SB yielded a significantly higher intuitive use rating. On the one hand, this can be again explained by the realization of this TT, i.e., using a mere button press to complete a transition. On the other hand, it is explainable by the common occurrence of SB in many media forms. SB represents a traditional TT which is commonly used and hence was potentially well internalized by the participants. Thus, the intuitive use rating could have been influenced by previous experiences that included a SB to change from one VE to another.

The study also revealed that SB is the preferred TT, closely followed by VMD. SB was rated easy to use and very efficient thus confirming its frequent implementation. VMD was rated to provide a high degree of self-control and to be natural as well as believable. A potential benefit for users who experience VR for the first time, e.g., during a user-centered experiment or a therapy application. TA, as a whole-body movement, physical and continuous technique, was rated as very dynamic and natural. This validates the indications drawn from previous research. The two tested physical and continuous TT metaphors were perceived as natural and partly as plausible. In the end, this is another important insight for game designers who like to implement natural interaction techniques.

H_{nat} The results confirm H_{nat}. VMD received almost similar preference ratings and was named the most natural TT that provides a high degree of self-control. TA, despite being the least preferred TT, was also rated dynamic and natural.

11 CONCLUSION AND FUTURE WORK

This paper analyzed the effects of techniques permitting a transition between different VEs on the experienced presence, IVBO, efficiency, and naturalness. For this purpose, three TT metaphors were identified: (1) *SB* achieves a transition by fading the user's view to black, changing the user's location, and fading the view in again, (2) *TA* requires a user to physically turn around to navigate to a different VE, and (3) *VMD* mimics the functionality of a real world HMD. They were selected to margin the design space of interaction type and motion type in terms of the theoretically best and theoretically worst characteristics with respect to the evaluated qualities.

The present study led to a twofold contribution: (1) In contrast to the theoretical conclusions drawn from literature, we provide evidence that the three tested TTs did not affect the experienced presence or IVBO in the frame of a game-like implementation. (2) We confirmed the frequent implementation of SB as it yielded a significantly higher intuitive use rating and was the most preferred TT. At the same time, we provided insights that the two continuous and physical TTs were perceived as natural and, in the case of VMD, as believable in contrast to SB. This is an important result for the scientific and game design community. Our results show that all of the tested TTs can safely be implemented without reducing the perceived presence and IVBO.

Future research aims at identifying a TT's effect on the perceived plausibility illusion which was out of scope for this paper. While not affecting presence and IVBO, TTs might have an effect on the perceived plausibility. Additionally, we like to explore the efficiency and acceptance of the three TT metaphors for achieving a nested VR experience, i.e., to utilize them for a vertical transition into different VE layers. Finally, we like to use our categorization of TTs and the insights gained from the present study to present a comprehensive taxonomy.

ACKNOWLEDGMENTS

We like to thank David Heidrich and Samantha Straka for implementing the system and helping us with carrying out the experiment. Also, we like to thank Rebecca Hein, Kilian Röder, and Henrik Steinmetz for helping us conducting the study.

REFERENCES

[1] Domna Banakou, Raphaela Groten, and Mel Slater. 2013. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences* 110, 31 (2013), 12846–12851.

[2] Domna Banakou, Parasuram D Hanumanthu, and Mel Slater. 2016. Virtual embodiment of white people in a black virtual body leads to a sustained reduction in their implicit racial bias. *Frontiers in human neuroscience* 10 (2016).

[3] Ilias Bergström, Konstantina Kilteni, and Mel Slater. 2016. First-person perspective virtual body posture influences stress: a virtual reality body ownership study. *PloS one* 11, 2 (2016), e0148060.

[4] Costas Boletsis. 2017. The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology. *Multimodal Technologies and Interaction* 1, 4 (2017). https://doi.org/10.3390/mti1040024

[5] Benjamin Bolte, Frank Steinicke, and Gerd Bruder. 2011. The jumper metaphor: an effective navigation technique for immersive display setups. In *Proceedings of Virtual Reality International Conference*.

[6] Stéphane Bouchard, Geneviéve Robillard, Julie St-Jacques, Stéphanie Dumoulin, Marie-Josée Patry, and Patrice Renaud. 2004. Reliability and validity of a single-item measure of presence in VR. In *Haptic, Audio and Visual Environments and Their Applications, 2004. HAVE 2004. Proceedings. The 3rd IEEE International Workshop on.* IEEE, 59–61.

[7] Stéphane Bouchard, Julie St-Jacques, Geneviéve Robillard, and Patrice Renaud. 2008. Anxiety Increases the Feeling of Presence in Virtual Reality. *Presence* 17, 4 (2008), 376–391.

[8] D. A. Bowman, D. Koller, and L. F. Hodges. 1997. Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques, In Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality. *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*, 45–52, 215. https://doi.org/10.1109/VRAIS.1997.583043

[9] Doug A Bowman, Ryan P McMahan, and Eric D Ragan. 2012. Questioning Naturalism in 3D User Interfaces. *Commun. ACM* 55, 9 (2012), 78–88. https://doi.org/10.1145/2330667.2330687

[10] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Locomotion in Virtual Reality for Individuals with Autism Spectrum Disorder. In *Proceedings of the 2016 Symposium on Spatial User Interaction (SUI '16)*. ACM, New York, NY, USA, 33–42. https://doi.org/10.1145/2983310.2985763

[11] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point & Teleport Locomotion Technique for Virtual Reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '16)*. ACM, New York, NY, USA, 205–216. https://doi.org/10.1145/2967934.2968105

[12] G. Bruder, P. Lubas, and F. Steinicke. 2015. Cognitive Resource Demands of Redirected Walking. *IEEE Transactions on Visualization and Computer Graphics* 21, 4 (2015), 539–544. https://doi.org/10.1109/TVCG.2015.2391864

[13] Gerd Bruder and Frank Steinicke. 2014. Threefolded Motion Perception During Immersive Walkthroughs. In *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology (VRST '14)*. ACM, New York, NY, USA, 177–185. https://doi.org/10.1145/2671015.2671026

[14] G. Bruder, F. Steinicke, and K. H. Hinrichs. 2009. Arch-Explore: A natural user interface for immersive architectural walkthroughs, In 2009 IEEE Symposium on 3D User Interfaces. *2009 IEEE Symposium on 3D User Interfaces*, 75–82. https://doi.org/10.1109/3DUI.2009.4811208

[15] Jorge C. S. Cardoso. 2016. Comparison of Gesture, Gamepad, and Gaze-based Locomotion for VR Worlds. In *Proceedings of the 22Nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*. ACM, New York, NY, USA, 319–320. https://doi.org/10.1145/2993369.2996327

[16] Damien Clergeaud, Joan Sol Roo, Martin Hachet, and Pascal Guitton. 2017. Towards Seamless Interaction between Physical and Virtual Locations for Asymmetric Collaboration. In *VRST 2017 - 23rd ACM Symposium on Virtual Reality Software and Technology*. Gothemburg, Sweden, 1–5. https://hal.archives-ouvertes.fr/hal-01649262

[17] Crows Crows Crows. 2018. Accounting. http://accountingvr.com. Last accessed 2017-06-26.

[18] S. Freitag, D. Rausch, and T. Kuhlen. 2014. Reorientation in virtual environments using interactive portals, In 2014 IEEE Symposium on 3D User Interfaces (3DUI). *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, 119–122. https://doi.org/10.1109/3DUI.2014.6798852

[19] Alexander R Galloway. 2006. *Gaming: Essays on algorithmic culture*. Vol. 18. U of Minnesota Press.

[20] Sanjay Ghosh, Chivukula Sai Shruthi, Himanshu Bansal, and Arvind Sethia. 2017. What is User's Perception of Naturalness? An Exploration of Natural User Experience. In *Human-Computer Interaction - INTERACT 2017*, Regina Bernhaupt, Girish Dalvi, Anirudha Joshi, Devanuj K. Balkrishan, Jacki O'Neill, and Marco Winckler (Eds.). Springer International Publishing, Cham, 224–242.

[21] Timofey Y Grechkin, Jodie M Plumert, and Joseph K Kearney. 2014. Dynamic affordances in embodied interactive systems: The role of display and mode of locomotion. *IEEE transactions on visualization and computer graphics* 20, 4 (2014), 596–605.

[22] Sandra G. Hart. 2006. NASA-Task Load Index (NASA-TLX); 20 Years Later. In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*. Santa Monica, 904–908.

[23] Sandra G. Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Human Mental Workload*, P. A. Hancock and N Meshkati (Eds.). Elsevier Science Publishers B.V., Amsterdam, 139–183.

[24] HTC Corporation. 2011–2017. HTC Vive. available at https://www.vive.com.

[25] HTC Corporation. 2016–2017. Vive Stereo Rendering Toolkit. available at https://www.assetstore.unity3d.com/en/#!/content/71255.

[26] Wijnand A IJsselsteijn, Yvonne A W de Kort, and Antal Haans. 2006. Is this my hand I see before me? The rubber hand illusion in reality, virtual reality, and mixed reality. *Presence: Teleoperators and Virtual Environments* 15, 4 (2006), 455–464.

[27] Indimo Labs. 2017. Vanishing Realms: Rite of Steel. http://www.vanishingrealms.com. Last accessed 2017-11-19.

[28] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (1993), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

[29] K. Kilteni, I. Bergstrom, and M. Slater. 2013. Drumming in Immersive Virtual Reality: The Body Shapes the Way We Play. *IEEE Transactions on Visualization and Computer Graphics* 19, 4 (2013), 597–605.

[30] Taeyong Kim and Frank Biocca. 1997. Telepresence via television: Two dimensions of telepresence may have different connections to memory and persuasion. *Journal of Computer-Mediated Communication* 3, 2 (1997), 0–0.

[31] Joshua Kohn and Stefan Rank. 2016. You'Re the Camera!: Physical Movements For Transitioning Between Environments in VR. In *Proceedings of the 13th International Conference on Advances in Computer Entertainment Technology (ACE '16)*. ACM, New York, NY, USA, Article 5, 9 pages. https://doi.org/10.1145/3001773.3001824

[32] André Kunert, Alexander Kulik, Stephan Beck, and Bernd Froehlich. 2014. Photoportals: Shared References in Space and Time. In *Proceedings of the 17th ACM*

Conference on Computer Supported Cooperative Work & Social Computing (CSCW '14). ACM, New York, NY, USA, 1388–1399. https://doi.org/10.1145/2531602.2531727

[33] Marc Erich Latoschik, Jean-Luc Lugrin, and Daniel Roth. 2016. FakeMi: A Fake Mirror System for Avatar Embodiment Studies. In *Proceeding of ACM Symposium on Virtual Reality Software and Technology*.

[34] Joseph J LaViola Jr, Ernst Kruijff, Ryan P McMahan, Doug Bowman, and Ivan P Poupyrev. 2017. *3D user interfaces: Theory and practice*. Addison-Wesley Professional.

[35] Jean-Luc Lugrin, Maximilian Ertl, Philip Krop, Richard Klüpfel, Sebastian Stierstorfer, Bianka Weisz, Maximilian Rück, Johann Schmitt, Nina Schmidt, and Marc Erich Latoschik. 2018. Any "Body" There? Avatar Visibility Effects in a Virtual Reality Game. In *IEEE Virtual Reality*. IEEE.

[36] Daniel Medeiros, Eduardo Cordeiro, Daniel Mendes, Maurício Sousa, Alberto Raposo, Alfredo Ferreira, and Joaquim Jorge. 2016. Effects of Speed and Transitions on Target-based Travel Techniques. In *Proceedings of the 22Nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*. ACM, New York, NY, USA, 327–328. https://doi.org/10.1145/2993369.2996348

[37] Michael Meehan, Brent Insko, Mary Whitton, and Frederick P. Brooks, Jr. 2002. Physiological Measures of Presence in Stressful Virtual Environments. *ACM Trans. Graph.* 21, 3 (July 2002), 645–652. https://doi.org/10.1145/566654.566630

[38] Liang Men, Nick Bryan-Kinns, Amelia Shivani Hassard, and Zixiang Ma. 2017. The Impact of Transitions on User Experience in Virtual Reality. In *IEEE Virtual Reality (VR)*. IEEE, Los Angeles, CA, USA. https://doi.org/10.13140/RG.2.2.19800.29449

[39] K. R. Moghadam and E. D. Ragan. 2017. Towards understanding scene transition techniques in immersive 360 movies and cinematic experiences, In 2017 IEEE Virtual Reality (VR). *2017 IEEE Virtual Reality (VR)*, 375–376. https://doi.org/10.1109/VR.2017.7892333

[40] William F Moroney, David W Biers, F Thomas Eggemeier, and Jennifer A Mitchell. 1992. A comparison of two scoring procedures with the NASA task load index in a simulated flight task. In *Proceedings of the IEEE 1992 National Aerospace and Electronics Conference (NAECON 1992)*. 734–740.

[41] Anja Naumann and Jörn Hurtienne. 2010. Benchmarks for Intuitive Interaction with Mobile Devices. In *Proceedings of MobileHCI'10*. Lisboa, Portugal.

[42] Neat Corporation. 2017. Budget Cuts. http://www.neatcorporation.com/BudgetCuts/. Last accessed 2017-11-19.

[43] Birgit Nierula, Matteo Martini, Marta Matamala-Gomez, Mel Slater, and Maria V Sanchez-Vives. 2017. Seeing an embodied virtual hand is analgesic contingent on colocation. *The Journal of Pain* 18, 6 (2017), 645–655.

[44] N. C. Nilsson, S. Serafin, and R. Nordahl. 2014. Establishing the Range of Perceptually Natural Visual Walking Speeds for Virtual Walking-In-Place Locomotion. *IEEE Transactions on Visualization and Computer Graphics* 20, 4 (2014), 569–578. https://doi.org/10.1109/TVCG.2014.21

[45] Sebastian Oberdörfer, David Heidrich, and Marc Erich Latoschik. 2017. Interactive Gamified Virtual Reality Training of Affine Transformations. In *Proceedings of DeLFI and GMW Workshops 2017*, Carsten Ullrich and Martin Wessner (Eds.). Chemnitz, Germany.

[46] Owlchemy Labs. 2017. Job Simulator—the 2050 archives. https://jobsimulatorgame.com. Last accessed 2017-11-19.

[47] Tabitha C Peck, Sofia Seinfeld, Salvatore M Aglioti, and Mel Slater. 2013. Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and cognition* 22, 3 (2013), 779–787.

[48] Ausiàs Pomés and Mel Slater. 2013. Drift and ownership toward a distant virtual body. *Frontiers in human neuroscience* 7 (2013).

[49] Daniel Roth, Jean-Luc Lugrin, Julia Büser, Gary Bente, Arnulph Fuhrmann, and Marc Erich Latoschik. 2016. A Simplified Inverse Kinematic Approach for Embodied VR Applications. In *in Proceedings of the 23rd IEEE Virtual Reality (IEEE VR) conference*.

[50] Daniel Roth, Jean-Luc Lugrin, Marc Erich Latoschik, and Stephan Huber. 2017. Alpha IVBO - Construction of a Scale to Measure the Illusion of Virtual Body Ownership. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '17)*. ACM, Denver, Colorado, USA, 2875–2883. https://doi.org/10.1145/3027063.3053272

[51] P. Salomoni, C. Prandi, M. Roccetti, L. Casanova, and L. Marchetti. 2016. Assessing the efficacy of a diegetic game interface with Oculus Rift, In 2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC). *2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC)*, 387–392. https://doi.org/10.1109/CCNC.2016.7444811

[52] Martijn J Schuemie, Peter Van Der Straaten, Merel Krijn, and Charles APG Van Der Mast. 2001. Research on presence in virtual reality: A survey. *CyberPsychology & Behavior* 4, 2 (2001), 183–201.

[53] Mel Slater. 2009. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 364, 1535 (2009), 3549–3557.

[54] Mel Slater, Vasilis Linakis, Martin Usoh, and Rob Kooper. 1996. Immersion, Presence, and Performance in Virtual Environments: An Experiment with Tri-Dimensional Chess. In *ACM Virtual Reality Software and Technology (VRST)*. 163–172.

[55] Mel Slater, John McCarthy, and Francesco Maringelli. 1998. The Influence of Body Movement on Subjective Presence in Virtual Environments. *Human Factors* 40, 3 (2017/11/19 1998), 469–477. https://doi.org/10.1518/001872098779591368

[56] Mel Slater, Daniel Perez-Marcos, H Henrik Ehrsson, and Maria V Sanchez-Vives. 2009. Inducing illusory ownership of a virtual body. *Frontiers in neuroscience* 3, 2 (2009), 214.

[57] Mel Slater, Bernhard Spanlang, and David Corominas. 2010. Simulating Virtual Environments Within Virtual Environments As the Basis for a Psychophysics of Presence. In *ACM SIGGRAPH 2010 Papers (SIGGRAPH '10)*. ACM, New York, NY, USA, Article 92, 9 pages. https://doi.org/10.1145/1833349.1778829

[58] Mel Slater, Anthony Steed, and Martin Usoh. 1995. *The Virtual Treadmill: A Naturalistic Metaphor for Navigation in Immersive Virtual Environments*. Springer Vienna, Vienna, 135–148. https://doi.org/10.1007/978-3-7091-9433-1_12

[59] Mel Slater, Martin Usoh, and Anthony Steed. 1994. Depth of Presence in Virtual Environments. *Presence* 3, 2 (1994), 130–144.

[60] Mel Slater and Sylvia Wilbur. 1997. A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. *Presence* 6, 6 (1997), 603–616. https://doi.org/10.1162/pres.1997.6.6.603

[61] Frank Steinicke, Gerd Bruder, Klaus Hinrichs, Markus Lappe, Brian Ries, and Victoria Interrante. 2009. Transitional Environments Enhance Distance Perception in Immersive Virtual Reality Systems. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization (APGV '09)*. ACM, New York, NY, USA, 19–26. https://doi.org/10.1145/1620993.1620998

[62] F. Steinicke, G. Bruder, K. Hinrichs, A. Steed, and A. L. Gerlach. 2009. Does a Gradual Transition to the Virtual World increase Presence?, In 2009 IEEE Virtual Reality Conference. *2009 IEEE Virtual Reality Conference*, 203–210. https://doi.org/10.1109/VR.2009.4811024

[63] SUPERHOT team. 2018. SuperHot VR. https://superhotgame.com/vr/. Last accessed 2017-06-26.

[64] Unity. 2018. unity 2017.3.1f1. available at https://unity3d.com/get-unity/download/archive.

[65] Dimitar Valkov and Steffen Flagge. 2017. Smooth Immersion: The Benefits of Making the Transition to Virtual Environments a Continuous Process. In *Proceedings of the 5th Symposium on Spatial User Interaction (SUI '17)*. ACM, New York, NY, USA, 12–19. https://doi.org/10.1145/3131277.3132183

[66] Valve Coorperation. 2015–2017. SteamVR Plugin. https://www.assetstore.unity3d.com/en/#!/content/32647.

[67] Thomas Waltemate, Dominik Gall, Daniel Roth, Mario Botsch, and Marc Erich Latoschik. 2018. The Impact of Avatar Personalization and Immersion on Virtual Body Ownership, Presence, and Emotional Response. *IEEE Transactions on Visualization and Computer Graphics* 24, 4 (2018), 1643–1652.

[68] Bob G Witmer, Christian J Jerome, and Michael J Singer. 2005. The Factor Structure of the Presence Questionnaire. *Presence* 14, 3 (2005), 298–314.

[69] Bob G Witmer and Michael J Singer. 1998. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence* 7, 3 (1998), 225–240.

6.2 GEtiT's Usability

In addition to testing for the effects of the Virtual HMD, validating the design of *GEtiT* and *GEtiT VR* was important to reveal potential issues that might affect the overall learning outcome. By evaluating *GEtiT VR*, the usability study also contributes the ongoing process of researching the educational potentials of immersive VR. Finally, the results of the study provide insights into the effectiveness of the Gamified Knowledge Encoding-driven development of serious games, thus contributing to the model's validation.

Table 9: Usability of Gamified Knowledge Learning in VR and Desktop-3D

Author	**Contribution**
Oberdörfer, S.	Literature review, conceptual design, experimental design, data analysis, discussion, manuscript preparation and revision
Heidrich, D.	Conceptual design, experimental design
Latoschik, M. E.	Manuscript revision

Oberdörfer, S., Heidrich, D., and Latoschik, M. E. Usability of Gamified Knowledge Learning in VR and Desktop-3D. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*, pages 175:1–175:13, Glasgow, Scotland UK, May 2019. ACM. doi: 10.1145/3290605.3300405

Usability of Gamified Knowledge Learning in VR and Desktop-3D

Sebastian Oberdörfer
University of Würzburg

David Heidrich
University of Würzburg

Marc Erich Latoschik
University of Würzburg

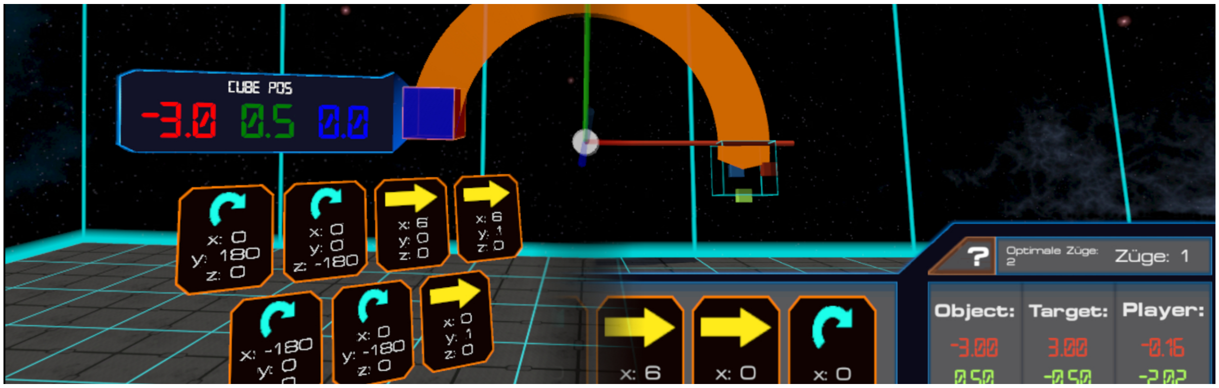


Figure 1: *GEtiT VR* (l) and *GEtiT* (r) challenge players to apply ATs to solve spatial puzzles.

ABSTRACT

Affine Transformations (ATs) often escape an intuitive approach due to their high complexity. Therefore, we developed GEtiT that directly encodes ATs in its game mechanics and scales the knowledge's level of abstraction. This results in an intuitive application as well as audiovisual presentation of ATs and hence in a knowledge learning. We also developed a specific Virtual Reality (VR) version to explore the effects of immersive VR on the learning outcomes. This paper presents our approach of directly encoding abstract knowledge in game mechanics, the conceptual design of GEtiT and its technical implementation. Both versions are compared in regard to their usability in a user study. The results show that both GEtiT versions induce a high degree of flow and elicit a good intuitive use. They validate the effectiveness of the design and the resulting knowledge application requirements. Participants favored GEtiT VR thus showing a potentially higher learning quality when using VR.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Empirical studies in HCI**; • **Applied computing → Interactive learning environments**;

KEYWORDS

Gamification, Knowledge Learning, Serious Games Design

ACM Reference Format:
Sebastian Oberdörfer, David Heidrich, and Marc Erich Latoschik. 2019. Usability of Gamified Knowledge Learning, in VR and Desktop-3D. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland UK*. ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3290605.3300405

1 INTRODUCTION

Affine Transformations (ATs) are a crucial knowledge for many engineering areas such as robotics [21], 3D computer graphics [19], and Virtual Reality (VR) and Augmented Reality (AR) development. Learning and practicing ATs often leads to a high degree of frustration. ATs cannot easily be demonstrated or visualized due to their high complexity. AT operations, i.e., a translation, rotation, scaling, shearing or reflection, in $\mathbb{R}^3$ are commonly expressed as 4×4 matrices. Students struggle when trying to comprehend how the

---

CHI 2019, May 4–9, 2019, Glasgow, Scotland UK

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300405

theoretically grounded mathematical aspects result in a transformation of an object. Using the homogeneous representation as 4 × 4 matrices, arbitrary matrices, each potentially representing an AT, can be multiplied together to combine transformations. This multiplication is order dependent. For instance, a rotation followed by a translation potentially has a different outcome than a translation followed by a rotation.

Therefore, we developed the *Gamified Training Environment for Affine Transformations (GEtiT)*[1] (see Figure 1) that requires the knowledge's *repetitive application* during the gameplay [50]. GEtiT challenges users with spatial puzzles that require the application of AT operations. When solving these puzzles, GEtiT provides learners with *immediate feedback* about the correctness of their actions. Thus, the gameplay results in an audiovisual demonstration of the underlying principles. Also, the serious game *moderates* the *level of abstraction* of ATs by implementing four different difficulty levels. Each difficulty encodes an adjusted subset of the knowledge. Hence, students learn the learning content in an intuitive and comprehensible way. Overall, GEtiT aims at a training transfer of the AT learning content. Training transfer is the application of knowledge trained in one context to a different context [16]. GEtiT's desktop version already demonstrated its educational effectiveness by yielding a similar learning outcome to a traditional method [52].

A *higher visual immersion* leads to a *higher presence* and *higher performance* [73] in the case of a virtual training simulation [77]. Presence also has a mediating effect on the learning outcome. It increases the intrinsic motivation and enjoyment of learners thus improving the perceived learning quality and satisfaction [41]. Therefore, we also developed a specific *GEtiT VR* version to potentially increase GEtiT's learning outcome and learning quality [48]. GEtiT VR implements the same core game mechanics as GEtiT but utilizes *Head Mounted Display (HMD) VR* to visualize the gameplay.

Our contribution: This paper's contribution is twofold. 1) *Conceptual presentation* of a serious game targeting a transfer-oriented learning of ATs in desktop-3D and HMD-VR. 2) *Usability and joy of use* evaluation of the two systems. The study's results show a *higher enjoyment* when using GEtiT VR suggesting that using VR enhances the learning quality. The user study *validates the design* and shows that the audiovisual presentation and the application requirement of ATs is effective. Also, the results reveal that both GEtiT versions induce a *high degree of flow* and elicit a *good intuitive use*. However, the user study also indicates the importance of researching selection-based text-input techniques for VR. Overall, this paper contributes to the on-going research of analyzing the educational potentials of VR technology.

The paper begins with an analysis of the related work, provides a brief overview of GEtiT's design and gameplay. Then, we describe our research method and present as well as discuss the results of a user study. This paper is concluded with a brief summary and an outlook for future research.

2 RELATED WORK

Acquiring and mastering knowledge or gaining expertise with its explicit application requires a high amount of deliberate practice [17]. Thus, repetitive knowledge training is a very effective learning method [7]. It achieves a knowledge automatization, deepening, and training transfer [15, 45]. Creating similar requirements with the targeted context facilitates a transfer-oriented knowledge training [12, 54, 76]. Computer games have the potential to simulate, demonstrate, and require any knowledge [56]. Hence, they are ideal environments for a transfer-oriented knowledge learning.

Game-Based Knowledge Learning

Each computer game encodes specific knowledge that is learned, practiced, and mastered during the gameplay [13, 27]. Research has shown that computer games are useful to train complex sets of skills [49], such as skills of laparoscopic surgery [65], communication [58, 68], collaboration [59, 63] and leadership [61, 71]. Also, they fulfill the conditions for optimal learning [17]. Computer games *keep players motivated* even when the content goes beyond the usual entertainment purpose [2] due to their flow-inducing aspects [11]. Flow is the central construct that mainly influences enjoyment and performance of gaming action [83] and hence knowledge learning. A well-designed video game continuously provides new challenges that increase in their difficulty to match a player's knowledge gain [43]. In this way, players *periodically repeat* [22] *preexisting knowledge* that is acquired during a game's gameplay, e.g., during a tutorial phase. Lastly, players receive *immediate feedback* about their progress towards solving a challenges and the correctness of their actions [10]. Serious games [14] combine these aspects of entertainment and learning with pedagogical elements [8] for a targeted knowledge learning.

A computer game consists of a series of game mechanics. Game mechanics are the rules of a computer game. They define what is possible inside a particular game environment by encoding the underlying principles as their internal rules. Thus, they create a game's virtual environment [1] and allow players to interact [70] with it. The interaction between individual game mechanics creates a game's gameplay.

The internal rules of a game mechanic can also consist of rules derived from a specific learning content thus achieving a *gamified knowledge encoding* [53]. Game mechanics then create *learning affordances* for the encoded knowledge by requiring its application and demonstrating the underlying

---

[1] Get GEtiT: http://www.hci.uni-wuerzburg.de/projects/getit/

principles [12, 34]. Executing these game mechanics takes place on a player's skill-based or rule-based level of human performance [60]. This leads to a compilation of situation specific *mental models* [40, 55]. Mental models are complex constructs that allow for a visualization and simulation of familiar situations [32, 79] and for the analysis of unfamiliar problems [69], e.g., a training transfer. By *moderating* the level of abstraction, i.e., adjusting the encoded knowledge rules in their complexity, an intuitive knowledge learning is achieved [53]. Thus, encoding the AT learning content in game mechanics realizes an effective transfer-oriented knowledge training.

The first learning effectiveness study of GEtiT already validated this approach [52]. Here, participants either played GEtiT or practiced the AT knowledge using paper-based assignments. At the end of the study, a paper-based exam was written and revealed a successful training-transfer from the serious game to the exam. Also, the *gamified knowledge encoding* was used to identify orbital mechanics knowledge rules encoded in Kerbal Space Program [78] and to predict its learning effect. In the study, participants played the game and showed a significant knowledge gain as well as effective training-transfer [51]. Thus, the gamified knowledge encoding also allows for a prediction of the learning outcome. In sum, knowledge learning using game mechanics is effective.

Educational Use of 3D Environments and VR

Learning of ATs requires an environment that visually demonstrates 3D geometrical problems. 3D action-based computer games train a player's spatial abilities such as the mental rotation skill [9], spatial visual attention [25], spatial resolution of vision [26], and spatial navigation [33]. This is crucial as a training of spatial abilities improves 3D geometry thinking [57]. Vice-versa, learning descriptive geometry assists the development of spatial abilities [24]. Thus, by visually demonstrating the AT knowledge in a 3D environment, the learning of it is facilitated.

VR technology visually immerses a user in a 3D environment allowing for such a presentation of 3D geometry. Visual immersion is achieved with system properties reducing sensory inputs from the real world and replacing them with digital information, e.g., by wearing an HMD [74]. Users then experience the effects of AT operations in a more natural and immersive way [44, 66]. This supports the compilation of mental models for the learning content [84]. Also, a higher visual immersion and a thus resulting higher presence leads to a higher performance in case of a training scenario [77]. Spatial presence describes the subjective sensation of being in a real place, e.g., inside the virtual environment, despite physically being in a different environment [72]. Presence has a mediating effect on the learning outcome as it affects a student's intrinsic motivation and enjoyment thus increasing the perceived learning quality and satisfaction [41]. Overall, VR technology increases a student's motivation as well as engagement, provides an immersive experience, and allows for a constructivist approach of learning [20, 42]. For instance, it can simulate complex machinery thus enabling learners to experience them in a normal classroom without requiring the actual hardware [64].

Therefore, designing a specific GEtiT VR version leads to a presentation of the learning content in a more natural way. This potentially allows for an easier compilation of mental models, a better understanding, and an improved learning effect. Also, it increases a learner's motivation and satisfaction when practicing the application of ATs.

Virtual Geometry Learning

Virtual learning of geometry was already approached with other projects. *Construct3D* represents an AR application that allows students to collaboratively create and manipulate geometrical objects [35, 36]. Similarly, *Mathland* provides a Mixed Reality learning platform that augments the real world with mathematical concepts [38]. Mathland allows learners to observe their environment thus achieving a constructionist mathematical learning. In contrast to the present system, both applications are not gamified training environments that target a highly motivating knowledge learning.

3 GETIT

Aside from encoding the AT knowledge, GEtiT needs to fulfill three additional requirements to achieve an effective knowledge learning:
(1) Different sets of knowledge rules that are scaled in their complexity need to be encoded in GEtiT's game mechanics to moderate the learning content's level of abstraction.
(2) The interaction of the game mechanics needs to provide feedback that not only informs the learners about the correctness and their learning progress, but also visualizes and demonstrates the effects of an AT operation.
(3) Finally, well designed and clear learning exercises need to be provided to motivate and to require learners to apply their knowledge.

Performance of an Affine Transformation Operation

To fulfill these requirements, GEtiT needs two central elements: an *input* game mechanic allowing for the configuration of a 4×4 transformation matrix and a *manipulable object* game mechanic that changes the state of the object based on the applied transformation. Thus, the object provides learners with an immediate feedback about the correctness and the effects of their inputs. Aside from immediately being transformed, the object also casts a trail indicating the path on which it translated through the game world. This path provides learners with a visual feedback about the additional

1	0	0	0
0	1	0	5
0	0	1	0
0	0	0	1

Figure 2: On expert difficulty, the direct value configuration screen has the structure of a 4×4 transformation matrix.

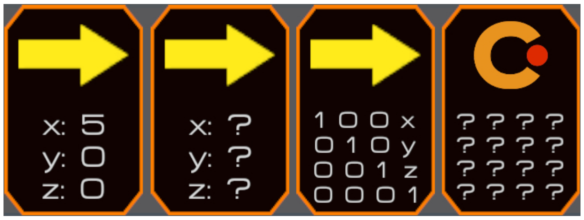


Figure 3: The AT cards change based on the selected difficulty rating: easy, medium, hard and expert.

effects of an AT operation, e.g., the object's translation when a rotation operation is applied while the object is not located in the level's origin.

Configuring and applying an AT in GEtiT is implemented with the players' ability to select, configure, and play cards of which each represents an individual mathematical operation. By activating an *AT card*, a *direct value configuration screen* (see Figure 2) representing an empty 4×4 transformation matrix that must be completed with self-obtained computational results is shown. Once an AT card's configuration is confirmed, the object immediately gets transformed according to the entered values. By providing these two game mechanics, GEtiT directly encodes the AT knowledge, requires its application, and provides immediate visual feedback. This direct AT knowledge encoding also represents the highest, i.e., *expert*, difficulty.

The AT cards moderate the knowledge's level of abstraction by encoding a specific simplified but more intuitive and comprehensible subsets of the total AT knowledge rules. GEtiT features *four different difficulty levels*, i.e., easy, medium, hard and expert, of which each achieves a different degree of the moderation. In particular, from easy to hard difficulty, each AT card only represents one specific AT type which is indicated by a symbol displayed on the cards. From easy to medium difficulty, the AT cards are even reduced to a transformation vector representation (see Figure 3). On *easy* difficulty, each card is predefined and hence a learner merely has to activate a card to transform the object according to the values displayed on it. On *medium* difficulty, the vector AT cards are undefined thus requiring users to enter self-obtained computational results in a vector direct value configuration screen. On *hard* difficulty, each AT card represents a transformation matrix and, upon activation, opens a direct value configuration screen which only provides access to matrix fields relevant to the selected transformation type. As a result, the difficulty levels not only scale the level of abstraction, but also reflect a learner's level of expertise with the explicit application of the AT knowledge. By periodically increasing the difficulty of the exercises, gaming flow is induced that further increases a learner's motivation to tackle the challenges [43].

GEtiT displays the available AT cards as clickable elements at the bottom of the player's User Interface (UI) that open the direct value configuration screen. GEtiT VR (see Figure 4), to achieve a diegetic UI design [67], gives the cards a physical property, displays them on a moveable card holder and integrates the direct value configuration screen directly into them. In contrast to GEtiT that is played with mouse and keyboard, GEtiT VR implements the HTC Vive controllers as input devices. They are used to realize a within arm's reach *selection and manipulation* interaction technique [4, 39]. A user selects an AT card by merely touching it with one controller. Using the controller's trackpad initiates the configuration process. After selecting a desired field on the card, the direct value configuration screen is shown. It is controlled using the second controller allowing for a selection and confirmation of inputs. Finally, a player activates a card by pulling the first controller's trigger button. As the controllers are part of the virtual environment, their realization is diegetic which increases GEtiT VR's naturalness and the experienced presence [44, 66]. The moveable card holder enables players to place it at a position from which they can simultaneously see the available cards and the object. This facilitates the process of analyzing the spatial puzzles and applying the correct AT operation.

Providing Clear Learning Exercises

GEtiT's learning exercises are created in form of an *escape scenario* [56]. Exercises challenge players with spatial puzzle tasks requiring the transformation of the object in such a way that it matches a level's victory conditions, i.e., a switch. Each puzzle consists of a sealed room featuring a closed exit, i.e., a portal, potential obstacles blocking the object's translation path, a half-transparent object displaying the victory conditions, the manipulable object, and a level-specific selection of AT cards. Internally, GEtiT compares the state of the

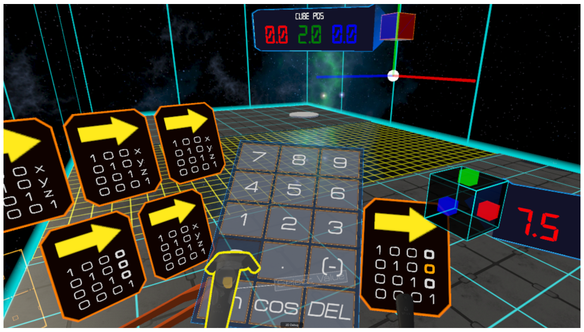


Figure 4: *GEtiT VR* allows for a direct value input via a diegetic input interface.

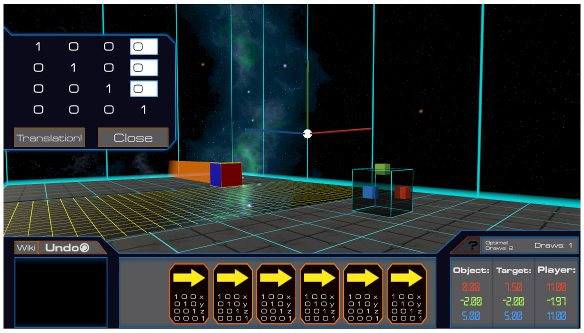


Figure 5: Players cannot walk on the yellow grid between the two platforms. They are challenged to utilize the object as a stepping stone to cross the gap.

manipulable object with the level's victory conditions and, once they are met, activates the portal. Then, players may leave the room and proceed to the next exercise.

The level design also creates additional challenges by placing the exit portal at unreachable places. This requires players to utilize the object as a stepping stone to overleap gaps (see Figure 5) or as a lift to get on top of a high obstacle. Thus, the application of the AT knowledge can become meaningful to players. It is no longer just a complex learning content but a means to solve puzzles and to ultimately beat the game. Overall, GEtiT provides 108 different spatial puzzles (27 per difficulty level).

An achievement and a point system got implemented to increase the game's motivational aspects. The point system bases on a performance rating system that challenges players to solve a level with a minimum amount of cards. Beating a level with the minimum or small deviation from the minimum rewards users with a performance dependent amount of points symbolized by stars. The points provide users with feedback about their progress towards the completion of the game, i.e., stars earned for a particular level are displayed in the level selection menu. Achievements are unlocked by solving levels in a perfect way, completing all levels of a particular transformation type or finding a hidden easter-egg.

Each level can freely be explored and, although a timer indicating the time spent in a particular level is shown, solved without a time constraint. GEtiT is played from a first-person perspective and implements the traditional first-person controls, e.g., WASD, to achieve a movement and view control using the keyboard and mouse. GEtiT VR implements the HTC Vive's room-scale VR technology thus allowing players to walk and to look around using the HMD. However, as GEtiT's levels are larger than the tracking area, the intuitive and easy *Point & Teleport* technique [5, 6] is implemented as a second interaction technique to perform a locomotion inside of the virtual environment.

Enhancing Usability

A player needs to be aware of the object's, target's, and origin's position as well as the direction of the level's three axes to successfully solve a level using ATs. In GEtiT, the object's and target's positions are directly displayed in the UI and are always visible independent of a player's view. As GEtiT VR requires a diegetic UI to avoid breaking a user's presence, the position indications are implemented as labels that are attached to the object and to the target, respectively. The position labels always face towards the player, are scaled up or down depending on the player's distance to them, and shine through obstacles to ensure a good visibility from any position inside of a particular level. The origin and a level's three axes are displayed in form of a white ball that features three differently colored bars symbolizing the axes.

To reduce the frustrating effects of giving a wrong input, an undo function is implemented that reverts the game to the status before the last AT card was used. However, players can only go one step back and are not able to revert the entire history of their gameplay.

GEtiT provides a small built-in AT wiki that informs about the theoretically grounded mathematical aspects to keep learners immersed when they need to look up further information to determine a spatial puzzle's correct solution. The wiki is implemented with a 2D interface overlay that is activated via the main UI. As static UI elements would reduce the naturalness and experienced presence of GEtiT VR [44, 66], a special menu in form of a futuristic playing room was implemented. It features a control console, a game console, and two wiki screens. This playing room also allows players to load and enter a level and to change the game's settings. While the control console provides access to the game's settings and the option to switch through the wiki slides, the game console allows learners to load and to enter levels. Levels are represented by cubes stored in shelfs that

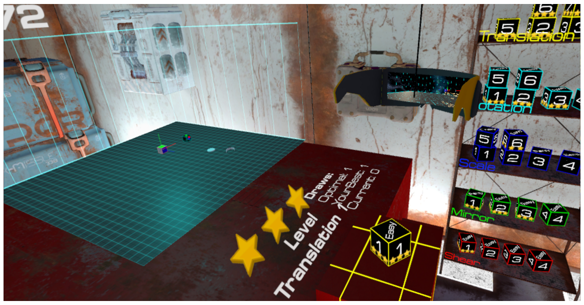


Figure 6: *GEtiT VR* uses an HMD metaphor to allow for a transition between the playing room and a level. On the right hand side, level cubes representing each individual level are shown.

are ordered by the targeted transformation type and difficulty level. By grabbing a cube and placing it on the game console, a level gets loaded. The game console is connected to a virtual HMD (see Figure 6) that can be grabbed with one of the controllers and put on with a gesture one would perform to put on glasses [47]. Subsequently, the player is teleported into the loaded level and can start or continue to solve the presented spatial puzzle. By taking off the virtual HMD, players return to the playing room to check the wiki or to load a different level.

Finally, GEtiT displays a summary screen when a level was successfully solved to provide additional immediate feedback. The victory screens informs learners about the amount of cards used, the level's minimum amount, the stars achieved based on their performance, the time needed, and the composite mathematical equation of the used AT operations. This screen also provides the options to continue to the next challenge, to retry the current challenge or to return to the level selection menu. Thus, the summary screen allows players to analyze their performance and to develop an in-depth understanding of the AT's theoretically grounded mathematical aspects [10]. This summary screen is implemented as a 2D UI overlay in GEtiT that is displayed once a player has entered a portal. In contrast, GEtiT VR teleports the player into a summary virtual environment featuring the relevant information in form of diegetic interface elements and providing the options to restart or continue in form of two labeled portals.

Achieving Optimal Knowledge Learning

Both GEtiT versions require preexisting knowledge during the gameplay and motivate learners to tackle the learning exercises by using reward game mechanics. By moderating the level of abstraction and implementing the resulting four difficulty levels, both games achieve a periodical repetition of the learning content. Furthermore, clear game goals, immediate feedback and a constant stream of new challenges induce gaming flow. Flow influences a player's performance of gaming action and leads to an increased learning performance. After starting a level and analyzing the presented spatial puzzle, learners are required to apply their AT knowledge to escape the room. For this purpose, they utilize the AT cards representing individual mathematical operations to transform the object in such a way that it matches the victory conditions (see Figure 7). At the same time, GEtiT provides immediate feedback to inform learners about the correctness of their self-obtained solutions and the effects of the used AT operation.

4 TECHNOLOGY

GEtiT and GEtiT VR are developed with *unity* in the version 5.5.2p1 [80] for PC and Mac. The gameplay is rendered to the connected main monitor and, in the case of GEtiT VR, to the HTC Vive HMD. The VR implementation of GEtiT VR is achieved using the *SteamVR Plugin* [82] in the version 1.2.0 which already provided functions for the point & teleport locomotion, controller-based system interaction, controller tooltips, and overall player controller. The playing room's furniture is freely available on the *unity asset store* [81] or part of the *unity standard assets*.

5 METHOD

The study was designed to evaluate and to compare the usability of both GEtiT versions, i.e., the *VR* and the *desktop-3D (3D)* conditions. This study, however, was not designed to test the serious game's learning effects.

Experimental Tasks

In total, participants were orally given six experimental tasks for each of the two systems. They assessed the usability of the game controls, the UI and the UI's adjustments based on the moderation of the level of abstraction. Table 1 provides an overview of the experimental tasks.

Measures

Simulator Sickness. The simulator sickness was measured for all participants before and after the GEtiT VR experimental playing session using the *simulator sickness questionnaire* (*SSQ*) [37].

Effectiveness. The effectiveness was measured by logging the successfully solved experimental tasks. Also, the amount and the content of questions regarding each individual experimental task was logged.

Efficiency. The efficiency was determined by measuring the *time* needed for the completion of each individual experimental task.

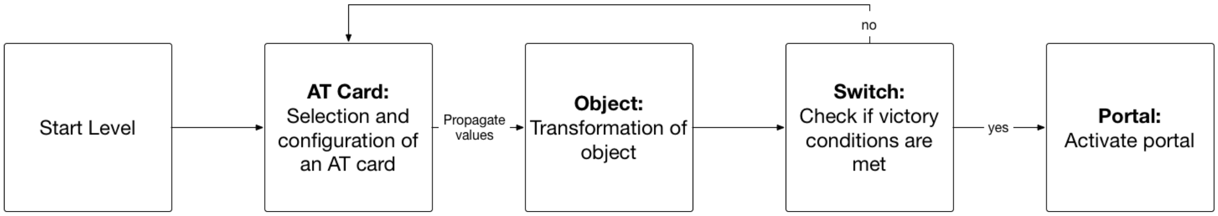
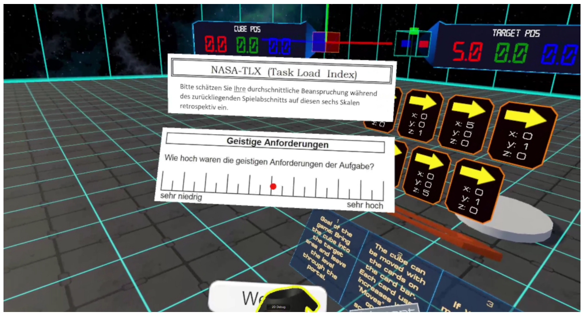


Figure 7: Schematic representation of GEtiT's gameplay.

Table 1: Overview of Experimental Tasks

Item	Task	Assessment goals
1	Create and load a profile	Text input UI design
2	Solve "Translation Easy 1"	AT card interaction Basic locomotion
3	Solve "Translation Easy 4"	AT card interaction Advanced locomotion (overleaping a gap, see Figure 5)
4	Solve a specific medium translation level (indicated by 2 stars)	Level selection interface AT card interaction Direct value configuration screen
5	Solve "Rotation Expert 1"	AT card interaction Wiki interaction Direct value configuration screen
6	Solve medium levels for 5 minutes	Gaming flow


NASA-TLX (Task Load Index)

Bitte schätzen Sie Ihre durchschnittliche Beanspruchung während des zurückliegenden Spielabschnitts auf diesen sechs Skalen retrospektiv ein.

Geistige Anforderungen

Wie hoch waren die geistigen Anforderungen der Aufgabe?

sehr niedrig — sehr hoch

Figure 8: Using the NASA-TLX questionnaire directly in VR.

Also, the perceived task load was measured using the *NASA-TLX* [29]. To facilitate the evaluation process, the modified *Raw NASA-TLX* [28] version was used. This version eliminates the weighting process and only implements the six sub-scales to measure the overall task load. Participants filled in the questionnaire after each experimental task. To streamline the procedure and to reduce a potential negative effect caused by the necessity to don and to remove the HMD on a frequent basis, the assessment tool was directly presented inside of the simulations. In GEtiT VR, a diegetic panel (apparent size of $1m \times 0.3m$) displayed one of the six continuous rating scales at a time (see Figure 8). Participants entered their ratings with one of the controllers by touching the scale and pulling the trigger button. In GEtiT, a 2D UI overlay displayed the continuous rating scales. Users entered their ratings with the mouse following the principle of an online web-based survey system.

Satisfaction. The *QUESI* [46] was used to assess the perceived intuitive use of both systems. It was filled in after each experimental playing session.

At the end of the experiment, participants were asked to express their *preference* for one of the two systems and to reason their selection.

Flow. For the purpose of measuring the flow-inducing aspects of the gameplay, the study included the *flow short scale* (*FSS*) [62]. The participants completed this assessment tool after both experimental conditions.

Aparatus

GEtiT and GEtiT VR were played on the same computer (CPU: Intel Core i7-6700K @ 4.00GHz, RAM: 16GB, Graphics card: MSI NVIDIA GeForce GTX 1080 Ti 16GB) in a climatized room. An HTC Vive HMD (resolution: 2160 × 1200, 1080 × 1200 per eye; refresh rate: 90 Hz) was connected to the computer and the HTC Vive's tracking area had a size of $2.5m \times 2.5m$ (see Figure 9). On this machine, GEtiT VR was continuously running with 90 frames per second. An over-ear headset (133,85 Ohm, 10 Hz - 30.000 Hz, sound pressure level: 96,31 dB) provided the participants with an immersive

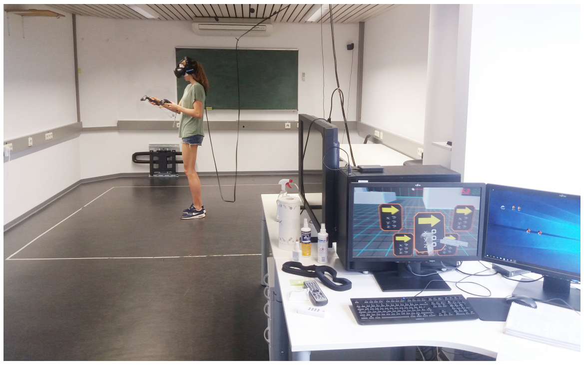


Figure 9: Playing *GEtiT VR* in the lab.

audio experience. The computer and the computer screen (24", resolution: 1920 × 1080) were placed on top of a rectangular ($1.5m \times 1m$) office table. A standard office chair was provided for playing GEtiT. The headphones and HMD were cleaned after a participant finished the experiment.

Procedure

The experiment consisted of seven stages and followed a within-design. The two GEtiT versions were played in counterbalanced order.

(1) *Introduction:* The participant is introduced to the overall design of the experiment and the implemented health and safety rules. Subsequently, a quick overview over the AT knowledge is given to allow for a self-assessment of the AT expertise level. The participant then signs a written consent form. Finally, a demography questionnaire is filled in.

(2) ***GEtiT VR*** *pre-questionnaire:* The participant fills in the pre-SSQ questionnaire.

(3) *GEtiT VR gameplay:* The participant dons the HTC Vive HMD, controllers, and headphones. Then the participant receives a quick introduction to the functionality of the devices and the chaperone system. After a check if the participant experiences an effect of simulation sickness, the first experimental task is orally communicated. Once the participant has solved a task, the in-VR NASA-TLX is filled in. This procedure is repeated until all six experimental tasks are completed. Once the participant has filled in the last NASA-TLX questionnaire, they receive assistance to remove the VR equipment.

(4) *GEtiT VR post-questionnaire:* The participant fills in the post-SSQ, QUESI and FSS questionnaires.

(5) ***GEtiT*** *gameplay:* The participant gets seated at the office desk. After a quick introduction, the first experimental task is orally communicated. After completion of a task, the in-simulation NASA-TLX is activated. This procedure is repeated until all six experimental tasks are completed.

(6) *GEtiT post-questionnaire:* The participant fills in the QUESI and FSS questionnaires.

(7) *Conclusion:* The participant is asked which of the systems would be the participant's choice for an AT knowledge learning. Also, the participant is asked to reason their choice.

Participants

In total, 13 participants were recruited from the undergraduate students who were enrolled at the University of Würzburg. An online participant recruitment system that rewards students with credits mandatory for obtaining their Bachelor's degrees was used. Two participants (novice computer game players based on self-report) had to be removed from the sample as they not only decided to stop trying to overleap the gap in GEtiT during experimental task 3, but also showed a high degree of frustration which potentially influenced their ratings of both systems. The remaining participants ($n = 11$, 7 females, 4 males) had a mean age of 20.45 ($SD = 1.51$) and reported no previous GEtiT or GEtiT VR experience. Also, none of them had severe visual impairments. Ten participants used an HTC Vive or Oculus Rift ($M = 1.45$ hours, $SD = 0.93$) before and six participants reported a previous computer game experience with a mean weekly playtime of 13.58 hours ($SD = 16.06$). The participants' mean AT knowledge was 2.18 (1 = no previous knowledge, 5 = expert knowledge, $SD = 0.87$) based on self-report.

6 RESULTS

As the study used two conditions and followed a within-design, all results were compared using *paired t-tests*. The effect size was determined by computing the *Cohen's D*. *Pearson's product-moment correlation* was computed to test for a correlation.

Simulator Sickness

The evaluation of the pre-SSQ and post-SSQ total scores revealed no effect of a simulator sickness ($M_{pre} = 27.54$, $SD_{pre} = 34.45$, $M_{post} = 15.98$, $SD_{post} = 17.47$, $t(10) = 1.65$, $p = 0.13$) during the gameplay of GEtiT VR.

Effectiveness

All participants managed to complete every experimental task while playing GEtiT VR, but two of them, who subsequently were excluded from the sample, decided to stop trying to solve experimental task 3 while playing GEtiT. The experiment conductor was asked 8 times in total for additional advise while GEtiT VR was played and 2 times during the GEtiT playing phase. GEtiT VR's problems were related to experimental task 1 that required participants to enter their name using the controllers (5 questions) and experimental task 4 (3 questions) challenging participants for the first time to configure a card's values. During the GEtiT

Table 2: Mean Times (s) for Each Experimental Task

Exp. Task	M_{VR}	SD_{VR}	M_{3D}	SD_{3D}	p
1	69.27	29.52	19.73	10.35	< 0.001
2	108.91	43.06	99.73	39.54	0.65
3	95.36	24.52	172.27	104.21	0.02
4	161.18	46.37	70.00	73.98	0.01
5	214.00	83.72	137.55	42.54	0.02
6	300	–	300	–	–

Table 3: Mean Total Task Load for Each Task

Exp. Task	M_{VR}	SD_{VR}	M_{3D}	SD_{3D}	p
1	33.03	13.63	19.62	13.37	< 0.001
2	34.85	13.06	30.76	14.01	0.38
3	38.86	13.70	44.24	13.97	0.26
4	44.55	10.87	26.89	20.01	0.002
5	44.70	16.65	33.41	15.87	0.03
6	42.58	13.22	43.33	13.46	0.79

playing phase, only experimental task 5 raised 2 questions concerning the input format of cosine values.

Efficiency

Time. On average, the participants needed 499.27s to solve all GEtiT tasks (SD_{3D} = 223, excluding exp. task 6) and 648.73s to complete all GEtiT VR tasks (SD_{VR} = 142.68, excluding exp. task 6). The two systems did not significantly differ in regard to the overall time needed ($t(10) = 1.81$, $p = 0.08$). However, as Table 2 depicts, experimental task 1, 4 and 5 were solved significantly faster while playing GEtiT and experimental task 3 was solved significantly faster while playing GEtiT VR. As overleaping a gap is a common computer game challenge, the Pearson's product-moment correlation was computed to check whether previous gameplay experience had an effect on a participant's performance. It revealed a significant correlation ($cor = 2.47$, $p = 0.04$) between the time needed for GEtiT experimental task 3 and the previous computer game experience.

NASA-TLX. The participants gave a mean total score of 33.04 ($SD_{3D} = 12.74$) for GEtiT and 39.76 ($SD_{VR} = 10.72$) for GEtiT VR on the NASA-TLX across all experimental tasks. A t-test revealed a significant difference ($t(10) = 2.53$, $p = 0.03$, $CohensD = 0.57$) between the task load of both system. The significant differences between the two systems (see Table 4) were in the physical demand ($t(10) = 4.44$, $p = 0.001$, $CohensD = 1.19$) and effort ($t(10) = 3.35$, $p = 0.007$, $CohensD = 0.48$). In particular, as Table 3 displays, a significant difference in the task load was also found for experimental task 1 ($t(10) = 4.65$, $p < 0.001$, $CohensD = 0.99$), 4 ($t(10) = 4.23$, $p = 0.002$, $CohensD = 1.10$), and 5 ($t(10) = 2.52$, $p = 0.03$, $CohensD = 0.69$). These tasks required the participants to enter a profile name and to enter values in the direct value configuration screen. Despite the significant difference between both systems, the overall and the task-specific task load were below the neutral mid-point of the scale (0 = low task load, 100 = high task load).

Table 4: Mean Subscale Load Across All Tasks

Scale	M_{VR}	SD_{VR}	M_{3D}	SD_{3D}	p
Mental Dem.	48.41	13.71	40.76	15.75	0.08
Physical Dem.	27.65	12.95	11.74	13.79	0.001
Temporal Dem.	39.39	14.40	37.27	14.64	0.62
Performance	46.14	12.57	39.77	15.86	0.20
Effort	44.47	11.90	37.73	15.87	0.007
Frustration	32.50	17.26	30.98	19.63	0.75

Satisfaction

No significant difference ($t(10) = 0.01$, $p = 0.99$) was found between the participants' intuitive use ratings ($M_{VR} = 3.41$, $SD_{VR} = 0.92$, $M_{3D} = 3.41$, $SD_{3D} = 1.18$) on the QUESI questionnaire. The total intuitive use scores for both systems were above the neutral mid-point of scale (1 = negative perception, 5 = positive perception).

All participants agreed that they would use one of the two systems for an AT knowledge learning. Nine (82%) participants expressed a preference for GEtiT VR, whereas two participants (18%) would rather use GEtiT. The participants who preferred GEtiT VR explained their decision with a higher fun factor and a more intuitive demonstration of the AT knowledge. The decision for GEtiT was based on the well know input techniques and a simpler interaction. Overall, the participants' statements indicated that both versions of the serious game elicit motivating, intuitive, and educational aspects.

Flow

The FSS measured the systems' overall flow experience (1 = low flow, 7 = high flow) and worry values (1 = low worry, 9 = high worry) testing for a potential boredom or anxiety of the users. No significant difference was found between the flow ($M_{VR} = 4.45$, $SD_{VR} = 0.68$, $M_{3D} = 4.18$, $SD_{3D} = 0.79$, $t(10) = 1.65$, $p = 0.13$) and the worry value ($M_{VR} = 4.67$, $SD_{VR} = 0.63$, $M_{3D} = 4.94$, $SD_{3D} = 0.61$, $t(10) = 1.69$, $p = 0.12$) of both system. GEtiT and GEtiT VR scored above the neutral mid-point of the flow scale and above the neutral mid-point of the worry scale.

7 DISCUSSION

The study evaluated the usability and the gameplay experience of both GEtiT versions. Aside from two participants who gave up on trying to cross the gap during experimental task 3, all tasks were successfully completed thus confirming GEtiT's intuitive design and effectiveness. As the participants rated their AT knowledge level low to medium, this result also indicates the effectiveness of the knowledge moderation. The participants managed to solve the tested levels without an in-depth preexisting knowledge. Hence, the moderation resulted in an intuitive and comprehensible presentation and application requirement of the AT knowledge.

The above neutral mid-point ratings on the FSS indicate that GEtiT exhibits flow-inducing aspects and creates a compelling gameplay. This is important as flow affects a user's performance thus also increasing the learning quality. The preference and reasoning of the participants confirmed a higher joy of use and a more intuitive knowledge demonstration when using the VR version. As a result, the user study indicates that VR technology is beneficial for the learning quality.

The time needed and the overall issues experienced by novice computer game players during the performance of experimental task 3 are explainable by the three stages of skill acquisition [3, 18]. During the *cognitive stage*, a motor skill, such as using the keyboard to achieve a locomotion inside of a computer game, is encoded in a *declarative form*. It describes all necessary steps for the skill's performance: using WASD for steering and pressing the spacebar to jump. During this stage, the skill's performance is poor and all encoded steps are followed closely. Subsequently, during the *associative* and the *autonomous* stage, errors are removed and, due to a periodical practice, the skill's performance gets automated and encoded in a *procedural form*. As a result, participants who were novice gamers needed more attempts and time to overcome the challenge of crossing the gap or even decided to abort this task. This assumption is supported by the correlation between previous computer game experience and time needed for the task. Despite only 4 of the 108 levels feature the gap, this outcome indicates the necessity to either provide an easier way to cross it or to label the 4 levels as particular difficult. Both methods potentially decrease a learner's frustration when playing GEtiT for the first time. However, the result that no participant experienced issues with the locomotion inside of GEtiT VR confirms the intuitive aspects of the *point & teleport* technique [5].

The time needed and the task load for experimental tasks that require a text input show that GEtiT's UI is well designed and allows for a high efficiency when a keyboard is used. This result is supported by the good perceived intuitive use rating. Simultaneously, the results of experimental task 2 and 3 show that the HTC Vive controllers enable users to easily perform natural gestures and interactions, such as selecting and activating a card. However, they are complicated to operate when a selection-based text input is required [75]. Instead of simply typing on a keyboard, users are challenged to individually select the inputs using the controller. The study indicates and confirms the importance of evaluating different VR typing techniques. Despite the higher task load and slower input times, the perceived intuitive use did not differ between GEtiT VR and GEtiT thus confirming the naturalness of the provided diegetic interface elements [23].

8 CONCLUSION AND FUTURE WORK

We developed, to the best of our knowledge, the first 3D and VR transfer-oriented serious game for ATs: GEtiT. It combines the learning effects of game mechanics with the potential of 3D and VR technology to provide an intuitive knowledge visualization. The gamified knowledge encoding transformed the AT knowledge into clear rules that subsequently were mapped to game mechanics as their internal rules. GEtiT fulfills the conditions for optimal learning by achieving a highly motivating and repetitive knowledge learning. The achieved learning requires preexisting knowledge and provides immediate feedback. Finally, by moderating the knowledge's level of abstraction, an intuitive and comprehensible learning and demonstration of ATs is achieved.

The study validated our conceptual approach by demonstrating GEtiT's high flow-inducing aspects, good perceived intuitive use, and low task load. The study's results show a higher enjoyment when using GEtiT VR suggesting that using immersive VR enhances the learning quality. The results also demonstrated the effectiveness of VR technology to visually present and to require abstract knowledge. However, when requiring selection-based text input, the results indicate the importance of researching further input techniques that reduce a user's task load and interaction time. Overall, this paper contributes to the on-going process of researching the educational potentials of immersive VR by presenting and evaluating a VR serious game.

Future research is needed to implement and evaluate intuitive selection-based text input techniques to increase GEtiT VR's overall usability. A different future research direction would be to add formative feedback to the gameplay. Feedback is an important influence on the learning outcome [30]. In case of computer graphics learning, providing formative feedback can improve the learning outcome [31]. GEtiT only provides feedback by providing a visual demonstration of the results, i.e., the object casts a trail, and showing a debriefing screen. Thus, providing additional formative feedback might result in an increased learning outcome.

REFERENCES

[1] Ernest Adams and Joris Dormans. 2012. *Game Mechanics*. New Riders, Berkeley.

[2] Eike Falk Anderson, Leigh McLoughlin, Fotis Liarokapis, Christopher Peters, Panagiotis Petridis, and Sara de Freitas. 2009. Serious Games in Cultural Heritage. In *The 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST*. Malta, 29–48.

[3] John R Anderson. 2015. *Cognitive Psychology and Its Implications* (8th ed.). Worth Publishers.

[4] Doug A Bowman, Ernst Kruijff, Joseph J LaViola Jr, and Ivan Poupyrev. 2001. An introduction to 3-D user interface design. *Presence: Teleoperators and virtual environments* 10, 1 (2001), 96–108.

[5] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point & Teleport Locomotion Technique for Virtual Reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*. ACM, Austin, TX, USA, 205–216.

[6] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2019. Locomotion in virtual reality for room scale tracked areas. *International Journal of Human-Computer Studies* 122 (2019), 38–49. https://doi.org/10.1016/j.ijhcs.2018.08.002

[7] Jere Brophy. 2000. *Teaching*. Educational Practices Series, Vol. 1. International Academy of Education & International Bureau of Education, Brussels.

[8] Dennis Charsky. 2010. From Edutainment to Serious Games: A Change in the Use of Game Characteristics. *Games and Culture* 5, 2 (March 2010), 177–198. https://doi.org/10.1177/1555412009354727

[9] Isabelle D Cherney. 2008. Mom, Let Me Play More Computer Games: They Improve My Mental Rotation Skills. *Sex Roles* 59, 11-12 (July 2008), 776–786.

[10] David Crookall. 2011. Serious Games, Debriefing, and Simulation/Gaming as a Discipline. *Simulation & Gaming* 41, 6 (Jan. 2011), 898–920. https://doi.org/10.1177/1046878110390784

[11] Mihaly Csikszentmihalyi. 1990. *Flow: The Psychology of Optimal Experience*. Harper-Perennial, New York, NY, USA.

[12] Barney Dalgarno and Mark J. W. Lee. 2010. What are the learning affordances of 3-D virtual environments? *British Journal of Educational Technology* 41, 1 (2010), 10–32. https://doi.org/10.1111/j.1467-8535.2009.01038.x

[13] Suzanne de Castell, Jennifer Jenson, and Nicholas Taylor. 2010. Educational Games: Moving from Theory to Practice. In *Educational gameplay and simulation environments : case studies and lessons learned*, David Kaufman and Louise Sauvé (Eds.). Information Science Reference, Hershey, PA, 133–145.

[14] Sara de Freitas and Fotis Liarokapis. 2011. Serious Games: A New Paradigm for Education? In *Serious Games and Edutainment Applications*, Minhua Ma, Andreas Oikonomou, and Lakhmi C Jain (Eds.). Springer-Verlag, London, 9–23. https://doi.org/10.1007/978-1-4471-2161-9_2

[15] Christopher J Dede. 2009. Immersive Interfaces for Engagement and Learning. *Science* 323 (2009).

[16] Christopher J Dede, Jeffrey Jacobson, and John Richards. 2017. Introduction: Virtual, Augmented, and Mixed Realities in Education. In *Virtual, Augmented, and Mixed Realities in Education*, Dejian Liu, Christopher J Dede, Ronghuai Huang, and John Richards (Eds.). Springer, Singapoore.

[17] K Anders Ericsson, Ralf Th Krampe, and Clemens Tesch-Römer. 1993. The Role of Deliberate Practice in the Acquisition of Expert Performance. *Psychological Review* 100, 3 (1993), 363–406.

[18] Paul Morris Fitts and Michael I Posner. 1967. *Human performance*. Brooks Cole.

[19] J Foley, A van Dam, S Feiner, and J Hughes. 1990. *Computer Graphics: Principles and Practice*. Addison-Wesley, Reading, MA, USA.

[20] Laura Freina and Michela Ott. 2015. A Literature Review on Immersive Virtual Reality in Education: State Of The Art and Perspectives. In *Proceedings of the 11th eLearning and Software for Education (eLSE)*. Bucharest, Romania.

[21] K S Fu, R Gonzalez, and C S G Lee. 1987. *Robotics: Control, Sensing, Vision and Intelligence*. McGraw-Hill Education, New York.

[22] James Paul Gee. 2007. *What video games have to teach us about learning and literacy* (1 ed.). Palgrave Macmillan, New York.

[23] Sanjay Ghosh, Chivukula Sai Shruthi, Himanshu Bansal, and Arvind Sethia. 2017. What is User's Perception of Naturalness? An Exploration of Natural User Experience. In *Human-Computer Interaction - INTERACT 2017*, Regina Bernhaupt, Girish Dalvi, Anirudha Joshi, Devanuj K. Balkrishan, Jacki O'Neill, and Marco Winckler (Eds.). Springer International Publishing, Cham, 224–242.

[24] Georg Gittler and Judith Glück. 1998. Differential transfer of learning: Effects of instruction in descriptive geometry on spatial test performance. *Journal of Geometry and Graphics* 2, 1 (1998), 71–84.

[25] C Shawn Green and Daphne Bavelier. 2003. Action video game modifies visual selective attention. *Nature* 423, 6939 (2003), 534–537.

[26] C Shawn Green and Daphne Bavelier. 2007. Action-video-game experience alters the spatial resolution of vision. *Psychological Science* 18, 1 (2007), 88–94.

[27] Anthony Gurr. 2010. Video Games and the Challenge of Engaging the 'Net' Generation. In *Educational gameplay and simulation environments : case studies and lessons learned*, David Kaufman and Louise Sauvé (Eds.). Information Science Reference, Hershey, PA, USA, 119–131.

[28] Sandra G. Hart. 2006. NASA-Task Load Index (NASA-TLX); 20 Years Later. In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*. Santa Monica, 904–908.

[29] Sandra G. Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Human Mental Workload*, P. A. Hancock and N Meshkati (Eds.). Elsevier Science Publishers B.V., Amsterdam, 139–183.

[30] John Hattie and Helen Timperley. 2007. The Power of Feedback. *Review of Educational Research* 77, 1 (2007), 81–112. https://doi.org/10.3102/003465430298487

[31] Blake Hodgkinson, Christof Lutteroth, and Burkhard Wünsche. 2016. glGetFeedback—Towards automatic feedback and assessment for OpenGL 3D modelling assignments. In *2016 International Conference on Image and Vision Computing New Zealand (IVCNZ)*. IEEE, 1–6.

[32] Philip N. Johnson-Laird. 1983. *Mental Models. Towards a Cognitive Science of Language, Inference, and Consciousness*. Harvard University Press.

[33] Mona Erfani Joorabchi and Magy Seif El-Nasr. 2011. Measuring the Impact of Knowledge Gained from Playing FPS and RPG Games on Gameplay Performance. In *Entertainment Computing – ICEC 2011*. Springer, Vancouver, BC, Canada, 300–306. https://doi.org/10.1007/978-3-642-24500-8_33

[34] Victor Kaptelinin and Bonnie A Nardi. 2012. Affordances in HCI: Toward a Mediated Action Perspective. In *CHI 2012 Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems*. ACM, Austin, TX, USA, 967–976. https://doi.org/10.1145/2207676.2208541

[35] Hannes Kaufmann. 2006. The potential of augmented reality in dynamic geometry education. *12th International Converence on Geometry and Graphics* (2006).

[36] Hannes Kaufmann, Dieter Schmalstieg, and Michael Wagner. 2000. Construct3D: A Virtual Reality Application for Mathematics and Geometry Education. *Education and Information Technologies* 5, 4 (2000), 263–276.

[37] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal*

of Aviation Psychology 3, 3 (1993), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

[38] Mina Khan, Fernando Trujano, Ashris Choudhury, and Pattie Maes. 2018. Mathland: Playful Mathematical Learning in Mixed Reality. In *CHI'18 Extended Abstracts*. Montréal, Canada.

[39] Joseph J LaViola Jr, Ernst Kruijff, Ryan P McMahan, Doug Bowman, and Ivan P Poupyrev. 2017. *3D user interfaces: Theory and practice*. Addison-Wesley Professional.

[40] Timothy Lynam, Raphael Mathevet, Michel Etienne, Samantha Stone-Jovicich, Anne Leitch, Nathalie Jones, Helen Ross, Derick Du Toit, Sharon Pollard, Harry Biggs, and Pascal Perez. 2012. Waypoints on a Journey of Discovery: Mental Models in Human-Environment Interactions. *Ecology and Society* 17, 3 (2012). https://doi.org/10.5751/ES-05118-170323

[41] Guido Makransky and Lau Lilleholt. 2018. A structural equation modeling investigation of the emotional value of immersive virtual reality in education. *Educational Technology Research and Development* (2018). https://doi.org/10.1007/s11423-018-9581-2

[42] Jorge Martín-Gutiérrez, Carlos Efrén Mora, Beatriz Añorbe-Díaz, and Antonio González-Marrero. 2017. Virtual Technologies Trends in Education. *EURASIA Journal of Mathematics Science and Technology Education* 13, 2 (2017), 469–486. https://doi.org/10.12973/eurasia.2017.00626a

[43] Jane McGonigal. 2011. *Reality is broken : why games make us better and how they can change the world* (1 ed.). Penguin Press, New York.

[44] Daniel Medeiros, Eduardo Cordeiro, Daniel Mendes, Maurício Sousa, Alberto Raposo, Alfredo Ferreira, and Joaquim Jorge. 2016. Effects of Speed and Transitions on Target-based Travel Techniques. In *Proceedings of the 22Nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*. ACM, New York, NY, USA, 327–328. https://doi.org/10.1145/2993369.2996348

[45] Jose Mestre. 2002. *Transfer of Learning: Issues and Research Agenda*. National Science Foundation, Washington, D.C.

[46] Anja Naumann and Jörn Hurtienne. 2010. Benchmarks for Intuitive Interaction with Mobile Devices. In *Proceedings of MobileHCI'10*. Lisboa, Portugal.

[47] Sebastian Oberdörfer, Martin Fischbach, and Marc Erich Latoschik. 2018. Effects of VE Transition Techniques on Presence, IVBO, Efficiency, and Naturalness. In *Proceedings of the 6th Symposium on Spatial User Interaction*. ACM, Berlin, Germany.

[48] Sebastian Oberdörfer, David Heidrich, and Marc Erich Latoschik. 2017. Interactive Gamified Virtual Reality Training of Affine Transformations. In *Proceedings of DeLFI and GMW Workshops 2017*, Carsten Ullrich and Martin Wessner (Eds.). Chemnitz, Germany.

[49] Sebastian Oberdörfer and Marc Erich Latoschik. 2013. Develop your strengths by gaming. In *Informatik 2013 - Proceedings of 43rd annual German conference on informatics*, Matthias Horbach (Ed.), Vol. P-220. Gesellschaft für Informatik, Koblenz, Germany, 2346–2357.

[50] Sebastian Oberdörfer and Marc Erich Latoschik. 2016. Interactive gamified 3D-training of affine transformations. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*. ACM Press, Garching, Germany, 343–344. https://doi.org/10.1145/2993369.2996314

[51] Sebastian Oberdörfer and Marc Erich Latoschik. 2018. Effective Orbital Mechanics Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018)*. Würzburg, Germany.

[52] Sebastian Oberdörfer and Marc Erich Latoschik. 2018. Effectivity of Affine Transformation Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018)*. Würzburg, Germany.

[53] Sebastian Oberdörfer and Marc Erich Latoschik. 2018. Gamified Knowledge Encoding: Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018)*. Würzburg, Germany.

[54] Adam C Oei and Michael D Patterson. 2013. Enhancing Cognition with Video Games: A Multiple Game Training Study. *PLoS ONE* 8, 3 (Feb. 2013), e58546. https://doi.org/10.1371/journal.pone.0058546

[55] Lauri-Matti Palmunen, Elina Pelto, Anni Paalumäki, and Timo Lainema. 2013. Formation of Novice Business Students' Mental Models Through Simulation Gaming. *Simulation & Gaming* 44, 6 (2013), 846–868.

[56] David Perry and Rusel DeMaria. 2009. *David Perry on Game Design: A Brainstorming Toolbox*. Course Technology, Boston, MA, USA.

[57] Marios Pittalis and Constantinos Christou. 2010. Types of reasoning in 3D geometry thinking and their relation with spatial ability. *Educational Studies in Mathematics* 75, 2 (2010), 191–212. https://doi.org/10.1007/s10649-010-9251-8

[58] Patrick Prax. 2010. Leadership Style in World of Warcraft Raid Guilds. In *Proceedings of DiGRA Nordic 2010*. DiGRA, Stockholm, Sweden.

[59] Lin Qiu, Wendy Weini Tay, and Junwei Wu. 2009. The impact of virtual teamwork on real-world collaboration. *ACE'09 Proceedings of the International Conference on Advances in Computer Enterntainment Technology* (2009), 44–51.

[60] Jens Rasmussen. 1983. Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. *IEEE Transactions on Systems, Man, and Cybernetics* 13, 3 (1983), 257–266.

[61] Byron Reeves, Thomas W Malone, and Tony O'Discoll. 2008. Leadership's Online Labs. *Harvard Business Review* 86, 5 (2008), 58–66.

[62] Falko Rheinberg, Regina Vollmeyer, and Stefan Engeser. 2003. Die Erfassung des Flow-Erlebens. In *Diagnostik von Motivation und Selbstkonzept*, J Stiensmeier-Pelster and Falko Rheinberg (Eds.). Hogrefe, Göttingen, 261–279.

[63] Sebastian Richter and Ulrike Lechner. 2011. Communication content relations to coordination and trust over time: a computer game perspective. In *C&T'11 Proceedings of the 5th International Conference on Communities and Technologies*. ACM, Brisbane, Australia, 60–68. https://doi.org/10.1145/2103354.2103363

[64] Christian B Rogers, Hazim El-Mounaryi, Tamer Wasfy, and Jesse Satterwhite. 2017. Assessment of STEM e-Learning in an Immersive Virtual Reality (VR) Environment. *Computers in Education* 8, 4 (2017).

[65] James C Rosser, Jr, Paul J Lynch, Laurie Cuddihy, Douglas A Gentile, Jonathan Klonsky, and Ronald Merrell. 2007. The impact of video games on training surgeons in the 21st century. *Archives of Surgery* 142, 2 (2007), 181.

[66] P Salomoni, C Prandi, M Roccetti, L Casanova, and L Marchetti. 2016. Assessing the efficacy of a diegetic game interface with Oculus Rift. In *2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC)*. 387–392. https://doi.org/10.1109/CCNC.2016.7444811

[67] Kevin Saunders and Jeannie Novak. 2013. *Game Development Essentials: Game Interface Design* (2nd ed.). Cengage Learning.

[68] Ralph Schroeder. 2011. *Being There Together : Social Interaction in Virtual Environments* (1 ed.). Oxford University Press, New York.

[69] Norbert M. Seel. 2003. *Psychologie des Lernens* (2 ed.). Reinhardt Verlag.

[70] Miguel Sicart. 2008. Defining game mechanics. *Game Studies* 8, 2 (2008).

[71] Anna Siewiorek and Andres Gegenfurtner. 2010. Leading to win: the influence of leadership styles on team performance during a computer game training. In *ICLS '10 Proceedings of the 9th International Conference of the Learning Sciences*, Vol. 1. ACM, Chicago, IL, USA, 524–531.

[72] Mel Slater. 2009. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 364, 1535 (2009),

3549–3557.

[73] Mel Slater, Vasilis Linakis, Martin Usoh, and Rob Kooper. 1996. Immersion, Presence, and Performance in Virtual Environments: An Experiment with Tri-Dimensional Chess. In *ACM Virtual Reality Software and Technology (VRST)*. 163–172.

[74] Mel Slater and Sylvia Wilbur. 1997. A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. *Presence* 6, 6 (1997), 603–616. https://doi.org/10.1162/pres.1997.6.6.603

[75] Marco Speicher, Anna Maria Feit, Pascal Ziegler, and Antonio Krüger. 2018. Selection-based Text Entry in Virtual Reality. In *Proceedings of CHI 2018*. Montréal, Canada.

[76] Larry R Squire. 1992. Declarative and Nondeclarative Memory: Multiple Brain Systems Supporting Learning and Memory. *Journal of Cognitive Neuroscience* 4, 3 (1992), 232–243.

[77] Jonathan A. Stevens and J. Peter Kincaid. 2015. The Relationship between Presence and Performance in Virtual Simulation Training. *Open Journal of Modelling and Simulation* 3 (2015), 41–48.

[78] Take-Two Interactive. 2011–2018. Kerbal Space Program. available at https://kerbalspaceprogram.com.

[79] Gerhard Tulodziecki, Bardo Herzig, and Silke Grafe. 2010. *Medienbildung in Schule und Unterricht*. Julius Klinkhardt.

[80] Unity. 2017. unity 5.5.2p1. available at https://unity3d.com/unity/qa/patch-releases/5.5.2p1.

[81] Unity. 2017. unity asset store. available at https://www.assetstore.unity3d.com.

[82] Valve Coorperation. 2015–2018. SteamVR Plugin. available at https://www.assetstore.unity3d.com/en/#!/content/32647.

[83] David Weibel and Bartholomäus Wissmath. 2011. Immersion in Computer Games: The Role of Spatial Presence and Flow. *International Journal of Computer Games Technology* 2011 (2011). https://doi.org/10.1155/2011/282345

[84] Bernd Weidenmann. 2009. Multimedia, Multicodierung und Multimodalität beim Online-Lernen. In *Online Lernen. Handbuch für Wissenschaft und Praxis*, L. J. Issing and P. Klimsa (Eds.). Oldenbourg, Chapter 5, 73–86.

6.3 Discussion

The validation of *GEtiT*'s design contributes to the answers of the following RQs:

RQ2: How do game mechanics demonstrate and require the application of knowledge during the gameplay?

RQ3: How can (abstract) knowledge be directly encoded in computer games using game mechanics?

The results of *GEtiT*'s usability study not only confirmed its overall design, but also validated the Gamified Knowledge Encoding-driven development. Players were able to solve the spatial puzzles independent of their affine transformation knowledge on lower difficulty levels. This supports the effectiveness of the knowledge moderation resulting in a gradual increase of the level of abstraction. Players also agreed that they would use *GEtiT* for an affine transformations learning. This confirms the direct knowledge encoding and creation of learning affordances as defined by the Gamified Knowledge Encoding. Both *GEtiT* versions mainly differed in their efficiency due to the complexity of the selection-based typing technique used in *GEtiT VR*. This, however, can be contributed to the development goal of keeping the gamification metaphors the same across both versions. The decision was made to allow for a direct comparability of the learning outcome in respect to the effects caused by the visualization technology used. As a result, the study confirmed the Gamified Knowledge Encoding as a method to design serious games.

7 Validating the Learning Outcome

This is going to be a research effort, with a bunch of experimentation. I'll have to become my own little NASA, figuring out how to explore far from the Hab. The good news is I have lots of time to figure it out. – Andy Weir (2014)

As *GEtiT* acts as a demonstrator for the Gamified Knowledge Encoding, testing for its learning outcome allows for an evaluation of the model's validity. This was approached in a three-step process. At first, *GEtiT* was tested in its prototype version played in a class-based setting as well as at home and compared to a traditional paper-based learning method in respect to learning outcome and joy of use. This first study revealed a similar learning outcome between *GEtiT* and the traditional method, but also a higher motivation to tackle the assignments when playing the serious game. Subsequently, *GEtiT*'s visual style received a major overhaul and was re-evaluated to confirm the first measurements. The second *GEtiT* study additionally analyzed the effects of changes in the audiovisual presentation of the learning content in respect to the learning outcome. As discussed in subsection 5.2, providing an immersive VR version of *GEtiT* might positively affect the learning outcome. For testing this assumption, *GEtiT VR* was compared to *GEtiT* in respect to learning outcome and learning quality in the third study. Finally, an approach to utilize the Gamified Knowledge Encoding for a structured quantitative analysis of existing computer games in respect to their learning outcomes is presented. Working with the model, *Kerbal Space Program* was analyzed from a theoretical point of view. This analysis then was validated in a user study.

This chapter reports on the results of these four studies.

7.1 First GEtiT Study

Effectivity of Affine Transformation Knowledge Training Using Game Mechanics compares *GEtiT* played either in a class-based setting or at home to a traditional learning method of using paper-based assignments.

Table 10: Effectivity of Affine Transformation Knowledge Training Using Game Mechanics

Author	Contribution
Oberdörfer, S.	Literature review, conceptual design, experimental design, data analysis, discussion, manuscript preparation and revision
Latoschik, M. E.	Manuscript revision

Oberdörfer, S. and Latoschik, M. E. Effectivity of Affine Transformation Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games '18)*, Würzburg, Germany, September 2018b. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493418

Effectivity of Affine Transformation Knowledge Training Using Game Mechanics

Sebastian Oberdörfer
Human-Computer Interaction
University of Würzburg
Würzburg, Germany
Email: sebastian.oberdoerfer@uni-wuerzburg.de

Marc Erich Latoschik
Human-Computer Interaction
University of Würzburg
Würzburg, Germany
Email: marc.latoschik@uni-wuerzburg.de

***Abstract*—The Gamified Training Environment for Affine Transformation (GEtiT) was developed as a demonstrator for the Gamified Knowledge Encoding model (GKE). The GKE is a novel framework that defines knowledge training using game mechanics (GMs). It describes the process of directly encoding learning contents in GMs to allow for an engaging and effective transfer-oriented knowledge training. Overall, GEtiT is developed to facilitate the training process of the complex and abstract Affine Transformation (AT) knowledge. The complexity of the AT makes it hard to demonstrate this learning content thus learners frequently experience issues when trying to develop an understanding for its application. During the gameplay, the application of the AT's mathematical grounded aspects is required and information about the underlying principles are provided. In this article, a short overview over GEtiT's structure and the knowledge encoding process is given. Also, this article presents the results of a study measuring the training effectivity and motivational aspects of GEtiT. The results indicate a training outcome similar to a traditional paper-based training method but a higher motivation of the GEtiT players. Hence, GEtiT yields a higher learning quality.**

I. INTRODUCTION

The ultimate goal of using gamified training environments for knowledge training is to achieve a training transfer from the simulation to a real world context [1], [2]. *Transfer* is the application of knowledge learned or trained in one context to a different context, e.g., transferring the training outcome from a computer game to a real world context [3]. For the purpose of facilitating the training transfer, the gamified training environment has to create similar requirements to the targeted real world context [4], [5]. This can be achieved by using game mechanics (GMs) to encode the knowledge by *moderating*, i.e., scaling its level of abstraction, and *mediating* it, i.e., demonstrating and requiring its application. GMs can be distinguished in *player-bound* and *game-bound* GMs [6], [7]. While game-bound GMs are used to create the game world and the game's challenges, player-bound GMs are executed by the players to interact with the game. The *interaction* between the two GM types creates a game's gameplay thus leading to a knowledge application and demonstration. In general, GMs are the underlying rules of a computer game as they define what is possible and how actions can be performed [7]. Thus, gamified training environments include any knowledge training application that utilizes GMs to implement a knowledge application and demonstration, such as regular computer games [8], serious games [9] or, to a certain extend, gamified e-learning systems [10].

So far, the actual process of encoding learning contents in gamified training environments is still unclear. One approach suggests the *Learning Mechanics-Game Mechanics* model combining pedagogy, learning and entertainment [11], [12]. However, this model still has a lot of uncertainties about the actual training effects of GMs and the process of encoding the learning content in them. Therefore, we propose the *Gamified Knowledge Encoding* model (*GKE*) [13] that maps knowledge rules to interacting GMs to create *learning affordances* [14]. The mapping process transforms the learning content into knowledge rules that are subsequently used as a GM's internal game knowledge rules. Learning affordances require the application of the encoded knowledge and inform about the underlying principles. This is achieved by utilizing player-bound GMs to periodically require the application of the knowledge inside of a gamified training environment. The resulting interaction with the game-bound GMs provides learners with feedback about the underlying principles and the correctness of their inputs. This repetitive training process achieves a compilation of *mental models* for the learning content and its application [15]. Mental models are mental representations of a particular knowledge that allow for an internal visualization, problem solving, and knowledge transfer [16], [17]. Also, GMs present the encoded knowledge in an audiovisual way that supports the compilation of mental models [18], [19].

Our contribution: The *Gamified Training Environment for Affine Transformation* (*GEtiT*) [20], [21] was developed as a demonstrator for the GKE (see Figure 1). It encodes the Affine Transformation (AT) knowledge in its GMs to allow for an effective training of this complex and abstract knowledge. Being part of linear algebra, ATs are a sub-field of mathematics. From a theoretical standpoint, they are specialized functions that map between affine spaces. Commonly, they are expressed as matrices, usually of dimensionality 4×4, and their operations as matrix-matrix multiplications, each matrix representing one desired mapping. ATs have pervasive applications in applied geometry where they are commonly used, e.g., in the field of robotics to realize kinematic controls [22], or in

Object:	Target:	Player:
0.00	7.50	10.98
-2.00	-2.00	-1.97
5.00	5.00	-1.42

Fig. 1. GEtiT challenges learners with spatial puzzles that can be solved using AT operations. Their main goal is to transform the object (solid cube) in such a way that it matches a level's victory conditions (transparent cube). AT operations can be applied and defined using the cards and the direct value configuration screen. The object immediately gets transformed according to the values and casts a trail to provide visual feedback.

computer graphics to display and position objects [23]. Due to their complexity, ATs cannot easily be demonstrated and hence learners often encounter issues when trying to develop an understanding of this learning content. Hence, they represent an ideal knowledge for a demonstration of the GKE. Working with the GKE, the AT learning content was segmented into rules that subsequently were mapped to interacting GMs. By moderating the knowledge, i.e., reducing its level of abstraction by only encoding a subset of the total rules, an intuitive training and scaling of GEtiT's complexity is achieved. In this article, a study measuring the training environment's training effect and motivational effects is presented.

In particular, the study is guided by the following hypotheses: (H1) GEtiT causes a similar training outcome in comparison to traditional training methods. (H2) GEtiT causes a higher motivation to solve the training tasks, although the same amount of time has to be invested. (H3) Adjusting the knowledge moderation is crucial for the training outcome.

This paper begins with an analysis of the current state of research and describes our method how GMs can be used to encode specific knowledge in a computer game. Subsequently, the structure of GEtiT is examined and the design of the study is explained. Finally, this article presents and discusses the results of the study and hence provides first insights about the effectivity of the GKE.

II. RELATED WORK

A. Game-based Training

Amongst other things, computer games have already been implemented to train complex sets of human skills such as surgery skills [24], leadership styles [25], [26], and skills of communication [27], [28] and cooperation [29], [30]. Also, video games were used to train human abilities such as the cognitive flexibility trait [31], spatial visual attention [32], and spatial resolution [33]. In general, computer games encode specific knowledge that can be learned and mastered during the gameplay [34], [35] as players periodically discover new challenges and multiple ways to solve them [36]. The immersive effect of playing a computer game can be used to introduce players to ethical questions [37] and moral problems thus achieving a training of moral decision making [38].

Well designed computer games automatically fulfill the conditions for *optimal learning* [39]. Due to their flow-inducing capabilities [40], they present the encoded game knowledge in a highly engaging and immersive way thus achieving a high player *motivation* to tackle a game's tasks. Also, computer games periodically increase the game goals' difficulty to compensate the training effect and to continuously provide players with new challenges [41]. In this way, a computer game requires *pre-existing* knowledge and even requires the knowledge learned during the gameplay. Computer games provide players with *immediate feedback* about the effects and correctness of their actions and their progress towards solving a challenge. Lastly, a game's general gameplay requires a *repetitive* application of the encoded knowledge thus ultimately achieving a training effect due to repetition [8].

The implementation of an AT training game requires an environment that allows for the presentation and training of geometry. The gameplay of adventure and strategy games provides players with clear objectives and puzzles they need to solve to proceed with the game [41]. Solving the game objectives challenges the players' skills of logic, memory, visualization, and problem-solving [42] which also are crucial for solving training exercises. The gameplay of action-based computer games results in a training of spatial abilities such as the mental rotation skill [43], spatial visual attention [32], spatial resolution of vision [33], and spatial navigation [44]. Playing action-based video games can also improve cognitive abilities [5], such as the working memory capacity, and hence enhance the players' ability to monitor task relevant information [45]. The improvement of the spatial abilities by playing action-based games can even have a positive impact on the understanding of geometry. It was shown that an improvement in spatial abilities can improve 3D geometry thinking [46]. Furthermore, research has shown that descriptive geometry instructions stimulate the development of spatial abilities [47]. Hence, designing GEtiT's GMs in a way that they challenge the cognitive spatial abilities of a player should support its training effect.

B. Construct 3D

Using virtual environments for the teaching of geometry was already approached with *Construct3D*, an Augmented Reality (AR) application to teach mathematics and geometry, which is based on the AR framework *Studierstube* [48]. Construct3D allows students to create geometrical objects from a selection of basic object types and to explore these new objects in detail by manipulating them.

The application's key feature is the strength to display abstract geometrical problems and to visualize geometrical objects almost haptically. Students can explore the geometrical objects by walking around them, hence developing a spatial understanding of the geometry.

1	0	0	0
0	1	0	5
0	0	1	0
0	0	0	1

Fig. 2. By activating an AT card, the direct value configuration screen is opened to allow for an input of self-obtained values.

In contrast to GEtiT discussed in this paper, Construct3D is not a gamified training environment and hence is not implementing GMs to present and require the knowledge. Although the users of the AR application can perform playful experiments with geometry [49], the main focus lies on the visual presentation of geometry with the aid of AR. Moreover, Construct3D is used for a more general education in geometry and does not only focus on a specific branch of it. Construct3D also does not provide the users with clear goals they need to achieve to proceed.

III. GAMIFIED TRAINING ENVIRONMENT FOR AFFINE TRANSFORMATION

Aside from encoding the AT knowledge in its GMs, GEtiT must fulfill three additional requirements to achieve an effective knowledge training. 1) Clear and well defined goals are needed that require learners to apply their AT knowledge to proceed with the game. 2) A manipulable object is required to give the users a concrete target for the AT operations and to provide them with immediate feedback about the effects and correctness of the applied AT operations. 3) Lastly, an input GM is needed that allows for the configuration and application of individual AT operations. Also, one of the GMs needs to scale the level of abstraction of the AT knowledge.

The manipulable object and the input GM represent the core GMs for the gamified knowledge encoding of the AT. A manipulable object is a commonly used GM. It is often implemented as a means to solve puzzles in an action or adventure game. Working with the GKE, the object GM is used to encode the knowledge rules that determine the effects of individual AT operations thus mediating them. As a result, the object changes its status when an AT operation is applied to it thus demonstrating and visualizing its effects. The object is implemented as a cube featuring three differently colored sides to allow for a visualization of the object's orientation.

The AT input GM, on the other hand, encodes the theoretically grounded mathematical aspects of the AT knowledge. In particular, this GM allows for a definition and application of an AT operation to transform the object. This input GM is implemented with the player's ability to select and play cards that open a direct value configuration screen resembling the structure of a 4×4 matrix (see Figure 2). This direct value configuration screen provides an interface for the configuration of an AT operation by using self-obtained values as inputs. After confirmation, the entered values are propagated to the object that immediately gets transformed thus demonstrating the AT's underlying principles. The cards and the configuration screen are not only visually representing, i.e., mediating, the knowledge rules, but also are moderating them. Depending on the selected difficulty level, i.e., the moderation of the abstraction, the cards display a symbol indicating the provided AT type and a symbolized vector or matrix representation. Cards can even be fully defined thus immediately applying an AT operation without requiring additional value inputs. Also, the direct value configuration screen gets adjusted and either displays an empty vector, a reduced 4×4 matrix giving only access to the fields relevant for a particular AT type, or the full matrix. Ultimately, the interaction between the game-bound object and the player-bound AT input GM requires the application of the learning content and demonstrates its underlying principles.

The game goals are implemented following the concept of an escape scenario [50]. At the start of each training level, the players find themselves trapped in a sealed room. They can only escape by solving spatial puzzles that ultimately unlock the level's exit. The spatial puzzles are created with the level design, i.e., the position of obstacles blocking the object's path and a switch GM. The switch displays a level's victory conditions in the form of a semi-transparent version of the object and simultaneously checks if these conditions are met to finally unlock the exit. As a result, GEtiT challenges the learners to analyze a spatial puzzle and to subsequently transform the object in such a way that it matches the victory conditions using the AT cards.

Ultimately, the mapping process of the AT knowledge rules to the two core GMs and the level design creates a gamification metaphor. A gamification metaphor represents and requires the learning content inside of a particular training environment. Thus, a gamification metaphor creates a knowledge's gamified meta-model that can fully be internalized in the form of mental models. In this way, the AT gamification metaphor achieves the compilation of mental models during the gameplay and is responsible for the training transfer to a different context.

GEtiT also features additional GMs to enhance its accessibility and usability. In order to successfully transform an object, four positions in a particular level must be known: the position of the object, the player, the origin, and the target. The origin's position is needed to correctly perform an AT operations when the object is not located directly inside of the origin as this will result in the object's translation. The indication of the player's position can be used to determine a specific position in the room whereas the object's position is required to correctly calculate a transformation. In addition, the indication of the object's position helps the learners to compile a mental model for the relation between the matrix representation and the actual transformation of the object.

Finally, the position of the target is shown to help the users to plan their steps ahead and to allow them to focus on the application of the AT knowledge instead of being required to determine the target's position by walking to it first.

Apart from the indication of these different positions, GEtiT displays the direction of the room's three axes to visually assist learners with the determination of the correct transformation. In order to immediately display the path on which the object has moved, the object casts a trail each time it gets transformed. This indication is implemented to visually support the compilation of a mental model for the effects of sequencing different AT operations and the individual operations' effects in general. Also, this GM is introduced to allow students to learn from wrong inputs as it provides a means to analyze own mistakes [51]. This feature is combined with an undo-function that allows the learners to revert their last action.

Finally, GEtiT provides learners with a clear bonus objective by providing an optimum amount of transformations for a particular level and keeping track of the amount of transformations a player needed. Based on the ratio between both variables, players are rewarded with highscore points that reflect a player's performance throughout the game. Furthermore, the game displays the time a player needed to solve a level to encourage the players to retry a level and to beat their own time.

In the end, GEtiT purely implements GMs relevant for the AT knowledge encoding and training. Therefore, the structure of GEtiT represents a direct implementation of the GKE. Thus, the GEtiT acts as a demonstrator for a transfer-oriented knowledge training using GMs and can be used to validate the GKE.

GEtiT is developed with *unity* in the version 5.5.2p1 [52] for PC and Mac. It runs without any performance issues on all current machines.

IV. METHODS

A. Measures

1) Training Outcome: The training outcome of GEtiT was measured with an exam assessing the AT knowledge of the participants. The exam consisted of 15 multiple choice assignments that were designed to be of equal difficulty to the assignments normally used in the final exam of an Interactive Computer Graphics lecture.

2) Gameplay Progress: In order to analyze the training progress and effectivity, a player's amount of successfully solved levels, amount of highscore points earned, and the time spent in each individual level was measured.

3) Joy of Use: For the purpose of comparing the joy of use of both training methods, a questionnaire (1 = disagree, 5 = agree) consisting of nine questions (Q1 - Q9) was designed. The questionnaire for GEtiT players also included further questions about GEtiT's motivational effects (Q10 - Q14).

Q1 Have you enjoyed playing GEtiT / solving the paper-based assignments?
Q2 Have GEtiT's puzzles / the assignments helped you to develop a better understanding of the AT?
Q3 Have you noticed a knowledge gain while you were solving the GEtiT puzzles / the assignments?
Q4 Has the raise in the difficulty matched your knowledge gain?
Q5 Were the tasks of the GEtiT puzzles / the assignments easy to understand?
Q6 Was the difficulty of the GEtiT puzzles / the assignments well adjusted?
Q7 Were you motivated by new challenges due to a raise in the difficulty?
Q8 Have you enjoyed the class that was based on GEtiT / the paper-based assignments?
Q9 Was it interesting to solve the GEtiT puzzles / the assignments by using AT operations?
Q10 Was the computer game-based training method more enjoyable than traditional training methods (e.g. paper-based assignments)?
Q11 Would you prefer to utilize a training game instead of visiting a regular class?
Q12 Have you noticed a higher motivation to play GEtiT to train your knowledge in contrast to other training methods?
Q13 Were you motivated by the additional feedback mechanisms, such as highscores and the amount of used operations?
Q14 Have the feedback mechanisms motivated you to try a particular level again to improve your performance?

B. Participants

All participants of a lecture on Interactive Computer Graphics at the University of Würzburg were invited to take part in the study. The students were rewarded with credits mandatory for obtaining their Bachelor's degrees. The group of participants who completed the study consisted of 64 students (16 females, 48 males), 21 of which were between 19 and 21, 24 between 22 and 24, nine between 25 and 27, one between 28 and 30, and two above 30 years old (M_{age} = 20.61, SD_{age} = 7.66). The remaining seven participants never reported their age. Except for two female participants, all other participants had previous experience with playing computer games, 17 of which played less than 1 hour, eleven between 1 and 5 hours, eleven between 5 and 10 hours, six between 10 and 15 hours, twelve between 15 and 20 hours, and seven more than 20 hours computer games per week.

C. Experimental Design

The study consisted of four weekly 90-minute training sessions and a final knowledge assessment test. The training began in the same week in which the first part of the AT learning content was presented in the lecture thus simulating a regular class-based training that aligns with a lecture's progress. For the purpose of analyzing the training outcome of playing GEtiT, the participants were randomly assigned to three different groups. The *paper group* ($n = 25$) trained their AT knowledge with traditional paper-based assignments, the *game group* ($n = 24$) and the *home group* ($n = 15$) played

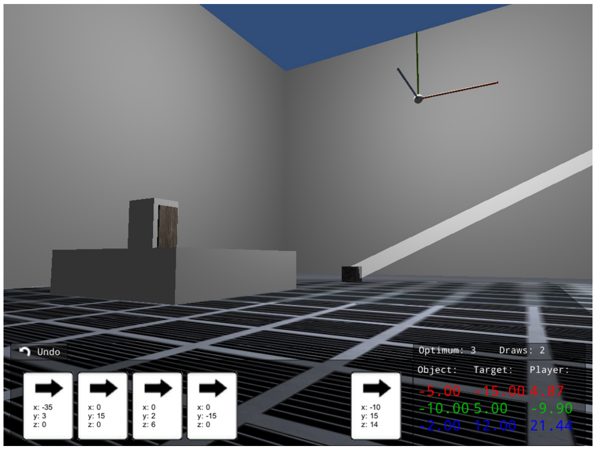


Fig. 3. GEtiT was played in its prototype status during the study. Although it lacks the current futuristic style and overall appearance of a regular game, it implements all GMs encoding the AT knowledge.

Fig. 4. Students playing GEtiT in the lab. The class-based training allows for a comparability with the traditional paper-based training method.

GEtiT. The game was used in its prototype version as Figure 3 displays. In contrast to the game group who played GEtiT on the computers in the lab (see Figure 4), the home group had no fixed appointments and was allowed to play the game as much as they liked. The paper group gathered in a class room and received a new set of paper-based training assignments they had to solve to foster their AT knowledge each week.

One week after the end of the training period, the exam was written. Also, the participants were asked to rate the joy of use of their training method by filling out the questionnaire.

V. RESULTS

A. Training Effects

Over the course of the training period, the game group solved $M_{game} = 72.58$ levels and the home group $M_{home} = 65.87$ levels on average.

TABLE I
OVERVIEW OF THE TEST RESULTS IN THE FINAL EXAM.

Group	n	mean result in %	sd	min	max
All	64	65.52	20.49	15	97
Paper	25	68.00	19.17	31	96
Game	24	64.33	23.09	15	97
Home	15	63.27	19.10	34	96

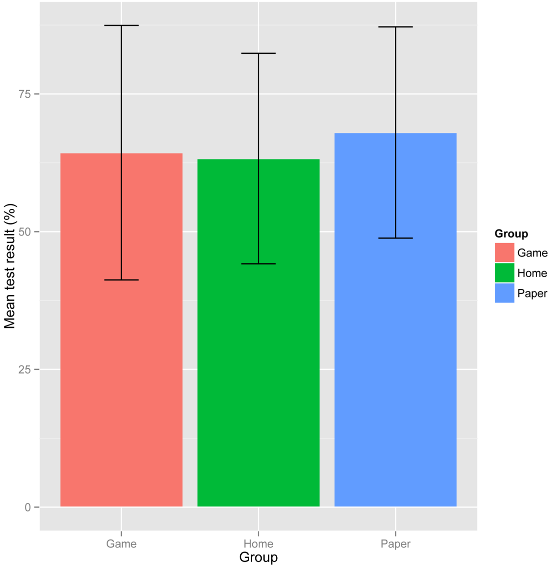


Fig. 5. Comparison of the mean results in the final exam in percent. The error bar indicates the standard deviation.

In the final exam, as shown in Figure 5 and Table I, the paper group achieved 68%, the game group 64.33%, and the home group 63.27% of the total amount of points on average. A one-way ANOVA test was applied to compare all three groups and revealed no significant difference in the test results between the groups ($F(62) = 0.469$, $p = 0.496$). Furthermore, no correlation could be found (Pearson's $cor = -0.087$, $t(62) = -0.68$, $p = 0.496$) between the test results and the groups.

A more in-depth analysis of the test results of the game group revealed a significant correlation (Pearson's $cor = 0.501$, $t(22) = 2.71$, $p = 0.013$) between the result in the exam and the amount of levels solved during the training period.

The analysis of the home group revealed no significant correlation between the result in the knowledge assessment test and the predictor variables. No correlation was found between the result and the amount of solved levels (Pearson's $cor = -0.202$, $t(13) = -0.745$, $p = 0.469$).

B. Motivational effects

The questionnaire was completed by 55 participants, 34 of which were GEtiT players and 21 belonged to the paper group. The two individual GEtiT groups got merged for the joy of

TABLE II
MEAN JOY OF USE RATINGS OF BOTH GROUPS (GAME GROUP: $n = 34$, PAPER GROUP: $n = 21$).

Q	game (SD)	paper (SD)	t(53)	p	Cohen's D
Q1	3.76(1.02)	3.24(1.22)	1.728	0.089	0.479
Q2	4.06(0.92)	4.24(1.09)	-0.654	0.516	0.182
Q3	4.12(0.98)	4.19(0.98)	-0.268	0.789	0.074
Q4	3.00(1.15)	3.05(1.07)	-0.153	0.879	0.042
Q5	3.76(0.78)	2.57(0.98)	4.995	< 0.001	1.386
Q6	3.71(1.12)	3.62(0.86)	0.304	0.762	0.085
Q7	3.85(0.96)	3.19(1.03)	2.421	0.019	0.672
Q8	4.00(0.89)	3.38(1.12)	2.275	0.027	0.634
Q9	4.00(0.92)	3.52(1.12)	1.712	0.093	0.475
Q10	4.24(1.10)	–	–	–	–
Q11	4.12(1.09)	–	–	–	–
Q12	3.91(1.00)	–	–	–	–
Q13	3.21(1.17)	–	–	–	–
Q14	3.56(1.16)	–	–	–	–

use evaluation as both groups played the same version of the game. Also, the questionnaire was designed to only evaluate GEtiT and not its implementation in a class-based or home-based training.

Although no significant difference between both groups could be found (see Table II), the GEtiT players slightly agreed that they have enjoyed playing the game, whereas the paper group neither agreed nor disagreed that they have enjoyed solving the paper tasks (Q1). The GEtiT players agreed that solving puzzles inside the game using AT operations (Q9) was enjoyable whereas the paper group neither agreed nor disagreed that they have enjoyed utilizing their knowledge to solve the assignments. Both groups agreed that their training method has helped them to develop a better understanding of the AT (Q2) and that they noticed a knowledge gain (Q3) over the course of the training sessions. Both groups neither agreed nor disagreed that the raise in the difficulty level matched their knowledge gain (Q4) and that the difficulty level of the tasks was well adjusted (Q6). The understandability of the game tasks was significantly ($p < 0.001$) rated higher than the understandability of the regular assignments (Q5). In total, the GEtiT players slightly agreed that the tasks inside the game were easy to understand whereas the paper group slightly disagreed with the understandability of their assignments. The GEtiT players gave a significantly higher rating ($p = 0.019$) on the motivational effects of a raise in the difficulty level over the course of the completed training tasks (Q7). Additionally, the GEtiT players gave a significantly higher rating ($p = 0.027$) on the overall enjoyment of the class (Q8).

All GEtiT players agreed that using the training game was more enjoyable than utilizing a regular training method to foster their knowledge (Q10). Furthermore, they would prefer to join a class that utilizes a training game (Q11) than joining a class that implements a traditional training method. The players also agreed that they experienced a higher motivation to train their knowledge using GEtiT than utilizing a traditional training method (Q12). The motivational effects of additional feedback mechanisms received an average rating (Q13) and was not really seen as an incentive to try again a certain level (Q14).

VI. DISCUSSION

A. Training Outcome

The results have shown that GEtiT yields a training effect that is similar to the training effect of a traditional paper-based training. In the exam, the results achieved by the game group and the home group were not significantly different to the results achieved by the paper group. As no correlation between the groups and the test results could be found, the results support the finding that both methods have a similar training effect. Also, the gamified training environment has a similar training effect independent from its application as a class-based or home-based training method. Both GEtiT groups yielded a similar result in the final exam. Hence, the results of the study *support hypothesis H1)* as GEtiT has achieved a training effect that is similar to the training outcome of a traditional training method.

The results also indicate a successful compilation of mental models and a successful training transfer on the side of the game groups. The exercises used in the final exam had a similar structure to the paper-based assignments and hence the paper group was able to directly apply their knowledge practiced during the training sessions. The GEtiT groups, however, were exposed to this type of exercise for the very first time. They not only had to solve the exercises, but also to develop an understanding of this particular representation and to transfer their knowledge while experiencing exam anxiety. This assumption is supported by the fact that the game groups had to deal with a different visual representation. In contrast to GEtiT's 3D environment, the visual representation used in the exam were reduced to 2D before-and-after pictures. Although both game groups had to deal with those additional challenges, they achieved a similar result to the paper group thus indicating a successful compilation of mental models for the AT learning content.

The signifiant positive correlation between the amount of solved levels and the test result validated the concept of the GKE. A more frequent application of the learning content and an increased amount of solved problems resulted in a gain of expertise in applying the AT. The visual demonstration of the effects supported the compilation and further improvement of mental models used to successfully transfer the training outcome from GEtiT to the paper-based exam. The results also indicate the importance of a periodical execution of the gamification metaphors to fully internalize the encoded meta-model for the knowledge.

In contrast to the performance of the game group, the home group showed no positive correlation between the gameplay and the test result. This phenomenon can be explained by the fact that the home group had not a clear playing schedule and might not have taken the knowledge training serious enough. Also, the gameplay of the home group took place in an uncontrolled environment. Hence, it is possible that some of the participants were not completely focussed on the gameplay as they might have played the game in a distractive environment.

B. Motivational Effects

The results of the joy of use evaluation support the finding that GEtiT has a similar training effect to a traditional training method. The GEtiT players and the participants of the paper group agreed that their training method has helped them to develop a better understanding of the AT. Also, they noticed a knowledge gain over the course of the training sessions which is a crucial outcome. The awareness of making progress gives learners the feeling that the implemented training method is useful thus increasing their acceptance and motivation. Moreover, this result indicates the effectivity of the GKE as the AT gamification metaphor not only achieved an effective knowledge training, but also seemed useful to the learners.

For the purpose of creating an engaging training environment and fulfilling the conditions for optimal learning, it is necessary to provide the learners with clear tasks that increase in difficulty over time to keep the motivation high. In contrast to the paper group, the GEtiT players gave a significant higher rating on the understandability of the training tasks in the evaluation. In total, the GEtiT players even slightly agreed that the tasks were easy to understand whereas the paper group slightly disagreed with the understandability of their assignments.

The evaluation has shown that finding the right difficulty level is a critical part of creating effective training environments. Both groups neither agreed nor disagreed with the overall adjustment of the difficulty for each individual assignments and the raise in the difficulty over time. Creating a constant stream of new challenges is one of the biggest strengths of computer games as this contributes to their flow-inducing characteristics. Players feel motivated when the game constantly provides them with new task thus keeping them challenged [41]. Once they have exhausted a challenge, their skill level has increased and they are prepared for the next challenge to put their skills to a test, again. The effectivity of motivational effects of an increasing difficulty level in the game was supported as the GEtiT players gave a significantly higher rating on the motivational effects of reaching higher difficulty levels.

This result also shows the importance of matching the learners' individual knowledge gain with the increase in the difficulty level to create an engaging learning environment. By adding more complex knowledge rules to the gamification metaphors over time, learners are not overwhelmed by the complexity and abstraction of the learning content. Instead, they can intuitively practice the knowledge and update their mental models as they progress through the training levels. Thus, the results *support hypothesis H3* as the knowledge moderation during the encoding process is crucial to intuitively introduce learners to a complex knowledge.

Finally, the GEtiT players agreed that they enjoyed playing the game and solving the game's puzzles using their AT knowledge to practice the targeted learning content. The paper group neither agreed nor disagreed to these three questions. As a result of this, GEtiT has not only achieved a similar training outcome to the traditional training method, but also proven to yield a higher motivation to tackle the learning content. Thus, the results of the study *support hypothesis H2* and show that GEtiT achieves a higher quality of learning.

VII. CONCLUSION

GEtiT was developed as a demonstrator for the GKE and uses GMs to require and to demonstrate the encoded learning content in an engaging way. During the gameplay, players are locked into sealed rooms from which they can only escape by solving spatial puzzles requiring the application of the AT learning content. Once a puzzle is solved, players can proceed to the next challenge by leaving the level through an exit. GEtiT moderates the learning content's level of abstraction by providing four different difficulty levels. Each difficulty level encodes a subset of the AT knowledge rules thus achieving a certain distance to the learning content which is decreased over time. In this way, GEtiT intuitively presents and requires the learning content. Learners practice the AT knowledge by periodically executing player-bound GMs encoding the AT knowledge and receiving immediate feedback from interacting game-bound GMs.

The present study compared the training effects and motivational aspects of GEtiT with a traditional training method of using paper-based assignments to practice the AT. Although GEtiT players had to invest the same amount of time to practice the learning content, they derived more enjoyment from the gameplay than learners who used a traditional paper-based training method. Additionally, GEtiT presents the tasks in a clear way and provides the users with constant and immediate feedback about their progress. A final knowledge assessment test revealed that GEtiT and the paper-based training method yield a similar training effect. Also, the study validated GEtiT's effectivity for transfer-oriented knowledge training as the participants were successful at transferring their training outcome from the training environment to a real world exam. Thus, GEtiT ultimately achieved a higher learning quality in comparison to a traditional training method.

Future research should be aimed at follow-up projects that utilize the GKE framework to encode specific knowledge in interacting GMs. This is critical as it would test for its general applicability. Concerning GEtiT, the next important steps are to improve and to subsequently evaluate the moderating effects of its audiovisual presentation. Also, it is critical to test the effects of a higher visual immersion on the training outcome by evaluating a virtual reality version of GEtiT.

REFERENCES

[1] J. Mestre, *Transfer of Learning: Issues and Research Agenda*. Washington, D.C.: National Science Foundation, 2002.

[2] C. J. Dede, "Immersive interfaces for engagement and learning," *Science*, vol. 323, 2009.

[3] C. J. Dede, J. Jacobson, and J. Richards, "Introduction: Virtual, augmented, and mixed realities in education," in *Virtual, Augmented, and Mixed Realities in Education*, ser. Smart Computing and Intelligence, D. Liu, C. J. Dede, R. Huang, and J. Richards, Eds. Singapoore: Springer, 2017.

[4] B. Dalgarno and M. J. W. Lee, "What are the learning affordances of 3-d virtual environments?" *British Journal of Educational Technology*, vol. 41, no. 1, pp. 10–32, 2010.

[5] A. C. Oei and M. D. Patterson, "Enhancing Cognition with Video Games: A Multiple Game Training Study," *PLoS ONE*, vol. 8, no. 3, p. e58546, Feb. 2013.

[6] M. Sicart, "Defining game mechanics," *Game Studies*, vol. 8, no. 2, 2008.

[7] E. Adams and J. Dormans, *Game Mechanics*, ser. Advanced Game Design. Berkeley: New Riders, 2012.

[8] J. P. Gee, *What video games have to teach us about learning and literacy*, 1st ed. New York: Palgrave Macmillan, 2007.

[9] E. F. Anderson, L. McLoughlin, F. Liarokapis, C. Peters, P. Petridis, and S. de Freitas, "Serious Games in Cultural Heritage," in *The 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST*, Malta, 2009, pp. 29–48.

[10] K. Seaborn and D. I. Fels, "Gamification in theory and action: A survey," *International Journal of Human-Computer Studies*, vol. 74, pp. 14–31, 2015.

[11] S. Arnab, T. Lim, M. B. Carvalho, F. Bellotti, S. de Freitas, S. Louchart, N. Suttie, R. Berta, and A. De Gloria, "Mapping learning and game mechanics for serious games analysis," *British Journal of Educational Technology*, vol. 46, no. 2, pp. 391–411, 2015.

[12] A. Moser, N. dos Santos, and L. F. Corcini, "Immersive 3d virtual and gamified environment: The learner model approach," *Journal of Research & Method in Education*, vol. 7, no. 3, pp. 26–35, 2017.

[13] S. Oberdörfer and M. E. Latoschik, "Gamified knowledge encoding: Knowledge training using game mechanics," in *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018)*, Würzburg, Germany, September 2018.

[14] V. Kaptelinin and B. A. Nardi, "Affordances in HCI: Toward a Mediated Action Perspective," *CHI 2012*, pp. 967–976, 2012.

[15] T. Lynam, R. Mathevet, M. Etienne, S. Stone-Jovicich, A. Leitch, N. Jones, H. Ross, D. Du Toit, S. Pollard, H. Biggs, and P. Perez, "Waypoints on a journey of discovery: Mental models in human-environment interactions," *Ecology and Society*, vol. 17, no. 3, 2012.

[16] P. N. Johnson-Laird, *Mental Models. Towards a Cognitive Science of Language, Inference, and Consciousness*. Harvard University Press, 1983.

[17] G. Tulodziecki, B. Herzig, and S. Grafe, *Medienbildung in Schule und Unterricht*. Julius Klinkhardt, 2010.

[18] L.-M. Palmunen, E. Pelto, A. Paalumäki, and T. Lainema, "Formation of novice business students' mental models through simulation gaming," *Simulation & Gaming*, vol. 44, no. 6, pp. 846–868, 2013.

[19] B. Weidenmann, "Multimedia, multicodierung und multimodalität beim online-lernen," in *Online Lernen. Handbuch für Wissenschaft und Praxis*, L. J. Issing and P. Klimsa, Eds. Oldenbourg, 2009.

[20] S. Oberdörfer and M. E. Latoschik, "Interactive gamified 3D-training of affine transformations," in *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*. Garching, Germany: ACM Press, 2016, pp. 343–344.

[21] S. Oberdörfer, D. Heidrich, and M. E. Latoschik, "Interactive gamified virtual reality training of affine transformations," in *Proceedings of DeLFI and GMW Workshops 2017*, C. Ullrich and M. Wessner, Eds., Chemnitz, Germany, 2017.

[22] K. S. Fu, R. Gonzalez, and C. S. G. Lee, *Robotics: Control, Sensing, Vision and Intelligence*. New York: McGraw-Hill Education, 1987.

[23] J. Foley, A. van Dam, S. Feiner, and J. Hughes, *Computer Graphics: Principles and Practice*, ser. Addison-WesleySystems Programming Series. Reading, MA, USA: Addison-Wesley, 1990.

[24] J. C. Rosser, Jr, P. J. Lynch, L. Cuddihy, D. A. Gentile, J. Klonsky, and R. Merrell, "The impact of video games on training surgeons in the 21st century," *Archives of Surgery*, vol. 142, no. 2, p. 181, 2007.

[25] B. Reeves, T. W. Malone, and T. O'Discoll, "Leadership's online labs," *Harvard Business Review*, vol. 86, no. 5, pp. 58–66, 2008.

[26] A. Siewiorek and A. Gegenfurtner, "Leading to win: the influence of leadership styles on team performance during a computer game training," *ICLS '10 Proceedings of the 9th International Conference of the Learning Sciences*, vol. 1, pp. 524–531, Aug. 2010.

[27] P. Prax, "Leadership style in world of warcraft raid guilds," *Proceedings of DiGRA Nordic 2010*, 2010.

[28] R. Schroeder, *Being There Together : Social Interaction in Virtual Environments*, 1st ed. New York: Oxford University Press, 2011.

[29] L. Qiu, W. W. Tay, and J. Wu, "The impact of virtual teamwork on real-world collaboration," *ACE'09 Proceedings of the International Conference on Advances in Computer Enterntainment Technology*, pp. 44–51, 2009.

[30] S. Richter and U. Lechner, "Communication content relations to coordination and trust over time: a computer game perspective," *C&T'11 Proceedings of the 5th International Conference on Communities and Technologies*, pp. 60–68, 2011.

[31] B. D. Glass, W. T. Maddox, and B. C. Love, "Real-Time Strategy Game Training: Emergence of a Cognitive Flexibility Trait," *PLoS ONE*, vol. 8, no. 8, pp. e70 350 EP –, 2013.

[32] C. S. Green and D. Bavelier, "Action video game modifies visual selective attention," *Nature*, vol. 423, no. 6939, pp. 534–537, 2003.

[33] ——, "Action-video-game experience alters the spatial resolution of vision," *Psychological Science*, vol. 18, no. 1, pp. 88–94, 2007.

[34] S. de Castell, J. Jenson, and N. Taylor, "Educational games: Moving from theory to practice," in *Educational gameplay and simulation environments : case studies and lessons learned*, D. Kaufman and L. Sauvé, Eds. Hershey, PA: Information Science Reference, 2010, pp. 133–145.

[35] A. Gurr, "Video games and the challenge of engaging the 'net' generation," in *Educational gameplay and simulation environments : case studies and lessons learned*, D. Kaufman and L. Sauvé, Eds. Hershey, PA: Information Science Reference, 2010, pp. 119–131.

[36] H. C. Arnseth, "Learning to play or playing to learn-a critical account of the models of communication informing educational research on computer gameplay," *Game Studies*, vol. 6, no. 1, 2006.

[37] M. Power and L. Langlois, "Designing a simulator for teaching ethical decision-making," in *Educational gameplay and simulation environments : case studies and lessons learned*, D. Kaufman and L. Sauvé, Eds. Hershey, PA: Information Science Reference, 2010, pp. 146–158.

[38] M. Schulzke, "Moral decision making in fallout," *Game Studies*, vol. 9, no. 2, 2009.

[39] K. A. Ericsson, R. T. Krampe, and C. Tesch-Römer, "The role of deliberate practice in the acquisition of expert performance," *Psychological Review*, vol. 100, no. 3, pp. 363–406, 1993.

[40] M. Csikszentmihalyi, *Flow: The Psychology of Optimal Experience*. New York, NY, USA: Harper-Perennial, 1990.

[41] J. McGonigal, *Reality is broken : why games make us better and how they can change the world*, 1st ed. New York: Penguin Press, 2011.

[42] A. Amory, K. Naicker, J. Vincent, and C. Adams, "The use of computer games as an educational tool: identification of appropriate game types and game elements," *British Journal of Educational Technology*, vol. 30, no. 4, pp. 311–321, 1999.

[43] I. D. Cherney, "Mom, let me play more computer games: They improve my mental rotation skills," *Sex Roles*, vol. 59, no. 11-12, pp. 776–786, Jul. 2008.

[44] M. E. Joorabchi and M. S. El-Nasr, "Measuring the impact of knowledge gained from playing fps and rpg games on gameplay performance," *Entertainment Computing – ICEC 2011*, pp. 300–306, 2011.

[45] L. S. Colzato, W. P. M. van den Wildenberg, S. Zmigrod, and B. Hommel, "Action video gaming and cognitive control: playing first person shooter games is associated with improvement in working memory but not action inhibition," *Psychological Research*, vol. 77, no. 2, pp. 234–239, 2013.

[46] M. Pittalis and C. Christou, "Types of reasoning in 3D geometry thinking and their relation with spatial ability," *Educational Studies in Mathematics*, vol. 75, no. 2, pp. 191–212, 2010.

[47] G. Gittler and J. Glück, "Differential transfer of learning: Effects of instruction in descriptive geometry on spatial test performance," *Journal of Geometry and Graphics*, vol. 2, no. 1, pp. 71–84, 1998.

[48] H. Kaufmann, "The potential of augmented reality in dynamic geometry education," *12th International Converence on Geometry and Graphics*, 2006.

[49] H. Kaufmann, D. Schmalstieg, and M. Wagner, "Construct3D: A Virtual Reality Application for Mathematics and Geometry Education," *Education and Information Technologies*, vol. 5, no. 4, pp. 263–276, 2000.

[50] D. Perry and R. DeMaria, *David Perry on Game Design: A Brainstorming Toolbox*. Boston, MA, USA: Course Technology, 2009.

[51] D. Charsky, "From edutainment to serious games: A change in the use of game characteristics," *Games and Culture*, vol. 5, no. 2, pp. 177–198, Mar. 2010.

[52] Unity, "unity 5.5.2p1," available at https://unity3d.com/unity/qa/patch-releases/5.5.2p1, March 2017.

7.2 Second and Third GEtiT Study

After the successful first test, *GEtiT*'s visual style received a major overhaul to match current state-of-the-art games. In parallel, *GEtiT VR* was developed. The continuation of *GEtiT*'s development allowed for further tests of the Gamified Knowledge Encoding model and the analysis of the effects of using different visualization methods in respect to the learning outcome.

Table 11: Knowledge Encoding in Game Mechanics: Transfer-Oriented Knowledge Learning in Desktop-3D and VR

Author	**Contribution**
Oberdörfer, S.	Literature review, conceptual design, experimental design, data analysis, discussion, manuscript preparation and revision
Latoschik, M. E.	Manuscript revision

Oberdörfer, S. and Latoschik, M. E. Knowledge Encoding in Game Mechanics: Transfer-Oriented Knowledge Learning in Desktop-3D and VR. *International Journal of Computer Games Technology*, 2019, 2019. doi: 10.1155/2019/7626349

Hindawi
International Journal of Computer Games Technology
Volume 2019, Article ID 7626349, 17 pages
https://doi.org/10.1155/2019/7626349

Research Article

Knowledge Encoding in Game Mechanics: Transfer-Oriented Knowledge Learning in Desktop-3D and VR

Sebastian Oberdörfer and Marc Erich Latoschik

Human-Computer Interaction, University of Würzburg, Würzburg, Germany

Correspondence should be addressed to Sebastian Oberdörfer; sebastian.oberdoerfer@uni-wuerzburg.de

Received 5 November 2018; Accepted 26 February 2019; Published 26 March 2019

Academic Editor: Michael J. Katchabaw

Affine Transformations (ATs) are a complex and abstract learning content. Encoding the AT knowledge in Game Mechanics (GMs) achieves a repetitive knowledge application and audiovisual demonstration. Playing a serious game providing these GMs leads to motivating and effective knowledge learning. Using immersive Virtual Reality (VR) has the potential to even further increase the serious game's learning outcome and learning quality. This paper compares the effectiveness and efficiency of desktop-3D and VR in respect to the achieved learning outcome. Also, the present study analyzes the effectiveness of an enhanced audiovisual knowledge encoding and the provision of a debriefing system. The results validate the effectiveness of the knowledge encoding in GMs to achieve knowledge learning. The study also indicates that VR is beneficial for the overall learning quality and that an enhanced audiovisual encoding has only a limited effect on the learning outcome.

1. Introduction

Affine Transformations (ATs) are part of linear algebra, used for kinematic control [1], computer graphics [2], and development of Virtual Reality (VR) applications. In case of computer graphics, learners are challenged to develop an understanding how the theoretically grounded mathematical aspects result in an object's transformation. ATs are expressed as matrices, usually of dimensionality 4×4, and their operations as matrix-matrix multiplications, each matrix representing one desired mapping. Hence, ATs are a very complex and abstract learning content that cannot easily be demonstrated.

The *Gamified Training Environment for Affine Transformations (GEtiT)* was specifically developed to address this problem. It intuitively requires the application of ATs and audiovisually demonstrates the underlying theoretical principles [3]. GEtiT yields a similar learning outcome to a traditional paper-based learning method while achieving a higher learning quality [4]. Also, GEtiT was developed as a demonstrator for the *Gamified Knowledge Encoding* model [5]. The Gamified Knowledge Encoding utilizes Game Mechanics (GMs) to directly encode a knowledge's underlying principles as their internal game rules. This achieves a learning content's repetitive application and audiovisual demonstration during the gameplay. GEtiT embeds the gameplay in complex problems, i.e., an escape scenario, to cause an intrinsic motivation in the learner to tackle the learning assignments.

The repetitive application of the encoded knowledge takes place on the *skill-based* or the *rule-based* layer of human performance [6] and leads to a compilation of *mental models* [7]. Mental models are complex mental constructs allowing for an internal visualization and are used for a knowledge application on the *knowledge-based* layer, i.e., a training transfer. Training transfer takes place when knowledge training in one context leads to an increased performance when applied in a different context [8]. In this way, the Gamified Knowledge Encoding defines how knowledge is learned with serious games.

However, it is unclear whether the audiovisual presentation of the encoded knowledge and the degree of the visual immersion has an effect on the learning effectiveness. For instance, immersive Virtual Reality (VR) has the potential to even further increase GEtiT's learning outcome by presenting the learning content in a visually immersive and more natural way. Therefore, a specific *GEtiT VR* version implementing the same core GMs was developed [9]. This allows for a direct comparison between the two visualization technologies in respect to the learning outcomes of knowledge encoding using GMs.

This paper's contribution is threefold: (1) *comparison* of the effectiveness as well as efficiency of GEtiT's desktop and VR version, (2) *validation* of GEtiT's learning outcomes [4], and (3) *analysis* of the effectiveness of an enhanced audiovisual encoding as well as the provision of a debriefing system. The present user study confirms the effectiveness of GEtiT by showing a *similar learning outcome* to a traditional paper-based learning method. Also, the results indicate a *higher learning quality* when using VR technology. Overall, this paper contributes to the ongoing research of analyzing the effectiveness of VR technology for educational purposes.

At first, an overview over the current state of research is given and the Gamified Knowledge Encoding is explained in detail. Subsequently, GEtiT is described and the study to compare the tested versions is explained. This is followed by the presentation of the study's results and an in-depth discussion of the findings. Finally, the paper is concluded with a summary and an outlook for future research.

2. Related Work

Well-designed computer games automatically fulfill the conditions for optimal learning [10]. They present the encoded game knowledge in a highly engaging and immersive way. This achieves a high player *motivation* to tackle a game's tasks and challenges. A game's overall gameplay requires a *repetitive* application of the encoded knowledge, thus ultimately achieving a learning effect due to repetition [11]. Computer games periodically increase the gameplay's difficulty to compensate for the learning effect and to continuously provide players with new tasks that keep them challenged [12]. In this way, a computer game requires *preexisting* knowledge and, over time, even requires the knowledge acquired during the gameplay. Computer games provide players with *immediate feedback* about the effects as well as the correctness of their actions and their progress towards solving a challenge. Simultaneously, a constant stream of new challenges paired with an immediate feedback increases a game's flow-inducing aspects [13]. Flow is the central construct that mainly influences enjoyment and performance of gaming action [14]. Hence, it increases a player's intrinsic motivation for knowledge learning [8].

2.1. Game-Based Learning.

2.1. Game-Based Learning. Computer games have already been implemented to learn complex sets of human skills such as leadership styles [15, 16], as well as skills of communication [17, 18] and cooperation [19, 20]. Video games were also used to train human abilities, such as the cognitive flexibility trait [21], the spatial visual attention [22], and the spatial resolution [23].

Game-based learning led to the development of serious games. Serious games feature an educational aspect and are not solely developed for entertainment [24, 25]. They are designed to educate players in a broad variety of topics like genetics [26] or biological consequences of alcohol abuse [27]. Also, serious games are not only used to teach about a specific knowledge, but also to motivate players to consider a science career [28].

In general, computer games encode specific knowledge being learned and mastered during the gameplay [29, 30]. Players periodically discover new challenges and multiple ways to solve them [31]. The immersive effect of playing a computer game [32, 33] can introduce players to ethical questions [34] and moral problems. This results in a training of moral decision making [35].

2.2. Game Mechanics. Each computer game consists of GMs encoding the underlying game rules. GMs are distinguished in *player-bound* GMs and *game-bound* GMs [5]. Game-bound GMs create the game world, provide challenges to a player and realize the overall narrative [36]. Player-bound GMs are executed by the player to achieve an interaction with game-bound GMs [37]. This interaction not only creates the gameplay, but also provides an immediate feedback about the effects of a player's actions. Hence, GMs structure the gameplay, encode underlying principles, and define the game world as well as a player's abilities [36].

For instance, a computer game might feature moving platforms on which a player is required to jump. The moving platform element is a game-bound GM as it is automatically executed and cannot be manipulated by the player. The ability to jump is a player-bound GM. Based on the outcome of the jump ability's execution, players are provided with a clear feedback about their performance as they either hit or miss a platform.

The game-specific knowledge, i.e., the encoded game rules and principles, needs to be understood by the players to successfully play a game [11]. For example, the moving platforms GM encodes the platforms' movement speeds and trajectories. The jump GM encodes the jump distance, the jump speed, and the actual action that needs to be performed, e.g., the key that needs to be pressed on a keyboard. Only when players have developed a basic understanding of this game-specific knowledge, they can master the challenges created by the GMs' interaction.

2.3. Educational Use of VR. Learning of ATs requires an environment that visually demonstrates 3D geometrical problems. Computer games challenge a player's skills of logic, memory, visualization, and problem-solving during the gameplay [38]. Fast-paced computer games, e.g., action-based computer games, improve cognitive abilities [39], thus enhancing a player's ability to monitor and to observe task-relevant information [40]. More importantly, 3D action-based computer games train a player's spatial abilities, such as the mental rotation skill [41], spatial visual attention [22], spatial resolution of vision [23], and spatial navigation [42]. This is crucial for GEtiT as a training of spatial abilities improves 3D geometry thinking [43]. Vice versa, training descriptive geometry assists the development of spatial abilities [44]. Thus, by visually demonstrating the AT knowledge in a 3D environment, the learning process is facilitated.

VR technology visually immerses a user in a 3D environment allowing for such a presentation of 3D geometry. As a result, designing a specific GEtiT VR version has the potential to enhance the learning effectiveness. VR technology provides the advantages of increasing a student's motivation as well as engagement, achieves an immersive experience, and allows for a constructivist approach of learning [45, 46]. Also, a higher visual immersion and presence leads to a higher performance in case of a training scenario [47]. Spatial presence describes the subjective sensation of being in a real place, i.e., the virtual environment (VE), despite physically being in a different environment [48]. Presence has a mediating effect on the learning outcome as it affects a student's intrinsic motivation and enjoyment, thus increasing the perceived learning quality and satisfaction [49]. Visual immersion is achieved with system properties reducing sensory inputs from the real world and replacing them with digital information, e.g., wearing a Head-Mounted Display (HMD) [50]. Utilizing HMD-VR allows users to easily change their perspectives which helps to analyze complex learning contents like 3D geometry [51]. Also, as an audiovisual presentation supports the compilation of mental models [52], a full visual immersion in such a presentation environment should further improve the learning outcome.

Therefore, designing a specific GEtiT VR version has the potential to increase the learning effectiveness and the learning quality.

2.4. Virtual Geometry Learning. Virtual learning of geometry was already approached with other projects. *Construct3D* represents an Augmented Reality application that allows students to collaboratively create and manipulate geometrical objects [53, 54]. Similarly, *Mathland* provides a learning platform that augments the real world with mathematical concepts like Newtonian physics, thus allowing for a learning in constructivistic ways [55]. In contrast to the present system, both applications are not gamified training environments that target a highly motivating knowledge learning.

3. Gamified Knowledge Encoding

The definition of the *Gamified Knowledge Encoding* [5] relies on the theoretically grounded concepts of knowledge [56, 57], human performance [6], mental models [7], and GMs [36, 58]. *Declarative knowledge* consists of information, facts, methods, and principles describing *what* a subject is, whereas *procedural knowledge* reflects motor or cognitive skills, hence describes *how* an action can be performed [56, 57]. The Gamified Knowledge Encoding maps the learning content as game rules to interacting GMs. In this way, the resulting gameplay creates learning affordances [59] for the knowledge to be learned. A learning affordance requires an interaction with the learning environment, i.e., an application of the knowledge, and simultaneously informs about the underlying principles [60]. The knowledge encoding is determined by the *moderation*, i.e., the degree to which knowledge rules are simplified, and *mediation*, i.e., the concrete realization of a GM. This section theoretically presents the proposed framework which then is demonstrated in Section 4.

3.1. Knowledge Encoding. Working with the Gamified Knowledge Encoding, players entrain the encoded knowledge on a skill-based and rule-based level of human performance during the gameplay. As a result, learners compile a mental model for the learning content [61] that allows them to transfer their knowledge to a different context, e.g., a real world application.

A *direct knowledge encoding using the Gamified Knowledge Encoding* is achieved by segmenting the learning content into smaller packages of which each describes a coherent part of the knowledge. Each knowledge package then is turned into a gameplay element requiring its application. For this purpose, the knowledge packages are transformed into clear and well-defined rules that are mapped to interacting GMs. This mapping process generates a *gamification metaphor* representing and requiring the learning content inside of a serious game. Player-bound GMs encode rules defining and requiring the actual knowledge application as game inputs. Game-bound GMs act as a verification system to check if a player's inputs are correct or as a demonstration system to visualize the inputs' effects. The interaction between a gamification metaphor's GMs requires the knowledge's application and informs about the underlying principles by providing immediate feedback.

3.2. Moderation and Mediation. Directly encoding the learning content in gamification metaphors might not necessarily result in an intuitive learning process. This especially is problematic in case of abstract knowledge which is hard to visualize and often escapes an intuitive approach. Therefore, the Gamified Knowledge Encoding also includes a *knowledge moderation* and a *knowledge mediation* to adjust the encoded knowledge's level of abstraction. Also, the moderation and the mediation determine the knowledge presentation inside of a serious game.

The *knowledge moderation* scales the level of abstraction of the encoded knowledge by adjusting the accuracy and the selection of the sets of knowledge rules mapped to the gamification metaphor. Thus, the Gamified Knowledge Encoding creates a direct knowledge encoding that ranges from a non-moderated accurate simulation to a highly moderated simplified and intuitive knowledge application. By adjusting the moderation over time, the level of abstraction matches a learner's knowledge gain. This relies on the game design principle of continuously increasing the difficulty to keep players challenged and in flow [12].

An abstract knowledge learning process can begin with a very intuitive demonstration of the learning contents. This is achieved by merely encoding a simplified set of rules, thus establishing a certain distance to the knowledge. Subsequently, as the learners progress through the gameplay, more complex sets of rules are mapped to the GMs. This reduces the initial distance to the knowledge over time. Finally, the complete and non-moderated set of rules is mapped to the GMs to completely close the distance and to achieve the knowledge's simulation. When adjusted well, the game's challenge and difficulty increase matches the current knowledge and/or skill level of the players. As a result, the gameplay's flow-inducing aspects are created and maintained.

The *knowledge mediation*, i.e., the selection and the realization of GMs, partly depends on the degree of the knowledge moderation. A low degree of knowledge moderation requires GMs that accurately encode the knowledge rules, i.e., they remodel and simulate a particular real world application. In contrast, a high degree of knowledge moderation reduces the requirements and allows for GMs that represent complex knowledge rules with generalized and intuitive interactions.

For instance, a driving simulation can require an individual utilization of the clutch but also automatically include it during a shifting process. In the former version, two separate GMs are needed while in the latter implementation one GM combines both activities resulting in a more simplified knowledge presentation. Thus, the knowledge mediation can also scale the level of abstraction. It allows for a direct encoding of non-moderated knowledge rules in GMs that integrate and combine several sets of rules to achieve an intuitive application. In conclusion, the moderation and the mediation define a knowledge's application and demonstration.

3.3. Optimal Knowledge Learning. Utilizing the Gamified Knowledge Encoding creates serious games that fulfill the conditions for optimal learning [10]. By encoding the learning content in interacting GMs, the serious game automatically provides learners with *immediate feedback* about the correctness of their inputs. By moderating the knowledge's level of abstraction, *highly motivating* flow as well as a requirement for *preexisting knowledge* is created. Finally, a *repetitive knowledge application* is established by the requirement to frequently execute the gamification metaphor's GMs during the gameplay.

The Gamified Knowledge Encoding describes the direct knowledge encoding in GMs and the resulting learning process during the gameplay. However, to ensure for a good playability, additional GMs targeting either entertaining aspects or providing further gameplay enhancements may be provided. For instance, the computer game *Kerbal Space Program* encodes knowledge of orbital mechanics in its core GMs [62]. As a result, players learn and practice this knowledge during the gameplay [63]. In addition to the orbital mechanics gamification metaphors, Kerbal Space Program implements further GMs to increase its playability, e.g., by realizing a career mode or by allowing players to plant flags on the surface of a celestial body. Thus, by providing further GMs in addition to the ones used in the gamification metaphors, a serious game's overall entertaining and motivating aspects may be improved.

In conclusion, the Gamified Knowledge Encoding utilizes GMs as an educational tool by mapping knowledge rules to them, thus directly encoding the learning content (see Figure 1). The Gamified Knowledge Encoding utilizes the interaction between at least one game-bound GM and one player-bound GM to require the application of the learning content on a rule-based or skill-based level of human performance. Subsequently, learners are provided with immediate feedback about their learning progress. This learning process results in the compilation of a mental model for the knowledge. This mental model ultimately is utilized to apply the knowledge on a knowledge level, i.e., transferring it from the serious game to a real world context. The GMs that encode the knowledge's rules and that interact with each other are metaphors for the learning content. They are responsible for a player's knowledge gain by acting as learning affordances. We define such a gamification metaphor as *knowledge's gamified metamodel* which can be fully internalized in the form of mental models.

4. Gamified Training Environment for Affine Transformations

GEtiT's development followed the guidelines of the Gamified Knowledge Encoding. The main goals of this development process were (1) to transform the AT knowledge into game rules and (2) to realize GMs that mediate them. Subsequently, after demonstrating its effectiveness in its prototype version [4], GEtiT's visual style was changed to a state-of-the-art style of modern computer games (see Figure 2). This major overhaul included the implementation of a background music and sound effects to provide learners with additional acoustic feedback. Also, GEtiT received a more advanced point system, an achievement system, a debriefing system, and a small built-in wiki. This section presents GEtiT's design, describes the realization of the new features as well as the specific VR version, and demonstrates the Gamified Knowledge Encoding.

4.1. Design

4.1.1. Core Gameplay. Working with the Gamified Knowledge Encoding, the AT knowledge first was separated into the individual theoretically grounded mathematical operations and the resulting transformation effects. The mathematical operations were mapped as game-knowledge rules to a player-bound GM *mediating* each individual operation as a playable *AT card*. Activating a card displays a *direct value configuration screen* resembling the structure of a 4×4 matrix that allows for the operation's configuration (see Figure 3).

The AT cards, of which each can only be played once during a particular level, *moderate* the level of abstraction of the learning content. The degree of the moderation is controlled by providing *four different difficulty levels*: easy, medium, hard, and expert. Depending on the selected difficulty level, a card represents either a specific AT operation vector (easy), an empty transformation vector (medium), or an empty transformation matrix (hard, expert). Empty AT cards need to be defined via the direct value configuration screen that further moderates the level of abstraction by either resembling the structure of a vector or a 4×4 matrix. The 4×4 matrix only provides access to fields relevant for the selected AT operation type on hard difficulty and needs to be completely configured on expert difficulty. The cards, which

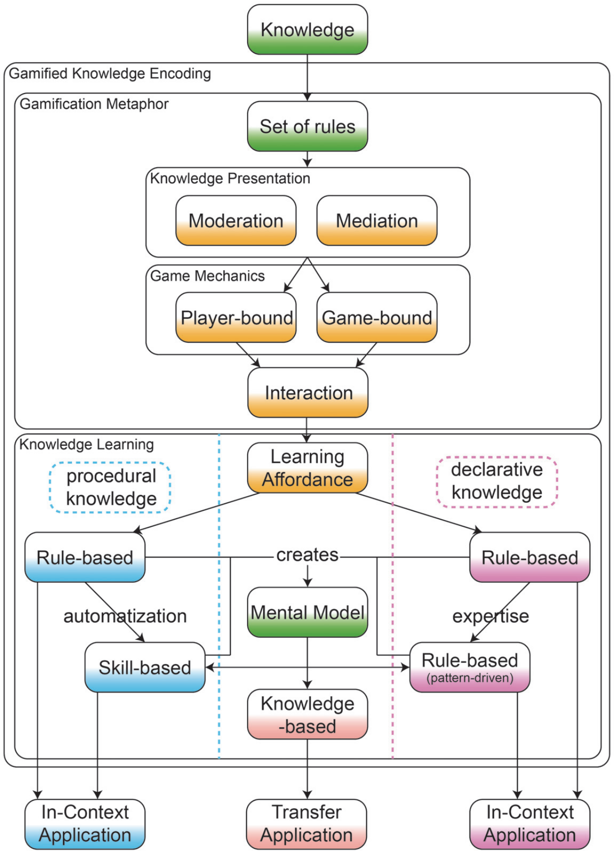
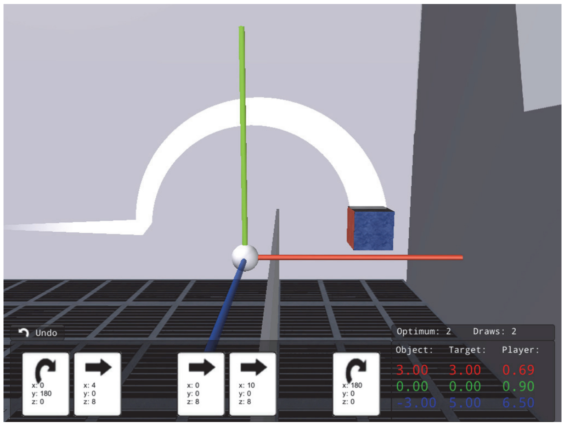


Figure 1: The Gamified Knowledge Encoding describes the process of knowledge encoding and learning using GMs. The knowledge gets segmented into coherent sets of rules which are mapped as game rules to interacting GMs. The interaction between these GMs creates a learning affordance for the encoded learning content. This initiates the theoretically grounded learning process.

are activated by clicking on them, are shown at the bottom of the user interface and display the predefined values as well as the transformation type. The transformation type is indicated with a symbol and a distinct color allowing for a fast and easy recognition (see Figure 4).

The transformation effects were mapped as knowledge rules to a *manipulable game object*, i.e., a game-bound GM, presented in the form of a cube. Configuring and subsequently playing a card internally propagates the entered values to the object GM that immediately changes its status. The object additionally casts an orange trail indicating the path on which it has translated. Thus, the object *mediates* the effects of an AT operation by providing an immediate feedback and visually demonstrating the underlying principles. The object's position is displayed in GEtiT's user interface to provide learners with concrete values they need to use to correctly compute further AT operations. In this way, GEtiT directly encodes the mathematical rules of matrix algebra and their utilization to express and to perform ATs (see Figure 5).

The application of ATs is required by GEtiT's *level design* following the concept of an escape scenario [64]. Each individual level challenges a player to activate an exit portal by solving a *spatial AT puzzle*. The spatial puzzle is solved by transforming the object in such a way that it matches a level's victory conditions. The victory conditions are presented in form of a semitransparent copy of the transformable object, i.e., a game-bound switch GM, that indicates the required position, rotation, and overall status of the object. GEtiT additionally displays the coordinates of the switch to allow learners to mainly focus on determining the correct mathematical solution instead of being challenged to locate the target position manually. As soon as the victory conditions are met, the exit portal is opened and the player can proceed to the next spatial puzzle (see Figure 6). The interaction



Optimum: 2 Draws: 2

Object:	Target:	Player:
3.00	3.00	0.69
0.00	0.00	0.90
-3.00	5.00	6.50

Figure 2: *GEtiT* used a very rudimentary visual presentation in its prototype version. This version also lacks a color-coding for the different AT operation types and an acoustic feedback when playing an AT card.

1	0	0	-1
0	1	0	6
0	0	1	0
0	0	0	1

Figure 3: *GEtiT* allows for the configuration of individual AT operations using the direct value configuration screen. This requires the application of the AT knowledge to correctly determine a desired transformation's values.

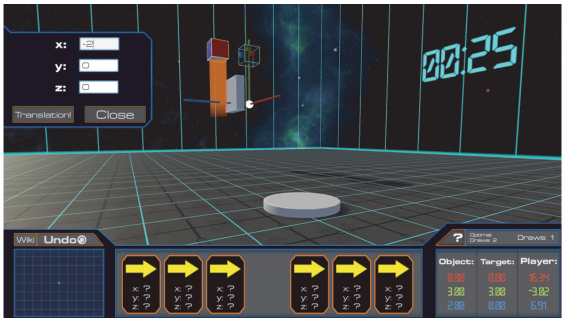
between these three GMs creates a gamification metaphor for ATs.

The AT gamification metaphor creates a learning affordance for the AT learning content. Users are required to execute the AT cards GM during the gameplay, thus repetitively applying their AT knowledge on a rule-based level of human performance. Subsequently, they get visually informed about the underlying principles as the object immediately changes its state. This repetitive practice leads to a compilation of mental models for ATs. These mental models ultimately achieve a training transfer from the serious game to a real world application like utilizing ATs to create VR systems or simply solving the assignments of an exam.

4.1.2. Gameplay Enhancements. Aside from the three core GMs, GEtiT includes additional GMs to enhance the usability as well as the playability and to increase the learners' motivation. For enhancing the usability, GEtiT displays the position of a level's origin and the direction of a level's axes. The former information is mostly needed when a rotation or reflection operation is desired. The latter information is relevant for every transformation operation. Also, GEtiT provides an undo function to allow learners to revert their last action in case of a wrong input. The serious game provides a small built-in AT wiki that informs about the underlying theoretically grounded mathematical aspects. The AT wiki keeps learners immersed when they need to look up further information to determine a spatial puzzle's correct solution.

For the purpose of enhancing GEtiT's motivational aspects and playability, an achievement and a point system got implemented. The point system is based on a performance rating system that challenges players to solve a level with a minimum amount of cards. Using the undo button keeps the draw counter unchanged to keep players from exploiting it. Beating a level with the minimum or small deviation from it rewards players with a performance dependent amount of points symbolized by stars. The points simultaneously provide users with feedback about their progress towards the completion of the game, i.e., stars earned for a particular level are displayed in the level selection menu. Also, the

Figure 4: *GEtiT* displays an individual symbol in a specific color for each AT operation type. From left to right: translation, rotation, scale, reflection, and shear. On easy difficulty, a card's values are indicated underneath the symbol.



Object:	Target:	Player:
0.00	0.00	16.34
3.00	3.00	-3.02
2.00	0.00	6.91

Figure 5: *GEtiT* challenges learners with spatial AT puzzles. The goal is to match a level's victory conditions symbolized by a half-transparent object (upper center right) with the object (upper center left) by transforming it using the AT cards (bottom). Activating a card opens a direct value configuration screen (upper left) allowing for an input of self-obtained values. After confirming the inputs, the object gets immediately transformed and casts an orange trail.

point system is used to create a ranking among all players when GEtiT is played in classroom mode. Here, GEtiT communicates with a database server to synchronize the points of all registered players. Achievements are unlocked by solving levels in a perfect way, completing all levels of a particular transformation type, or finding a hidden Easter-egg.

4.1.3. Debriefing. GEtiT displays a debriefing screen after a level was solved (see Figure 7). The debriefing system provides additional immediate feedback that allows learners to reflect on their computational results [65, 66]. The debriefing screen informs about the number of cards used, the level's minimum, the stars achieved, the time needed, and a composite mathematical equation of the used ATs. The composite mathematical equation aims at the development of an understanding of different forms of expressing AT operations. This is critical as it directly integrates the theoretically grounded mathematical aspects into the gameplay. By displaying concrete matrix-matrix multiplications, learners can integrate this knowledge in their mental models. The debriefing screen also provides options to continue to the next puzzle, to retry the current puzzle, or to return to the level selection menu.

4.1.4. Audiovisual Encoding. Various sound effects were implemented in GEtiT to provide learners with acoustic feedback [64]. Each AT type received an individual sound effect that is played when an AT card is activated. This provides players with an acoustic feedback when a specific AT operation type successfully was applied. Furthermore, GEtiT provides sound effects for walking (footsteps), jumping, touching a card, using the undo button, and a general event indication. The game includes a dubstep-like background music to support its futuristic visual style.

4.2. GEtiT VR. GEtiT VR utilizes the same GMs as GEtiT but realizes them in a diegetic way [67] to increase the system's naturalness, presence, and usability [68, 69]. Naturalness refers to the degree with which actions and effects in a VE correspond to the actions and effects in the real world [70]. The naturalness of an interaction depends on the degree with which it matches the task context [70]. Thus, naturalness is affected by the intuitiveness of the interaction [71]. This main design decision was made to allow for a comparison of the learning outcomes between the two different visualization technologies without confounding the results by implementing different GMs. GEtiT VR presents the AT cards as physical objects inside of the VE (see Figure 8). A moveable card holder gives players access to the cards. Selecting and configuring an AT card is realized with a *selection and manipulation* interaction technique. Selection and manipulation techniques are one of the three fundamental 3D interaction tasks [72]. Their realization is defined in terms of a user's *distance* to the target element. The distance can either be *remote* requiring an artificial *pointing metaphor*, e.g., a virtual ray, or within *arm's reach* allowing for a direct interaction [73].

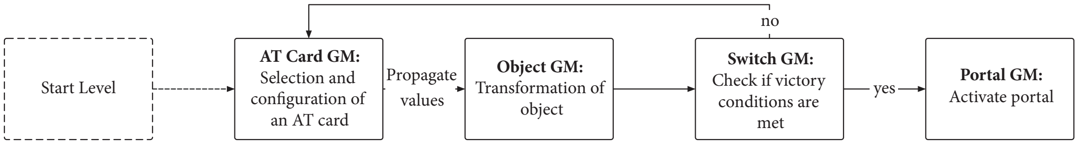


Figure 6: Solving a spatial puzzle requires players to select and to configure AT cards. The system then checks if the victory conditions are met.


Good Job!
Draws: 1
Optimal Draws: 1
Time: 11.61

Optimal Draws: 1 Draws: 1

Object:	Target:	Player:
0.00	0.00	-5.56
-1.00	-1.00	-2.02
0.00	0.00	5.92

Figure 7: The *debriefing screen* provides information about a player's gameplay performance and displays the mathematical equation of the used ATs.

The latter approach is a very natural interaction technique and can be realized with *grasping metaphors* simulating a user's hand or controller inside of an VE [72].

Implementing a within arm's reach grasping metaphor, players select a card by merely touching it with one of the game controllers (see Figure 9). A controller's position is indicated with its 3D asset inside of the VE. Pulling the controller's trigger button activates the selected AT card. Touching the controller's trackpad displays the direct value configuration screen and allows players to configure a card using the second controller. This is done by selecting a value in the configuration screen. Subsequently, pulling the controller's trigger button confirms the selected input.

The positions of the object and of the target are communicated via diegetic labels being directly attached to the objects inside of the VE. Other pieces of information, such as the level selection screen, the main menu, and the AT wiki, are presented in a diegetic way by providing a playing room (see Figure 10). Players can transition between the playing room and the spatial puzzle levels using a *Virtual HMD metaphor* [74]. This diegetic transition technique metaphor is very natural and provides a high degree of self-control. By slowly putting on or taking off the Virtual HMD, users are in full control over the actual transition. As GEtiT's levels are normally larger than the tracking area, GEtiT VR implements the intuitive and easy *Point & Teleport* technology [75] to perform a locomotion inside of the VE aside from real walking [76, 77].

The development of this specific GEtiT VR version was mainly guided by the research goal to analyze if providing a full visual immersion while keeping the gamification metaphor the same leads to an increased learning outcome. GEtiT's GMs were directly ported to VR and realized as diegetic and natural interfaces. This approach, however, neglected further adaptions to ensure a similar usability to GEtiT. Both GEtiT versions were compared in respect to their usability in a user study [78]. In particular, the study analyzed the games' efficiency as well as flow-inducing aspects and the users' satisfaction. The efficiency was evaluated by measuring the elapsed time and experienced task load when solving specific tasks, e.g., solving a particular level. The satisfaction was determined by assessing the games' intuitive use and by analyzing the users' preference. The results revealed slower times when using the direct value configuration screen as well as a higher task load in GEtiT VR. The intuitive use did not differ significantly between both versions and the majority of the participants favored GEtiT VR. Also, flow did not differ significantly between both versions. Thus, the results validated the overall design and the overall playability but indicated potential issues with the realization of the direct value configuration screen in VR. As a result, GEtiT VR is a mere prototype and potentially not directly comparable to GEtiT in respect to its learning effectiveness. A comparison of both systems still is very critical to gain insights into the overall feasibility of this approach and to draw technical design guidelines from the results.

4.3. Learning Approach. GEtiT fulfills some aspects of *situated learning* [79–81]. The serious game guides the learning process with a *complex problem* and embeds it in an *authentic context*. GEtiT provokes an intrinsic motivation in the learner to solve the learning assignments, i.e., to find a solution to the spatial puzzles, by providing an escape scenario. Targeting a training transfer to a computer graphics context [2], GEtiT

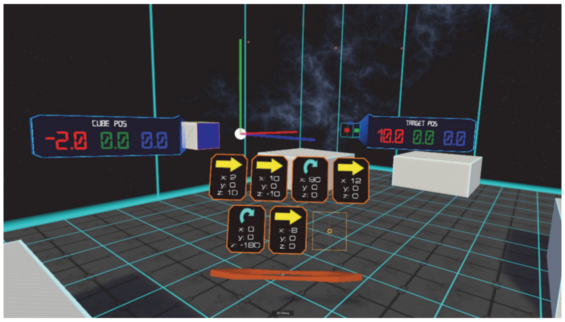


Figure 8: *GEtiT VR* utilizes the same GMs as the desktop version but realizes the interface elements in a diegetic way.

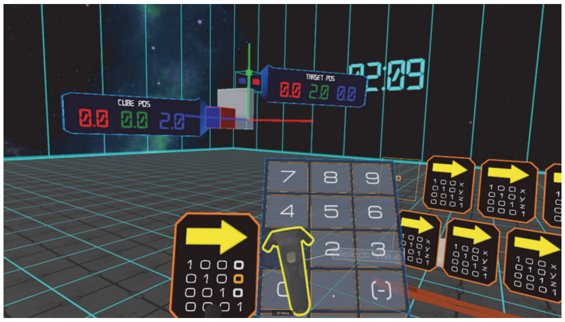


Figure 9: AT cards are grabbed with one controller, configured with the second controller, and played by pressing the first controller's trigger button in *GEtiT VR*.

creates an authentic context by requiring the application of ATs to transform a virtual game object inside the VE. This is achieved by providing the direct value configuration screen requiring the completion of 4 × 4 matrices. However, the serious game lacks the aspects of collaborative construction and reflection of the learning content which is typically associated with the situated learning theory [82]. Also, GEtiT is designed to achieve a transfer-oriented learning of ATs instead of mainly linking the learning content's application to the situations created during the gameplay.

GEtiT also fulfills some aspects of *problem-based learning* [83, 84]. Problem-based learning is self-directed learning being motivated with a complex problem [85] and being assisted with scaffolding that guides the learning process [86]. Solving the presented task provides learners with the opportunity to develop an understanding of the underlying principles and to acquire new knowledge. GEtiT acts as a tutorial system, provides learners with complex tasks and scaffolds them. In this way, GEtiT provides opportunities for a transfer-oriented learning.

4.4. Technology. GEtiT and GEtiT VR are developed with *unity* in the version 5.5.2p1 [87] for PC and Mac. The gameplay is rendered to the connected main monitor and, in case of GEtiT VR, to the HTC Vive HMD. The VR implementation of GEtiT VR is achieved using the *SteamVR Plugin* [88] in the version 1.2.0 which already provided functions for the point & teleport locomotion, controller-based system interaction, controller tooltips, and overall player controller. The playing room's furniture was freely available on the *unity asset store* [89] or part of the *unity standard assets*.

5. Experimental Design

Due to the overall indications discussed in Section 2, the underlying design principles derived from Section 3, and the concrete implementation described in Section 4, we assume the following hypotheses:

H1 The learning outcome is improved when the mediation of the knowledge is audiovisually enhanced.

H2 The learning outcome is improved when a debriefing system is provided.

H3 The learning outcome is improved when the learning process takes place in immersive VR.

The experiment to test these hypotheses, to confirm GEtiT's measured effectiveness, and to validate the Gamified Knowledge Encoding model consisted of *two phases*. The *first* phase was designed to analyze the effects of an audiovisual enrichment by comparing two different GEtiT versions.

Figure 10: *GEtiT VR* realizes the game's menu as a playing room. The Virtual HMD allows for a transition between the menu and a level.

GEtiT in the *enriched* version utilized the aforementioned audiovisual encoding of the AT cards by providing a distinct symbol color and sound effect for each individual transformation type. The *reduced* version utilized the same color and provided the same sound effect for every transformation type. The first phase included a traditional paper-based learning method as a third condition. The *second* phase was designed to compare GEtiT with GEtiT VR in regard to their effectiveness and efficiency. Both GEtiT versions contained the debriefing system and the achievement system which were not implemented in phase 1.

Internally, both phases implemented the same experimental design to achieve comparability. The overall procedure was designed to follow the structure of a traditional class-based learning. The GEtiT-based learning began after the learning content was presented in an interactive computer graphics lecture and before it was fully discussed in the preceding session. In this way, the experiment simulated the implementation of GEtiT in the context of a regular curriculum at a university.

The experiment consisted of four 90-minute learning sessions taking place on a weekly basis. In the week preceding the last learning session, an AT knowledge assessment test was written. The participants who were assigned to one of the desktop-3D GEtiT groups or the paper-Group completed the sessions in the form of a traditional class. The vr-Group was split into smaller two-participant teams due to the amount of available HTC Vive systems in the lab. The vr-Group was required to take a break in the middle of their sessions to reduce the chances for an effect of cybersickness [90] and to avoid a strong effect of exhaustion.

6. Measures

All questionnaires were translated to the common language at the study's location. For ensuring that all questions were understood properly, the participants' language proficiency was assessed.

6.1. Simulator Sickness. During phase 2, the simulator sickness was measured for all participants assigned to GEtiT VR before, during the mandatory break, and after a playing session using the *simulator sickness questionnaire* (*SSQ*) [91]. The results were used to measure the overall quality of the VR simulation and to identify potential negative effects that could have affected the study's results.

6.2. Effectiveness and Efficiency. The learning outcome was measured using a 16-assignment pen-and-paper exam assessing the participants' overall AT knowledge. The assignments were designed to be of similar difficulty to the assignments given in a regular final exam of the interactive computer graphics lecture. Also, GEtiT recorded a participant's solved levels to analyze the efficiency.

6.3. Learning Quality. The learning quality of the tested learning methods was measured using a self-designed questionnaire (1 = disagree; 5 = agree) following the idea of the assessment method used for the prototype version [4]. The questionnaire consists of two subcategories and specific questions relevant for each of the two phases. The *Learning Quality* subcategory consists of nine questions (Q1-Q9) and the system-specific *Motivational Aspects* subcategory consists of six questions (Q10-16). Q17 and Q18 were added to analyze the audiovisual encoding in phase 1. Q19 and Q20 were designed to assess the achievement system and the debriefing system added to the system in phase 2. For evaluating the results, the overall mean for the sum of a subcategory's questions is computed.

Learning Quality

Q1 Did you enjoy playing GEtiT / solving the paper-based assignments?

Q2 Did GEtiT's puzzles / the assignments help you to develop a better understanding of ATs?

Q3 Did you notice a knowledge gain while you were solving the GEtiT puzzles / the assignments?

Q4 Did the raise in the difficulty match your knowledge gain?

Q5 Were the tasks of the GEtiT puzzles / the assignments easy to understand?

- Q6 Was the difficulty of the GEtiT puzzles / the assignments well adjusted?
- Q7 Were you motivated by new challenges due to a raise in the difficulty?
- Q8 Did you enjoy the class that was based on GEtiT / the paper-based assignments?
- Q9 Was it interesting to solve the GEtiT puzzles / the assignments by using AT operations?

Motivational Aspects

- Q10 Was the serious game-based learning method more enjoyable than traditional learning methods, e.g., paper-based assignments?
- Q11 Would you prefer to utilize a serious game instead of visiting a regular class?
- Q12 Did you notice a higher motivation to play GEtiT to practice your knowledge in contrast to other learning methods?
- Q13 Were you motivated by the additional feedback mechanisms, such as highscores and the number of used operations?
- Q14 Did the feedback mechanisms motivate you to try a particular level again to improve your performance?
- Q15 Were you motivated by the indication of the needed time?
- Q16 Were you motivated by the ranking system?

Phase 1

- Q17 Did the color(s) of the AT cards help you to internalize the different AT operation types?
- Q18 Did the sound effects of the AT cards help you to internalize the different AT operation types?

Phase 2

- Q19 Did you find the possibility of unlocking achievements motivating?
- Q20 Did the mathematical representation of your solution at the end of each level help you to develop a better understanding of ATs?

6.4. Participants. The participants were recruited from the students participating in the lecture on interactive computer graphics. They were offered credits mandatory for obtaining their Bachelor's degree and bonus points for the lecture's final exam. After being introduced to the experiment, the participants signed an informed consent form.

Phase 1. In total, 34 students volunteered to take part in the study. Unfortunately, 13 of them missed at least one session and had to be excluded from the sample. The remaining 21 participants (8 females; 13 males) had a mean age of 23.52 years (*SD* = 3.30). Based on self-report, 13 participants were frequent computer game players. They were randomly assigned to the *enriched-Group* (*n* = 8), the *reduced-Group* (*n* = 5), and the *paper-Group* (*n* = 8).

Phase 2. In total, 27 students volunteered to take part in the study. Unfortunately, 6 of them who were assigned to the GEtiT group missed at least one session and had to be excluded from the sample. The remaining 21 participants (6 females, 15 males) had a mean age of 21.90 years (*SD* = 1.89). Based on self-report, 13 participants were frequent computer game players. They were randomly assigned to the *vr-Group* (*n* = 13) and the GEtiT *phase 2 -Group* (*n* = 8).

Table 1: SSQ total scores.

Session	Pre	Mid	Post	F(37)	p
1	31.07	33.08	38.26	0.56	0.46
2	39.70	44.88	51.50	0.49	0.45
3	33.66	44.02	37.98	0.09	0.77
4	22.44	20.43	35.10	2.77	0.11

Table 2: Test results in the AT knowledge assessment test.

Group	Mean result in %	SD	Min	Max
Desktop	58.14	17.08	28	92
Reduced	58.00	17.13	29	73
Enriched	61.12	17.27	32	86
Phase 2	55.25	18.65	28	92
VR	51.08	14.86	22	72
Paper	67.00	18.05	28	84

7. Results

In this section, the results of the user study are presented and evaluated according to the given hypotheses and the additional goals of this experiment. The results were compared by calculating either a one-way ANOVA or a two-sample t-test [92]. The effect size was determined using Cohen's D. For determining a correlation, the Pearson's product-moment correlation was computed.

7.1. Simulator Sickness. The participants of the vr-Group were asked to complete the SSQ before the start of the learning session (pre), right after they started their break (mid), and at the end of the session (post). As Table 1 displays, no significant change in the SSQ ratings was found for each of the practice sessions.

7.2. Effectiveness and Efficiency. Initially, the three different GEtiT conditions were compared in regard to the yielded test result ($F(19) = 0.22$, $p = 0.65$; see Table 2) and the number of successfully solved levels ($F(19) = 0.75$, $p = 0.40$; see Table 3) but no significant difference was found. Thus, to increase the accuracy of further analyses, the GEtiT groups were combined and called *desktop-Group* (*n* = 21) in the remainder of this paper. The test results of the remaining three different conditions did not differ significantly ($F(40) = 0.56$, $p = 0.46$; see Figure 11). Further analyses revealed a

Table 3: Gameplay progress at the end of the experiment.

Group	Solved levels	SD	Min	Max
Desktop	115.86	20.07	79	153
Reduced	116.40	16.65	94	136
Enriched	109.25	14.89	86	126
Phase 2	122.12	26.00	79	153
VR	81.15	25.08	41	128

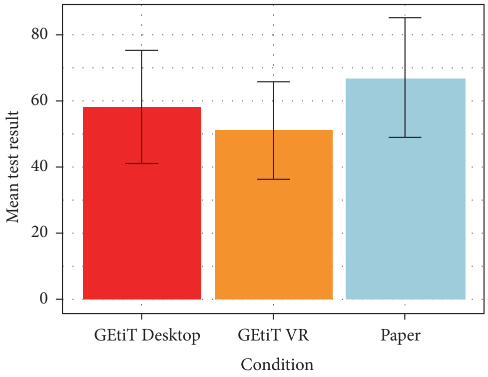


Figure 11: Graphical comparison of the test results between the *desktop-Group*, the *vr-Group*, and the *paper-Group*. Error bars indicate standard deviations.

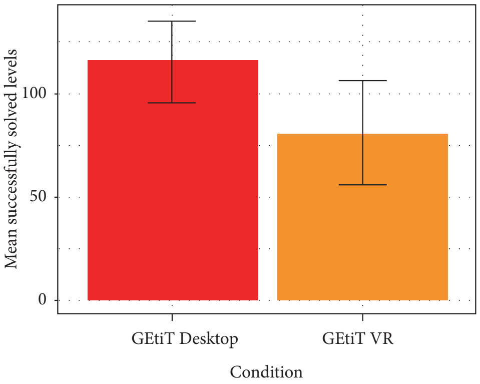


Figure 12: Graphical comparison of the mean gameplay progress between the *desktop-Group* and the *vr-Group*. Error bars indicate standard deviations.

significantly higher number of solved levels in the desktop-Group with a very large effect size ($t(32) = 4.45$, $p > 0.001$, $d = 1.57$; see Figure 12). No significant correlation was found for the vr-Group between the test result and the number of solved levels ($r(11) = 0.41$, $p = 0.69$). A significant correlation, however, was found for the desktop-Group between the test result and the number of solved levels ($r(19) = 2.34$, $p = 0.03$).

7.3. Learning Quality. At the end of the experiment, the participants were asked to rate the learning quality. In phase 1, 18 of the 21 participants filled in the questionnaire. In phase 2, all participants completed the learning quality questionnaire. A one-way ANOVA revealed no significant difference between the mean ratings of the *learning quality* subcategory ($F(37) = 3.88$, $p = 0.06$; see Table 4). Also, no significant difference was found between the individual four tested versions in regard to the *motivational aspects* subcategory ($F(30) = 0.80$, $p = 0.38$).

No difference was found between the reduced and the enriched version for Q17 ($t(9) = 0.14$, $p = 0.89$) and Q18 ($t(9) = 0.23$, $p = 0.82$) measuring the perceived educational effect of the audiovisual encoding in phase 1. Both visual approaches received a mean rating at the scale's neutral midpoint. The mean rating for the acoustic encoding was below the scale's neutral midpoint. The achievement system added in phase 2 received a mean motivational rating above the scale's neutral midpoint for GEtiT VR and a mean motivational rating slightly below the scale's neutral midpoint for GEtiT. The ratings were not significantly different ($t(19) = 2.02$, $p = 0.06$). The perceived learning effect of the debriefing system had a mean rating above the scale's neutral midpoint for both GEtiT versions. The ratings were not significantly different ($t(19) = 0.38$, $p = 0.71$).

8. Discussion

Although a lack of statistical significance does not imply an equivalence, the results indicate that GEtiT achieves a *similar* AT knowledge learning outcome to traditional learning methods, i.e., by using paper-based assignments. Thus, the effectiveness measurements *validate* the findings of the initial prototype evaluation by *confirming* GEtiT's transfer-oriented learning effects [4]. Also the significant correlation between the number of solved levels and the test result contributes to the ongoing validation of the Gamified Knowledge Encoding. By encoding the AT knowledge as game rules in GMs, a repetitive application of the learning content is achieved during the gameplay. This repetitive practice leads to an internalization of the AT knowledge in form of mental models. It also achieves a shift to a more pattern-driven application. The compiled mental models allow for a training transfer from GEtiT to a real world context. This was tested by implementing a pen-and-paper exam that only uses 2D pre- and post-images to visualize a desired AT operation. The participants of the GEtiT groups were not only required to solve the assignments, but also to transfer their knowledge from the 3D serious games to a 2D paper-based exam. As a result, the learning outcome of playing GEtiT could be even higher than using traditional learning methods.

8.1. Effectiveness and Efficiency. Interestingly, the learning outcome was not affected by the difference in the audiovisual encoding tested in phase 1 and the debriefing system provided in phase 2. The lack of an effect due to the *audiovisual encoding* is explainable by the fact that the two tested versions were only different in respect to the used AT card colors and

Table 4: Mean learning quality ratings (Reduced: n = 5, Enriched: n = 6, Phase 2: n = 8, VR: n = 13, and Paper: n = 7).

Q	Reduced (SD)	Enriched (SD)	Phase 2 (SD)	VR (SD)	Paper (SD)
Learning Quality	3.89(0.69)	3.80(0.75)	4.15(0.76)	4.27(0.37)	3.73(0.52)
Motivational Aspects	4.11(0.47)	3.71(0.84)	3.71(0.90)	3.68(0.71)	–
Q17	2.40(1.34)	2.50(1.05)	3.12(0.99)	3.54(1.51)	–
Q18	1.80(1.10)	1.67(0.82)	1.25(0.71)	2.23(1.42)	–
Q19	–	–	2.38(1.30)	3.54(1.27)	–
Q20	–	–	3.00(1.51)	3.23(1.24)	–

sound effects. The overall gameplay and application of the AT knowledge remained the same. Participants potentially were only focused on finding the correct solution to the spatial puzzles without paying attention to the audiovisual realization of the knowledge application. Hence, the learning effect is mainly caused by the frequent application of the AT knowledge independent of the application's enhanced audiovisual mediation. However, the lack of an increased learning outcome caused by the implementation of the *debriefing system* is surprising. The reason for this could be an issue with the realization of the debriefing system. Instead of only focusing on the mathematical equation, the screen also provides information about the overall gameplay-related performance. This additional information might have distracted learners from the actual learning content. The participants could also have been in a strong state of flow and hence immediately continued to the next spatial puzzle without analyzing the debriefing screen. A solution would be to directly display and to update the composite mathematical equation during the gameplay. As a result, learners would then be able to directly connect their gameplay actions with the changes in the mathematical equation. Also, separating the mathematical equations from the gameplay information in the debriefing screen could improve its effectiveness.

Therefore, *H1* and *H2* have to be rejected as no significant difference in the learning outcome was found.

Despite not being significantly different, the results indicate a tendency that GEtiT VR has a lower learning outcome in contrast to GEtiT's desktop version. This tendency is explainable by the significantly lower number of solved levels in the vr-Group. Despite having invested the same amount of time, the vr-Group was not able to complete as many spatial puzzles as the desktop-Group. A reason for this could be the complex interaction technique on higher difficulties. Instead of merely completing a matrix using mouse and keyboard, GEtiT VR requires the usage of both HTC Vive controllers to define an AT card. GEtiT VR's learning outcome could potentially be improved by finding a more efficient input method for the direct value configuration screen. Thus, the analysis of GEtiT VR's efficiency has not only confirmed an issue with the realization of the AT card GM in VR [78], but also revealed the importance of a high efficiency for serious games. This is a critical insight for developers and educators. It demonstrates that differences in the efficiency, i.e., an important usability factor, have a direct influence on the achieved learning outcome. In this way, it is of high importance to check for all usability factors during the development of a serious game. Overall, this leads to the outcome that both GEtiT versions cannot directly be compared in respect to their learning effectiveness. Also, it is not possible to draw generalizable insights about the effectiveness of VR technology for an AT knowledge learning based on this study's results. Despite these limitations, the study indicated that using GEtiT VR leads to a successful training transfer and successfully demonstrated that the Gamified Knowledge Encoding is also valid for VR serious games. This is a *valuable insight* for scientists, game designers, and educators aiming at the development of serious games targeting HMD-VR.

Thus, *H3* cannot be verified as both GEtiT versions ultimately were too different to be directly compared in regard to their learning outcome.

8.2. Learning Quality.

The learning quality analysis validates the concept of developing GEtiT to achieve a higher learning quality when practicing the complex and abstract ATs. In this way, the present study also validates GEtiT's design as well as playability. Although no significant difference was found in the learning quality subcategory between the tested learning methods, the results indicate a clear trend that GEtiT and GEtiT VR achieve a higher learning quality. This outcome is critical as all participants had to invest the same amount of time but felt more engaged when using the serious game. As a result, GEtiT not only yields effective knowledge learning, but also achieves a higher learning quality thus *indicating its overall* effectiveness. The results also align with previous research [45, 46] by showing the highest learning quality rating in the vr-Group. In this way, the user study confirms that using VR technology can be beneficial for the overall learning quality of a serious game. This result is supported by the behavior of the participants. Except for the vr-Group, all other conditions showed some drop outs. The vr-Group, however, even reported to have experienced a strong intrinsic motivation to attend every session, thus confirming the measured high learning quality.

The system-specific motivational aspects subcategory revealed that all tested GEtiT versions were perceived as an engaging and motivating learning method. Interestingly, GEtiT VR showed no trend to yield a higher motivation than the desktop version. This outcome is explainable by a habituation effect. Instead of playing GEtiT VR for a single learning session only, the participants used the system over the course of 4 weeks. As a result, the initial motivational benefit of providing an immersive VR version might have ceased over time. Interestingly, the implementation of an achievement system had no impact on the motivational aspects subcategory despite being rated as somewhat motivating. This could be a result of the general functionality of an achievement system. It rewards progress milestones but provides no constant feedback like the point system.

The specific questions targeting the audiovisual encoding tested in phase 1 revealed that the visual presentation of the core player-bound GMs requiring the knowledge application has only a limited effect on the perceived learning effect. This aligns with the assumptions drawn from the effectiveness measurement results. The results also show that acoustic effects are of lower priority when designing a serious game. This insight is important for designers who need to prioritize their development goals.

Finally, the perceived learning effect of the debriefing system was seen as helpful but not as a critical element relevant for knowledge learning. This aligns with the finding that the debriefing GM had no effect on the overall learning outcome.

9. Conclusion and Future Work

This paper presents two versions of GEtiT targeting a transfer-oriented learning of ATs. Both versions of the game implement the same core GMs to encode the learning content but use either desktop-3D or immersive VR to visualize the gameplay. In addition, a comprehensive presentation of the Gamified Knowledge Encoding is given for the first time. The two GEtiT versions were compared to a traditional paper-based learning method in regard to the learning outcome and learning quality. Also, the two versions were compared in respect to their efficiency. Lastly, this paper evaluates the effects of a debriefing system and of two different audiovisual encodings, i.e., reduced and enriched, of the learning content on the overall learning outcome and the perceived learning effects.

The results of the present study show that encoding and presenting complex knowledge using GMs leads to an effective transfer-oriented knowledge learning. Thus, the results validate the design of GEtiT and the underlying framework of the Gamified Knowledge Encoding. The effectiveness of the learning, however, was not affected by the audiovisual presentation or the provision of a debriefing system. Also, while showing VR technology being beneficial for the learning quality, the study revealed a flaw in GEtiT VR's design negatively affecting its efficiency. Hence, no conclusions can be drawn from the comparison of the learning effectiveness of both versions. However, the study indicated a higher learning quality for the VR version. This is a critical insight for the ongoing research of VR-based education and an important finding for game designers who like to create effective serious games.

Future work needs to be aimed at further evaluations of the knowledge encoding in GMs as proposed with the Gamified Knowledge Encoding. Also, new methods to realize the AT card GM in GEtiT VR need to be implemented and tested. This would allow for a comparison of the different visualization techniques and potentially reveal new insights about knowledge learning in immersive VR. Finally, instead of assessing the learning outcome with a paper-based exam only, the measurement could additionally be performed inside of GEtiT. This would allow for a more in-depth analysis of its training transfer.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

We like to thank Mario Reutter and Jonathan Stahl for developing the first prototype of GEtiT. Also, we like to thank David Heidrich for his work in overhauling GEtiT, changing its visual style, and developing GEtiT VR. This publication was funded by the German Research Foundation (DFG) and the University of Würzburg in the funding programme Open Access Publishing.

Supplementary Materials

GEtiT - Gameplay shows the encoded AT operations and their visual effects. The video also provides an overview of GEtiT's gameplay and of the knowledge learning process. *GEtiT - Difficulties* demonstrates the four different difficulty levels and shows how the AT knowledge is moderated and mediated. *GEtiT VR* showcases the specific VR version by showing the main menu and the successful completion of an easy as well as a hard spatial puzzle. *(Supplementary Materials)*

References

[1] K. S. Fu, R. Gonzalez, and C. S. G. Lee, *Robotics: Control, Sensing, Vision and Intelligence*, McGraw-Hill Education, New York, NY, USA, 1987.

[2] J. Foley, A. van Dam, S. Feiner, and J. Hughes, "Computer graphics: principles and practice," in *Addison-WesleySystems Programming Series*, Addison-Wesley, Reading, MA, USA, 1990.

[3] S. Oberdörfer and M. E. Latoschik, "Interactive gamified 3D-training of affine transformations," in *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*, pp. 343-344, ACM Press, Garching, Germany, November 2016.

[4] S. Oberdörfer and M. E. Latoschik, "Effectivity of affine transformation knowledge training using game mechanics," in *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018)*, Würzburg, Germany, September 2018.

[5] S. Oberdörfer and M. E. Latoschik, "Gamified knowledge encoding: knowledge training using game mechanics," in

Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018), Würzburg, Germany, September 2018.

[6] J. Rasmussen, "Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 13, no. 3, pp. 257–266, 1983.

[7] P. N. Johnson-Laird, *Mental Models. Towards a Cognitive Science of Language, Inference, and Consciousness*, Harvard University Press, 1983.

[8] C. J. Dede, J. Jacobson, and J. Richards, "Introduction: virtual, augmented, and mixed realities in education," in *Virtual, Augmented, and Mixed Realities in Education*, D. Liu, C. J. Dede, R. Huang, and J. Richards, Eds., Smart Computing and Intelligence, pp. 1–16, Springer, Singapoore, 2017.

[9] S. Oberdörfer, D. Heidrich, and M. E. Latoschik, "Interactive gamified virtual reality training of affine transformations," in *Proceedings of the DeLFI and GMW Workshops 2017*, C. Ullrich and M. Wessner, Eds., Chemnitz, Germany, 2017.

[10] K. A. Ericsson, R. T. Krampe, and C. Tesch-Römer, "The role of deliberate practice in the acquisition of expert performance," *Psychological Review*, vol. 100, no. 3, pp. 363–406, 1993.

[11] J. P. Gee, *What Video Games Have to Teach Us about Learning and Literacy*, Palgrave Macmillan, New York, NY, USA, 1st edition, 2007.

[12] J. McGonigal, *Reality Is Broken: Why Games Make Us Better And How They Can Change The World*, Penguin Press, New York, NY, USA, 1st edition, 2011.

[13] M. Csikszentmihalyi, *Flow: Das Geheimnis des Glücks*, Klett-Cotta, Stuttgart, 15th edition, 2010.

[14] D. Weibel and B. Wissmath, "Immersion in computer games: the role of spatial presence and flow," *International Journal of Computer Games Technology*, vol. 2011, Article ID 282345, 14 pages, 2011.

[15] B. Reeves, T. W. Malone, and T. O'Discoll, "Leadership's online labs," *Harvard Business Review*, vol. 86, no. 5, pp. 58–66, 2008.

[16] A. Siewiorek and A. Gegenfurtner, "Leading to win: the influence of leadership styles on team performance during a computer game training," in *Proceedings of the 9th International Conference of the Learning Sciences, ICLS '10*, vol. 1, pp. 524–531, ACM, Chicago, IL, USA, 2010.

[17] P. Prax, "Leadership style in world of warcraft raid guilds," in *Proceedings of the DiGRA Nordic 2010*, DiGRA, Stockholm, Sweden, 2010.

[18] R. Schroeder, *Being There Together: Social Interaction in Virtual Environments*, Oxford University Press, New York, NY, USA, 1st edition, 2011.

[19] L. Qiu, W. W. Tay, and J. Wu, "The impact of virtual teamwork on real-world collaboration," in *Proceedings of the International Conference on Advances in Computer Enterntainment Technology, ACE'09*, pp. 44–51, ACM, Athens, Greece, October 2009.

[20] S. Richter and U. Lechner, "Communication content relations to coordination and trust over time: a computer game perspective," in *Proceedings of the 5th International Conference on Communities and Technologies, C&T'11*, pp. 60–68, ACM, Brisbane, Australia, 2011.

[21] B. D. Glass, W. T. Maddox, and B. C. Love, "Real-time strategy game training: emergence of a cognitive flexibility trait," *PLoS ONE*, vol. 8, no. 8, Article ID e70350, 2013.

[22] C. S. Green and D. Bavelier, "Action video game modifies visual selective attention," *Nature*, vol. 423, no. 6939, pp. 534–537, 2003.

[23] C. S. Green and D. Bavelier, "Action-video-game experience alters the spatial resolution of vision," *Psychological Science*, vol. 18, no. 1, pp. 88–94, 2007.

[24] E. F. Anderson, L. McLoughlin, F. Liarokapis, C. Peters, P. Petridis, and S. de Freitas, "Serious games in cultural heritage," in *Proceedings of the 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST*, pp. 29–48, Malta, 2009.

[25] S. de Freitas and F. Liarokapis, "Serious games: a new paradigm for education?" in *Serious Games and Edutainment Applications*, M. Ma, A. Oikonomou, and L. C. Jain, Eds., pp. 9–23, Springer-Verlag, London, UK, 2011.

[26] L. A. Annetta, J. Minogue, S. Y. Holmes, and M.-T. Cheng, "Investigating the impact of video games on high school students' engagement and learning about genetics," *Computers & Education*, vol. 53, no. 1, pp. 74–85, 2009.

[27] Y. Klisch, L. M. Miller, M. E. Beier, and S. Wang, "Teaching the biological consequences of alcohol abuse through an online game: Impacts among secondary students," *CBE-Life Sciences Education*, vol. 11, no. 1, pp. 94–102, 2012.

[28] L. M. Miller, C.-I. Chang, S. Wang, M. E. Beier, and Y. Klisch, "Learning and motivational impacts of a multimedia science game," *Computers & Education*, vol. 57, no. 1, pp. 1425–1433, 2011.

[29] S. de Castell, J. Jenson, and N. Taylor, "Educational games: moving from theory to practice," in *Educational Gameplay and Simulation Environments: Case Studies and Lessons Learned*, D. Kaufman and L. Sauvé, Eds., pp. 133–145, Information Science Reference, Hershey, PA, USA, 2010.

[30] A. Gurr, "Video games and the challenge of engaging the 'net' generation," in *Educational Gameplay and Simulation Environments: Case Studies and Lessons Learned*, D. Kaufman and L. Sauvé, Eds., pp. 119–131, Information Science Reference, Hershey, PA, USA, 2010.

[31] H. C. Arnseth, "Learning to play or playing to learn - A critical account of the models of communication informing educational research on computer gameplay," *Game Studies*, vol. 6, no. 1, 2006.

[32] E. Brown and P. Cairns, "A grounded investigation of game immersion," in *Proceedings of the Extended Abstracts on Human Factors in Computing Systems (CHI '04)*, pp. 1297–1300, ACM Press, Vienna, Austria, April 2004.

[33] C. Jennett, A. L. Cox, P. Cairns et al., "Measuring and defining the experience of immersion in games," *International Journal of Human-Computer Studies*, vol. 66, no. 9, pp. 641–661, 2008.

[34] M. Power and L. Langlois, "Designing a simulator for teaching ethical decision-making," in *Educational Gameplay and Simulation Environments: Case Studies and Lessons Learned*, D. Kaufman and L. Sauvé, Eds., pp. 146–158, Information Science Reference, Hershey, PA, USA, 2010.

[35] M. Schulzke, "Moral decision making in fallout," *Game Studies*, vol. 9, no. 2, 2009.

[36] E. Adams and J. Dormans, *Game Mechanics*, Advanced Game Design, New Riders, Berkeley, USA, 2012.

[37] M. Sicart, "Defining game mechanics," *Game Studies*, vol. 8, no. 2, 2008.

[38] A. Amory, K. Naicker, J. Vincent, and C. Adams, "The use of computer games as an educational tool: identification of appropriate game types and game elements," *British Journal of Educational Technology*, vol. 30, no. 4, pp. 311–321, 1999.

[39] A. C. Oei and M. D. Patterson, "Enhancing cognition with video games: a multiple game training study," *PLoS ONE*, vol. 8, no. 3, Article ID e58546, 2013.

[40] L. S. Colzato, W. P. M. van den Wildenberg, S. Zmigrod, and B. Hommel, "Action video gaming and cognitive control: playing first person shooter games is associated with improvement in working memory but not action inhibition," *Psychological Research*, vol. 77, no. 2, pp. 234–239, 2013.

[41] I. D. Cherney, "Mom, let me play more computer games: they improve my mental rotation skills," *Sex Roles*, vol. 59, no. 11-12, pp. 776–786, 2008.

[42] M. E. Joorabchi and M. S. El-Nasr, "Measuring the impact of knowledge gained from playing FPS and RPG games on gameplay performance," in *Proceedings of the Entertainment Computing – ICEC 2011*, pp. 300–306, Springer, Vancouver, BC, Canada, October 2011.

[43] M. Pittalis and C. Christou, "Types of reasoning in 3D geometry thinking and their relation with spatial ability," *Educational Studies in Mathematics*, vol. 75, no. 2, pp. 191–212, 2010.

[44] G. Gittler and J. Glück, "Differential transfer of learning: effects of instruction in descriptive geometry on spatial test performance," *Journal for Geometry and Graphics*, vol. 2, no. 1, pp. 71–84, 1998.

[45] L. Freina and M. Ott, "A literature review on immersive virtual reality in education: state of the art and perspectives," in *Proceedings of the 11th eLearning and Software for Education (eLSE)*, no. 1, Bucharest, Romania, April 2015.

[46] J. Martn-Gutiérrez, C. E. Mora, B. Añorbe-Daz, and A. González-Marrero, "Virtual technologies trends in education," *EURASIA Journal of Mathematics Science and Technology Education*, vol. 13, no. 2, pp. 469–486, 2017.

[47] J. A. Stevens and J. P. Kincaid, "The relationship between presence and performance in virtual simulation training," *Open Journal of Modelling and Simulation*, vol. 03, no. 02, pp. 41–48, 2015.

[48] M. Slater, "Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments," *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, vol. 364, no. 1535, pp. 3549–3557, 2009.

[49] G. Makransky and L. Lilleholt, "A structural equation modeling investigation of the emotional value of immersive virtual reality in education," *Educational Technology Research and Development*, vol. 66, no. 5, pp. 1141–1164, 2018.

[50] M. Slater and S. Wilbur, "A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 6, pp. 603–616, 1997.

[51] C. Dede, "Immersive interfaces for engagement and learning," *Science*, vol. 323, no. 5910, pp. 66–69, 2009.

[52] B. Weidenmann, "Multimedia, multicodierung und multimodalität beim online-lernen," in *Online Lernen. Handbuch für Wissenschaft und Praxis*, L. J. Issing and P. Klimsa, Eds., ch. 5, pp. 73–86, Oldenbourg, Germany, 2009.

[53] H. Kaufmann, D. Schmalstieg, and M. Wagner, "Construct3D: a virtual reality application for mathematics and geometry education," *Education and Information Technologies*, vol. 5, no. 4, pp. 263–276, 2000.

[54] H. Kaufmann, "The potential of augmented reality in dynamic geometry education," in *Proceedings of the 12th International Converence on Geometry and Graphics*, 2006.

[55] M. Khan, F. Trujano, A. Choudhury, and P. Maes, "Mathland: playful mathematical learning in mixed reality," in *Proceedings of the Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems, CHI'18*, Montreal, QC, Canada, April 2018.

[56] J. R. Anderson, *Cognitive Psychology and Its Implications*, Worth Publishers, 8th edition, 2015.

[57] F. Nickols, "The knowledge in knowledge management," *The Knowledge Management Yearbook 2000-2001*, pp. 12–21, 2000.

[58] S. Oberdörfer and M. E. Latoschik, "Develop your strengths by gaming," in *Proceedings of the 43rd Annual German Conference on Informatics, Informatik 2013*, M. Horbach, Ed., vol. P-220, pp. 2346–2357, Gesellschaft für Informatik, Koblenz, Germany, September 2013.

[59] B. Dalgarno and M. J. W. Lee, "What are the learning affordances of 3-D virtual environments?" *British Journal of Educational Technology*, vol. 41, no. 1, pp. 10–32, 2010.

[60] V. Kaptelinin and B. A. Nardi, "Affordances in HCI: Toward a mediated action perspective," in *Proceedings of the 2012 ACM Annual Conference on Human Factors in Computing Systems, CHI 2012*, pp. 967–976, ACM, Austin, Texas, USA, May 2012.

[61] T. Lynam, R. Mathevet, M. Etienne et al., "Waypoints on a journey of discovery: Mental models in human- environment interactions," *Ecology and Society*, vol. 17, no. 3, 2012.

[62] Take-Two Interactive, "Kerbal space program," 2011–2019, https://kerbalspaceprogram.com.

[63] S. Oberdörfer and M. E. Latoschik, "Effective orbital mechanics knowledge training using game mechanics," in *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018)*, IEEE, Würzburg, Germany, September 2018.

[64] D. Perry and R. DeMaria, *David Perry on Game Design: A Brainstorming Toolbox*, Course Technology, Boston, MA, USA, 2009.

[65] D. Crookall, "Serious games, debriefing, and simulation/gaming as a discipline," *Simulation & Gaming*, vol. 41, no. 6, pp. 898–920, 2011.

[66] K. T. Dreifuerst, "The essentials of Debriefing in simulation learning: a concept analysis," *Nursing Education Perspectives*, vol. 30, no. 2, pp. 109–114, 2009.

[67] A. R. Galloway, *Gaming: Essays on Algorithmic Culture*, vol. 18, Minnesota Press, 2006.

[68] P. Salomoni, C. Prandi, M. Roccetti, L. Casanova, and L. Marchetti, "Assessing the efficacy of a diegetic game interface with oculus rift," in *Proceedings of the 13th IEEE Annual Consumer Communications & Networking Conference (CCNC 2016)*, pp. 387–392, 2016.

[69] D. Medeiros, E. Cordeiro, D. Mendes et al., "Effects of speed and transitions on target-based travel techniques," in *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology, VRST '16*, pp. 327-328, ACM, New York, NY, USA, November 2016, http://doi.acm.org/10.1145/2993369.2996348=0pt.

[70] D. A. Bowman, R. P. McMahan, and E. D. Ragan, "Questioning naturalism in 3D user interfaces," *Communications of the ACM*, vol. 55, no. 9, pp. 78–88, 2012.

[71] S. Ghosh, C. S. Shruthi, H. Bansal, and A. Sethia, "What is user's perception of naturalness? an exploration of natural user experience," in *Proceedings of the Human-Computer Interaction - INTERACT 2017*, R. Bernhaupt, G. Dalvi, A. Joshi, D. K. Balkrishan, J. O'Neill, and M. Winckler, Eds., vol. 10514 of *Lecture Notes in Computer Science*, pp. 224–242, Springer International Publishing, Cham, Switzerland, 2017.

[72] J. J. LaViola Jr., E. Kruijff, R. P. McMahan, D. Bowman, and I. P. Poupyrev, *3D User Interfaces: Theory And Practice*, Addison-Wesley Professional, 2017.

[73] D. A. Bowman, E. Kruijff, J. J. LaViola Jr., and I. Poupyrev, "An introduction to 3-D user interface design," *Presence: Teleoperators and Virtual Environments*, vol. 10, no. 1, pp. 96–108, 2001.

[74] S. Oberdörfer, M. Fischbach, and M. E. Latoschik, "Effects of VE transition techniques on presence, ivbo, efficiency, and naturalness," in *Proceedings of the 6th Symposium on Spatial User Interaction*, pp. 89–99, ACM, Berlin, Germany, October 2018.

[75] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey, "Point & teleport locomotion technique for virtual reality," in *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, pp. 205–216, Austin, TX, USA, October 2016.

[76] G. Bruder and F. Steinicke, "Threefolded motion perception during immersive walkthroughs," in *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology, VRST '14*, pp. 177–185, ACM, New York, NY, USA, 2014, http://doi.acm.org/10.1145/2671015.2671026=0pt.

[77] T. Y. Grechkin, J. M. Plumert, and J. K. Kearney, "Dynamic affordances in embodied interactive systems: The role of display and mode of locomotion," *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, no. 4, pp. 596–605, 2014.

[78] S. Oberdörfer, D. Heidrich, and M. E. Latoschik, "Usability of gamified knowledge learning in VR and desktop-3D," in *Proceedings of the CHI 2019*, ACM Press, Glasgow, UK, 2019.

[79] J. Herrington and R. Oliver, "Critical characteristics of situated learning: Implications for the instructional design of multimedia," in *Proceedings of the ASCILITE 1995 Conference*, pp. 253–262, Melbourne, Australia, December 1995.

[80] J. R. Anderson, L. M. Reder, and H. A. Simon, "Situated lerning and education," *Educational Researcher*, vol. 25, no. 4, pp. 5–11, 1996.

[81] D. W. Shaffer, K. R. Squire, R. Halverson, and J. P. Gee, "Video games and the future of learning," *Phi Delta Kappan*, vol. 87, no. 2, pp. 104–111, 2005.

[82] A. Woolfalk, *Educational Psychology*, Allyn and Bacon, New Jersey, USA, 10th edition, 2008.

[83] H. S. Barrows, "Problem-based learning in medicine and beyond: a brief overview," *New Directions for Teaching and Learning*, vol. 1996, no. 68, pp. 3–12, 1996.

[84] F. Dochy, M. Segers, P. Van den Bossche, and D. Gijbels, "Effects of problem-based learning: a meta-analysis," *Learning and Instruction*, vol. 13, no. 5, pp. 533–568, 2003.

[85] M. Wilhelm and D. Brovelli, "Problembasiertes lernen (pbl) in der lehrpersonenbildung: der drei-phasen-ansatz der naturwissenschaften," *Beiträge zur Lehrerinnen- und Lehrerbildung*, vol. 27, no. 2, pp. 195–203, 2009.

[86] C. E. Hmelo-Silver, R. G. Duncan, and C. A. Chinn, "Scaffolding and achievement in problem-based and inquiry learning: a response to Kirschner, Sweller, and Clark," *Educational Psychologist*, vol. 42, no. 2, pp. 99–107, 2007.

[87] Unity, "Unity 5.5.2p1," March 2017, https://unity3d.com/unity/qa/patch-releases/5.5.2p1.

[88] Valve Coorperation, "Steamvr plugin," 2015–2018, https://www.assetstore.unity3d.com/en/#!/content/32647.

[89] Unity, "Unity asset store," 2017, https://www.assetstore.unity3d.com.

[90] K. M. Stanney, K. S. Kingdon, D. Graeber, and R. S. Kennedy, "Human performance in immersive virtual environments: effects of exposure duration, user control, and scene complexity," *Human Performance*, vol. 15, no. 4, pp. 339–366, 2002.

[91] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness," *The International Journal of Aviation Psychology*, vol. 3, no. 3, pp. 203–220, 1993.

[92] G. Norman, "Likert scales, levels of measurement and the 'laws' of statistics," *Advances in Health Sciences Education*, vol. 15, no. 5, pp. 625–632, 2010.

7.3 Prediction of Learning Outcomes

As a second approach to validate the definition of knowledge learning using game mechanics, the Gamified Knowledge Encoding was also applied to analyze and to predict the learning outcome of other serious games. For quantitatively predicting the learning outcomes, the game mechanics of *Kerbal Space Program* were analyzed in respect to the encoded orbital mechanics knowledge rules. In a user study, the learning outcome of playing the game was measured to validate the theoretical assumptions of knowledge encoding and knowledge learning using game mechanics.

Table 12: Effective Orbital Mechanics Knowledge Training Using Game Mechanics

Author	**Contribution**
Oberdörfer, S.	Literature review, conceptual design, experimental design, data analysis, discussion, manuscript preparation and revision
Latoschik, M. E.	Manuscript revision

Oberdörfer, S. and Latoschik, M. E. Effective Orbital Mechanics Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games '18)*, Würzburg, Germany, September 2018c. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493417

Effective Orbital Mechanics Knowledge Training Using Game Mechanics

Sebastian Oberdörfer
Human-Computer Interaction
University of Würzburg
Würzburg, Germany
Email: sebastian.oberdoerfer@uni-wuerzburg.de

Marc Erich Latoschik
Human-Computer Interaction
University of Würzburg
Würzburg, Germany
Email: marc.latoschik@uni-wuerzburg.de

***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, 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.

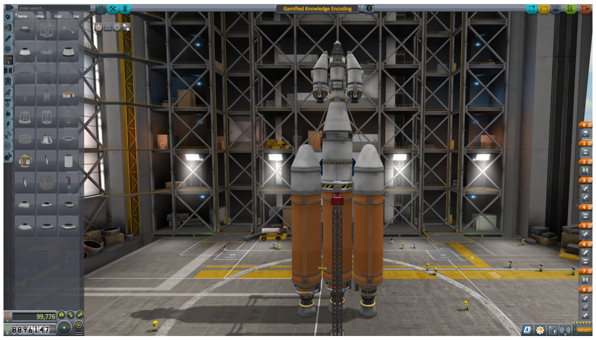


Fig. 1. Assembling a rocket in KSP: players can choose from a broad selection of various parts (left) and attach them to their spacecraft (center). KSP provides an interface to adjust a rocket's staging sequence (right).

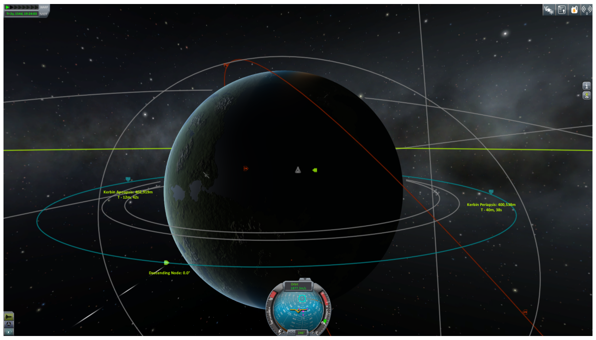


Fig. 2. The orbital map displays essential information about the trajectories of all flying spacecraft. This screen allows players to develop an understanding of an orbit's characteristics. Here, the apoapsis, periapsis, and inclination is shown.

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 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.


LV-909 "Terrier" Liquid Fuel Engine

Mass: 0.5 t
Crash Tolerance: 7.0 m/s
Max. Temp. Int/Skin: 2000/2000 K

Max. Thrust (ASL): 14.783 kN
Max. Thrust (Vac.): 60.0 kN

Engine
Max. Thrust (ASL): 14.783 kN
Max. Thrust (Vac.): 60.0 kN
Min. Thrust: 0.0 kN
Engine Isp: 85 (ASL) - 345 (Vac.)

Propellants:
- Liquid Fuel: 1.596/sec. Max.
- Oxidizer: 1.951/sec. Max.
Flameout under: 10%

Manufacturer:
Jebediah Kerman's Junkyard and Spacecraft Parts Co

Gimbal
Vectoring Range: 4.00°

The 909 model was initially received with some skepticism

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.

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

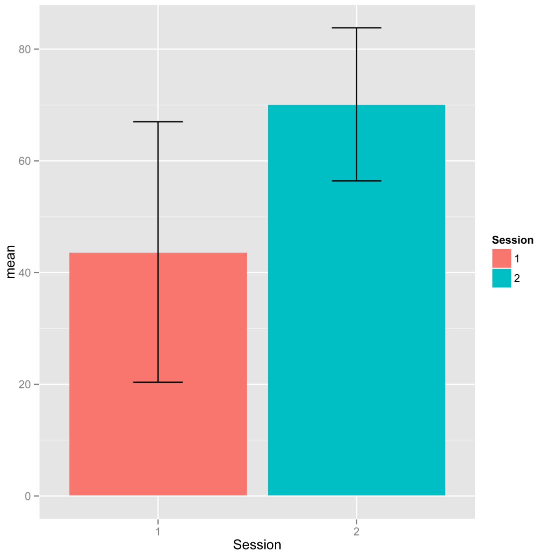


Fig. 4. Comparison of the mean results between pre-test and post-test spaceflight knowledge assessment results of the new KSP players ($N = 11$).

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.

REFERENCES

[1] E. Adams and J. Dormans, *Game Mechanics*, ser. Advanced Game Design. Berkeley: New Riders, 2012.

[2] M. Sicart, "Defining game mechanics," *Game Studies*, vol. 8, no. 2, 2008.

[3] S. de Castell, J. Jenson, and N. Taylor, "Educational games: Moving from theory to practice," in *Educational gameplay and simulation environments : case studies and lessons learned*, D. Kaufman and L. Sauvé, Eds. Hershey, PA: Information Science Reference, 2010, pp. 133–145.

[4] A. Gurr, "Video games and the challenge of engaging the 'net' generation," in *Educational gameplay and simulation environments : case studies and lessons learned*, D. Kaufman and L. Sauvé, Eds. Hershey, PA: Information Science Reference, 2010, pp. 119–131.

[5] J. P. Gee, *What video games have to teach us about learning and literacy*, 1st ed. New York: Palgrave Macmillan, 2007.

[6] B. Dalgarno and M. J. W. Lee, "What are the learning affordances of 3-d virtual environments?" *British Journal of Educational Technology*, vol. 41, no. 1, pp. 10–32, 2010.

[7] V. Kaptelinin and B. A. Nardi, "Affordances in hci: Toward a mediated action perspective," in *CHI 2012 Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems*. Austin, TX, USA: ACM, May 2012, pp. 967–976.

[8] J. Mestre, *Transfer of Learning: Issues and Research Agenda*. Washington, D.C.: National Science Foundation, 2002.

[9] C. J. Dede, "Immersive interfaces for engagement and learning," *Science*, vol. 323, 2009.

[10] L.-M. Palmunen, E. Pelto, A. Paalumäki, and T. Lainema, "Formation of novice business students' mental models through simulation gaming," *Simulation & Gaming*, vol. 44, no. 6, pp. 846–868, 2013.

[11] B. Weidenmann, "Multimedia, multicodierung und multimodalität beim online-lernen," in *Online Lernen. Handbuch für Wissenschaft und Praxis*, L. J. Issing and P. Klimsa, Eds. Oldenbourg, 2009, ch. 5, pp. 73–86.

[12] P. N. Johnson-Laird, *Mental Models. Towards a Cognitive Science of Language, Inference, and Consciousness*. Harvard University Press, 1983.

[13] G. Tulodziecki, B. Herzig, and S. Grafe, *Medienbildung in Schule und Unterricht*. Julius Klinkhardt, 2010.

[14] A. C. Oei and M. D. Patterson, "Enhancing Cognition with Video Games: A Multiple Game Training Study," *PLoS ONE*, vol. 8, no. 3, p. e58546, Feb. 2013.

[15] S. Arnab, T. Lim, M. B. Carvalho, F. Bellotti, S. de Freitas, S. Louchart, N. Suttie, R. Berta, and A. De Gloria, "Mapping learning and game mechanics for serious games analysis," *British Journal of Educational Technology*, vol. 46, no. 2, pp. 391–411, 2015.

[16] A. Moser, N. dos Santos, and L. F. Corcini, "Immersive 3d virtual and gamified environment: The learner model approach," *Journal of Research & Method in Education*, vol. 7, no. 3, pp. 26–35, 2017.

[17] S. Oberdörfer and M. E. Latoschik, "Gamified knowledge encoding: Knowledge training using game mechanics," in *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018)*, Würzburg, Germany, September 2018.

[18] Take-Two Interactive, "Kerbal space program," available at https://kerbalspaceprogram.com, 2011–2018.

[19] H. Curtis, *Orbital Mechanics for Engineering Students*, 3rd ed., ser. Elsevier aerospace engineering series. Butterworth-Heinemann, Oxford, 2013.

[20] K. A. Ericsson, R. T. Krampe, and C. Tesch-Römer, "The role of deliberate practice in the acquisition of expert performance," *Psychological Review*, vol. 100, no. 3, pp. 363–406, 1993.

[21] M. Csikszentmihalyi, *Flow: The Psychology of Optimal Experience*. New York, NY, USA: Harper-Perennial, 1990.

[22] J. McGonigal, *Reality is broken : why games make us better and how they can change the world*, 1st ed. New York: Penguin Press, 2011.

[23] D. Weibel and B. Wissmath, "Immersion in computer games: The role of spatial presence and flow," *International Journal of Computer Games Technology*, vol. 2011, 2011.

[24] S. Oberdörfer and M. E. Latoschik, "Develop your strengths by gaming," *Informatik 2013 - Proceedings of 43rd annual German conference on informatics*, vol. P-220, pp. 2346–2357, 2013.

[25] J. C. Rosser, Jr, P. J. Lynch, L. Cuddihy, D. A. Gentile, J. Klonsky, and R. Merrell, "The impact of video games on training surgeons in the 21st century," *Archives of Surgery*, vol. 142, no. 2, p. 181, 2007.

[26] P. Prax, "Leadership style in world of warcraft raid guilds," *Proceedings of DiGRA Nordic 2010*, 2010.

[27] R. Schroeder, *Being There Together : Social Interaction in Virtual Environments*, 1st ed. New York: Oxford University Press, 2011.

[28] L. Qiu, W. W. Tay, and J. Wu, "The impact of virtual teamwork on real-world collaboration," *ACE'09 Proceedings of the International Conference on Advances in Computer Enterntainment Technology*, pp. 44–51, 2009.

[29] S. Richter and U. Lechner, "Communication content relations to coordination and trust over time: a computer game perspective," *C&T'11 Proceedings of the 5th International Conference on Communities and Technologies*, pp. 60–68, 2011.

[30] B. Reeves, T. W. Malone, and T. O'Discoll, "Leadership's online labs," *Harvard Business Review*, vol. 86, no. 5, pp. 58–66, 2008.

[31] A. Siewiorek and A. Gegenfurtner, "Leading to win: the influence of leadership styles on team performance during a computer game training," *ICLS '10 Proceedings of the 9th International Conference of the Learning Sciences*, vol. 1, pp. 524–531, Aug. 2010.

[32] B. D. Glass, W. T. Maddox, and B. C. Love, "Real-Time Strategy Game Training: Emergence of a Cognitive Flexibility Trait," *PLoS ONE*, vol. 8, no. 8, pp. e70 350 EP –, 2013.

[33] C. S. Green and D. Bavelier, "Action-video-game experience alters the spatial resolution of vision," *Psychological Science*, vol. 18, no. 1, pp. 88–94, 2007.

[34] ——, "Action video game modifies visual selective attention," *Nature*, vol. 423, no. 6939, pp. 534–537, 2003.

[35] M. Power and L. Langlois, "Designing a simulator for teaching ethical decision-making," in *Educational gameplay and simulation environments : case studies and lessons learned*, D. Kaufman and L. Sauvé, Eds. Hershey, PA: Information Science Reference, 2010, pp. 146–158.

[36] M. Schulzke, "Moral decision making in fallout," *Game Studies*, vol. 9, no. 2, 2009.

[37] S. de Freitas and F. Liarokapis, "Serious games: A new paradigm for education?" in *Serious Games and Edutainment Applications*, M. Ma, A. Oikonomou, and L. C. Jain, Eds. London: Springer-Verlag, 2011, pp. 9–23.

[38] D. Charsky, "From edutainment to serious games: A change in the use of game characteristics," *Games and Culture*, vol. 5, no. 2, pp. 177–198, Mar. 2010.

[39] E. F. Anderson, L. McLoughlin, F. Liarokapis, C. Peters, P. Petridis, and S. de Freitas, "Serious Games in Cultural Heritage," in *The 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST*, Malta, 2009, pp. 29–48.

[40] R. P. Riegle and W. A. Matejka, "The learning guild: Mmorpgs as educational environments," *Proceedings of the 22nd Annual Conference on Distance Teaching and Learning*, 2006.

[41] A. S. Reber, "Implicit learning and tacit knowledge," *Journal of Experimental Psychology*, vol. 118, no. 3, pp. 219–235, 1989.

[42] M. Slater, "Implicit learning through embodiment in immersive virtual reality," in *Virtual, Augmented, and Mixed Realities in Education*, ser. Smart Computing and Intelligence, D. Liu, C. J. Dede, R. Huang, and J. Richards, Eds. Singapoore: Springer, 2017.

[43] L. Sauvé, "Effective educational games," in *Educational gameplay and simulation environments : case studies and lessons learned*, D. Kaufman and L. Sauvé, Eds. Hershey, PA: Information Science Reference, 2010, pp. 27–50.

7.4 Discussion

The studies presented in this section address the last RQ:

RQ4: How effective is knowledge learning using game mechanics?

Based on the results of the user studies, the knowledge learning using game mechanics as defined by the Gamified Knowledge Encoding is validated. The three learning effect studies confirmed *GEtiT*'s design by revealing a similar learning outcome to the traditional paper-based learning method. The learning outcome potentially might be even higher as the *GEtiT* conditions had to transfer their knowledge from the game context to a paper-based exam. While this confirmed the transfer-oriented learning of using game mechanics, it potentially has confounded the comparison of the yielded learning outcomes. Future research is needed to measure the learning outcome with a system that requires a learning transfer for all learning method conditions.

As *GEtiT* was developed in accordance to the Gamified Knowledge Encoding, the model's definition of a learning process using game mechanics is confirmed. This result is supported by the successful learning outcome prediction of playing *Kerbal Space Program*. In this study, the model was applied to identify relevant game mechanics as well as the orbital mechanics gamification metaphors that create learning affordances. As predicted, participants yielded a significant knowledge gain during the experiment. In conclusion, the Gamified Knowledge Encoding provides a guideline for effective serious game development and provides a working definition of knowledge learning using game mechanics.

8 A Look into the Future

Explorers delight in having the game expose its internal machinations to them. They try progressively esoteric actions in wild, out-of-the-way places, looking for interesting features (ie. bugs) and figuring out how things work. – Richard A. Bartle (1996)

The validation of the educational potential of game mechanics as defined by the Gamified Knowledge Encoding leads to the question what other effects can be achieved when using game mechanics in contexts that go beyond the normal entertainment purpose. In the case of serious games, game mechanics require the application of the learning content, demonstrate the underlying principles of the knowledge, and achieve a higher motivation to tackle learning assignments. These use cases, however, can also be utilized to motivate users to continue a problematic activity. In virtual gambling games, game mechanics create the core gameplay, i.e., they encode the knowledge rules of a specific gambling game, and evoke erroneous beliefs in players. The provided game mechanics are designed to mediate the rules in such a way that the underlying principles are hidden instead of being clearly demonstrated. For instance, a stop button has no influence on the final result of a game round, but suggests such an effect. Motivating game mechanics, e.g., the provision of experience points after each game round, are exploited to keep users playing and hence spending their money. This approach might be even more effective when other factors, such as the immersion, are increased. Thus, to create a comprehensive understanding of game mechanics and their use cases, it is also important to analyze other contexts of application.

8.1 The Dark Side of the Game Mechanics

As an outlook for future research, this thesis approaches the utilization of game mechanics for creating virtual gambling games. In particular, the effects of realizing a gambling game consisting of the exact same game mechanics but being presented in two degrees of immersion, i.e., a desktop-3D and an immersive VR version of a slot machine, are analyzed in respect to the overall risk potential.

Table 13: The Effects of Immersion on Harm-Inducing Factors in Virtual Slot Machines

Author	Contribution
Heidrich, D.	Literature review, conceptual design, experimental design, data analysis, discussion, manuscript preparation and revision
Oberdörfer, S.	Literature review, conceptual design, experimental design, data analysis, discussion, manuscript preparation and revision
Latoschik, M. E.	Manuscript revision

Heidrich, D., Oberdörfer, S., and Latoschik, M. E. The Effects of Immersion on Harm-Inducing Factors in Virtual Slot Machines. In *Proceedings of the 26th IEEE Virtual Reality conference (VR ’19)*, Osaka, Japan, March 2019. IEEE, ©2019 IEEE. Reprinted, with permission

The Effects of Immersion on Harm-inducing Factors in Virtual Slot Machines

David Heidrich
University of Würzburg

Sebastian Oberdörfer[*]
University of Würzburg

Marc Erich Latoschik[†]
University of Würzburg

Figure 1: The core element of the slot machine game is the grid displaying the drawn symbols. Payouts are emphasized with audiovisual effects, here, big win. Particularly large wins trigger a rain of gold coins.

ABSTRACT

Slot machines are one of the most played games by pathological gamblers. New technologies, e.g. immersive Virtual Reality (VR), offer more possibilities to exploit erroneous beliefs in the context of gambling. However, the risk potential of VR-based gambling has not been researched, yet. A higher immersion might increase harmful aspects, thus making VR realizations more dangerous. Measuring harm-inducing factors reveals the risk potential of virtual gambling. In a user study, we analyze a slot machine realized as a desktop 3D and as an immersive VR version. Both versions are compared in respect to effects on dissociation, urge to gamble, dark flow, and illusion of control. Our study shows significantly higher values of dissociation, dark flow, and urge to gamble in the VR version. Presence significantly correlates with all measured harm-inducing factors. We demonstrate that VR-based gambling has a higher risk potential. This creates the importance of regulating VR-based gambling.

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods; Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI; Human-centered computing—Interaction paradigms—Virtual Reality;

1 INTRODUCTION

Gambling disorder or pathological gambling dominates a patient's lifestyle and leads to a deterioration of social, professional, material as well as family values and commitments [72]. While millions of people suffer from this disorder [15], the gambling industry continues to use new and more attractive gambling methods, e.g., online-gambling and gambling in immersive Virtual Reality (VR) [29]. Using new technologies has the potential to increase the risk potential of gambling [3], e.g., the potential to evoke an addiction. By now, several immersive VR gambling games have been released. Targeting Head-Mounted Display VR, Gonzo's Quest VR [47] provides a virtual slot machine and PokerStars VR [39] allows multiple players to play poker in a social and visually exaggerated virtual environment (VE). However, the effects of VR-based gambling on the risk potential are *unclear* [26].

It was shown that immersive VR increases several harm-inducing factors, such as dissociation [1] and urge to gamble [50]. Higher harm-inducing factors potentially increase the risk potential of gambling. This suggests a higher dangerousness of gambling games when transferred from a desktop environment, i.e., online gambling, to an immersive VR version. However, current methods for assessing the risk potential are based on the analysis of game mechanics [14,53]. This neglects the effects caused by the visualization technology used.

Hence, based on the upcoming stream of new VR-based gambling products, it is critical to analyze their risk potential. Measuring harm-inducing factors allows for a direct comparison of gambling games in respect to this quality. This approach is in line with assessing the effectiveness of harm-minimization strategies intended to lower a game's risk potential [8, 18]. Working with this approach, the risk potential of gambling games providing the same game mechanics but being visualized with different technologies can be compared.

1.1 Contribution

We evaluate the *risk potential* of VR-based gambling by measuring the effects of immersive VR on harm-inducing factors, i.e., dissociation, dark flow, urge to gamble, and illusion of control. In a novel user study, two versions of a virtual slot machine (see Fig. 1), i.e., a desktop version and an immersive VR version, are compared in respect to these factors. The study's results show significantly higher values in dissociation, dark flow, and urge to gamble when playing the VR slot machine. Also, presence significantly correlates with all measured harm-inducing factors. Thus, our contribution is twofold:

---

[*] e-mail: sebastian.oberdoerfer@uni-wuerzburg.de
[†] e-mail: marc.latoschik@uni-wuerzburg.de

1) We show that immersive VR increases the risk potential of virtual slot machines. 2) We demonstrate that measuring harm-inducing factors allows for a comparison of gambling games in respect to their risk potential.

1.2 Structure

This paper begins with a review of the related work. Then, we present the system design of our slot machine. This is followed by the description of our user study including the experimental design, the measurements, and the procedure used. After that, we present and interpret the results and conclude the paper with indications for future work.

2 RELATED WORK

Both the *International Statistical Classification of Diseases and Related Health Problems* and the *Diagnostic and Statistical Manual of Mental Disorders* classified pathological gambling in their current editions as disorders due to substance use or addictive behavior [73] [4]. Thus, gambling addiction is on the *same* level as alcohol and cannabis addiction. Gambling addiction typically is measured using the Problem Gambling Severity Index [16]. This 9-item questionnaire measures the severity of a gambling addiction by considering a person's gambling behavior over the past year [22]. The problem gambling rates across different countries in the world are 0.12%-5.8% [15].

One can distinguish gambling in soft and hard gambling games [42]. Soft gambling games have a rather low risk potential. In most countries, one of the most played soft gambling games are lotteries [15]. Hard gambling games have a comparatively high risk potential. Slot machines are one of the most played games by pathological gamblers [15]. They demonstrate the highest risk potential [6, 15]. Also, they generate the highest revenue with only a fraction of the player base of lotteries [6]. Thus, we target *slot machines* to evaluate the effects of immersive VR on the risk potential of gambling.

2.1 Slot Machines

Slot machines exist for several technologies, such as video-based casino slot machines, desktop-based online slot machines [46] and VR-based slot machines [47]. They are classified as *Electronic Gambling Machines (EGMs)* which also include video poker and video lottery machines [66]. EGMs can provide many different game mechanics [2] that affect a game's risk potential. Game mechanics encode a game's underlying principles, thus structuring the overall gameplay [49]. For instance, *losses disguised as wins* audiovisually presents payouts that are smaller than the initial bet like a win. This increases the trial-by-trial enjoyment of non-win outcomes [59] and leads to the illusion of winning more frequently [27]. Overall, gambling related game mechanics target one particular goal: the evocation and/or exploitation of erroneous beliefs in respect to gambling [66].

There are, however, strategies to reduce the risk potential of gambling by adding constraints to the gameplay. Typically used *harm-minimization strategies* are breaks in play, warning messages, limit setting and behavioral tracking [31]. Harm-minimization strategies mostly target specific factors. For instance, breaks in play aim at preventing players from getting into a dissociative state and from building up urge to gamble [8]. To evaluate the effectiveness, the individually targeted harm-inducing factors are measured. These factors include the urge to gamble and the dissociation [8], the risk taken, the number of plays and the number of spins [24], the arousal, the excitement and the enjoyment [27] or whether participants adhere to their pre-set monetary limits [71]. Harm-minimization studies demonstrated the feasibility of comparing two versions of the same gambling game by evaluating specific harm-inducing factors. As a result, by analyzing a game in respect to multiple harm-inducing factors, an analysis as well as a comparison of the risk potential is possible.

2.2 Harm-inducing Factors

One of the current assessment methods of a game's risk potential is the *AsTERiG* tool [53]. It determines the risk potential by analyzing the realization of specific game mechanics, e.g., the event frequency as well as the size of the jackpot, and the availability of the game. However, studies indicate an influence of a higher immersion on a player's gambling experience [1, 23, 41]. Hence, AsTERiG might be useful to determine the risk potential of traditional gambling games, but does not allow for a comparison between different technologies.

In contrast, the *VICES* framework compares gambling games in respect to their general characteristics, e.g., visual and auditory enhancements, illusions of control, and cognitive complexity [3]. Thus, VICES determines the effects and the changes in gambling behavior caused by a transfer process between technologies. While this allows for a comparison of traditional gambling games to their digital counterparts, it provides no insights about the risk potential of an EGM. This is especially critical as the development of VR gambling games can result in new forms of gambling that have not existed before.

Thus, it is necessary to find a different method for analyzing the risk potential of gambling games. We present a collection of different measurable factors capable of causing harm in the context of EGMs. These factors are not dependent on specific game mechanics and can therefore be applied to any EGM. Measuring these factors provides insights into the harm-inducing properties. This approach is in line with the effectiveness measurements of harm-minimization strategies [8, 18]. We identified the following harm-inducing factors as relevant as they are not a game mechanic and they demonstrated to increase the risk potential:

Dissociation describes a state of changed identity [33], colloquially called the *zone* [58]. Pathological players often report various types of dissociative states either during or shortly after their participation in a gambling activity [34]. Characteristics of dissociation include losing track of time, feeling like being someone else, blacking out, not recalling own actions or being in a trance-like state [30]. The player hides problems and loses track of the lost money while gambling. This makes dissociation the most harmful factor [34].

Urge to gamble is the desire, craving and motivation to gamble again. It is a key factor involved in the development, maintenance and relapse of gambling disorder [74]. Urge to gamble is often a symptom of gambling addiction [51]. A desire to gamble also occurs when being interrupted while gambling [65]. For instance, Candy Crush implements a forced break after a defeat. This causes a craving resulting in some players spending money to skip the forced break [8]. An increased urge to gamble value in non-pathological gamblers could indicate a high chance to gamble again.

Dark flow has its origins in sports describing a possible cause for exercise addiction [52]. Flow is the complete absorption of a person into the performance of an activity [19]. Dark flow describes the dependency on the experience of flow by repeating a specific activity, e.g., running or surfing [52]. This phenomenon also is observable in gambling. Gamblers with a higher Problem Gambling Severity Index showed more dark flow on a slot machine [21].

Illusion of control is one of the main fallacies involved in the maintenance of gambling behavior [3]. There are multiple factors creating an illusion of control, like active or passive involvement, choice, familiarity and competition [37]. It leads to the experience of a **sense of personal competence** and **perception of skill**. This experience results in higher bets when being allowed to throw the ball in roulette [35] or the dice in dice games [37]. Despite having no influence on the final outcome, slot machine game mechanics, such as stop buttons, can evoke illusion of control [20].

2.3 Immersive VR

Immersion is achieved with objective system properties reducing sensory inputs from the real world and replacing them with digital information [63], e.g., by wearing a head mounted display. *Presence*, telepresence, or place illusion is the subjective sensation of being in a real place, i.e., the VE, despite physically being located in a different environment [60]. The experience of this quality depends on the degree of the immersion [61,69]. For presence to occur, it is important to support sensorimotor contingencies, e.g., allowing users to move their heads or to walk [60]. For maintaining presence, a continuous stream of stimuli and experience is required [70]. Presence distinguishes from *plausibility illusion* describing the subjective illusion of perceiving events taking place in a VE as real events [60]. Achieving a high degree of presence can be a central goal, e.g., for VR storytelling [57]. Presence increases, amongst other things, a user's intrinsic motivation for knowledge learning [40] and overall performance in a training scenario [64]. It was shown that presence positively correlates with dissociation in a non-gambling context [44]. This makes it necessary to also investigate the relationship between presence and the identified harm-inducing factors in a gambling context. Aiming at other VR specific factors can positively increase presence. For instance, a VR application can provide an avatar as a proxy for a user's body [32] leading to the illusion of virtual body ownership [62]. This illusion increases presence [69]. Hence, by only changing the degree of the immersion without adding other VR specific factors to it, measuring presence can confirm the desired difference.

Immersive VR is successfully being used in therapy of gambling disorder [9,51]. It provides emotionally charged contexts to patients in the safety of the therapist's office [10]. During therapy sessions, VR induced a strong urge to gamble which is comparable to physical EGM terminals commonly found in casinos [10]. This contributes to the overall indication that immersive VR potentially increases the overall attractiveness as well as the risk potential of gambling.

The analysis of previous work revealed that immersive VR increases harm-inducing factors. Measuring specific harm-inducing factors allows for a comparison of two games in the case of harm-minimization strategy effectiveness measurements. This also suggests that measuring the identified factors in Sect. 2.2 provides a means to compare gambling games. Hence, this approach should provide insights into the risk potential of VR-based games.

3 SLOT MACHINE SYSTEM

To validate our assumptions, we compare two versions of a slot machine: desktop 3D (see Fig. 2 top) and immersive VR (see Fig. 2 bottom). Slot machines only require two core interaction possibilities. These interactions are to determine the size of the bet and to start a game round. These two interactions can easily be realized in both versions of the game without confounding the results, e.g., by mapping them to the same buttons on a controller used for both versions.

Both applications utilize (1) the same user interface (UI) elements, both in size and position, (2) the same input methods, (3) the same sound effects and (4) the same game mechanics.

3.1 Core Gameplay

A slot machine game round typically involves (1) selection of a bet level, i.e., the amount of coins, (2) start of the round, (3) draw of a random selection of available symbols, and (4) payout of a potential win. The bet level is limited to a certain maximum thus prohibiting all-in bets.

A slot machine provides multiple symbols displayed in a grid. Each symbol has a different value and chance of appearance in a game round. After starting a game round, the slot machine draws a random selection of symbols. A win depends on the order of the symbols in specific lines. A line corresponds to a pre-defined sequence of specific fields on the grid (see Fig. 3). In our slot machine, we use 8 different symbols and 10 lines. At least one line must contain three identical symbols (starting from the left) for a win to occur. The symbol's value in combination with the number of matching symbols in a line determines the size of the win per line. The overall win is the sum of the wins across all lines multiplied by the player's bet level and a multiplier. If a win occurred, the involved symbols are replaced by randomly drawn symbols and the multiplier is increased. Then, the game checks again the lines for potential wins. When no (further) wins are detected, a game round ends, and all intermediate wins are summed up to the final payout (see Fig. 4 and Fig. 5).

Figure 2: Our slot machine user interface realized for desktop (top) and VR (bottom). Both use the same UI elements.

In particular, the combination of the symbol's value and chance of appearance results in the *return to player* value. This value indicates the percentage to which the overall bets are returned as wins. While video-based casino slot machines typically have a return to player of 70 - 90% [28], online slot machines provide a return to player up to 99% [7]. Another important feature is the *hit frequency*. Hit frequency is the rate of how often a game round results in a win independent of the win size. In contrast, the *real hit frequency* indicates how often the player receives a payout larger than the bet

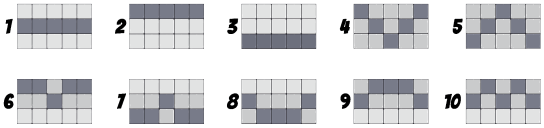


Figure 3: Our slot machine provides 10 different lines. A line is a specific sequence of fields on the grid. For a win to occur a line must contain at least three identical symbols.

Figure 4: A player can select the size of the bet and start a game round (left). Then, the slot machine draws symbols and displays wins (middle). Finally, the slot machine displays the final win (right).

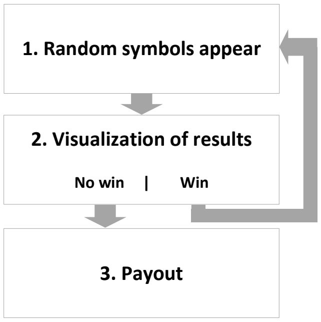


Figure 5: Random symbols are drawn at the start of a round (1). Then, the game checks all lines for wins. In case of a win, they are visualized (2) and new symbols are drawn. If no (further) wins are detected, the final payout is displayed (3).

made. To align with state-of-the-art online slot machines, our slot machine has a return to player value of 97%, a hit frequency of 66%, and a real hit frequency of 33%.

For visualizing the gameplay, we chose an underwater scenario. For symbols, we use aquatic animals that are displayed on stone cubes. Symbols removed after detecting a win dissolve into bubbles. New symbols fall down from above.

3.2 Game Mechanics and Properties

To achieve a better comparability to commercial virtual slot machines, we implemented further game mechanics. Since the primary goal of our research is to identify risks of a higher immersion on gambling, we limited our selection of game mechanics to the ones that already exist. Naturally, more entertaining and possibly more harm-inducing game mechanics would be possible in VR. However, we do not want to provide any considerations or recommendations for effective gambling design. Thus, we selected the following commonly found game mechanics:

Losses disguised as wins: Losses, i.e. payouts that are smaller than the bet, are presented the same way as a win, i.e. payouts that are bigger than the bet.

Near wins: If there is a chance of a full line, the game slows down to create excitement independent of the final outcome.

Level system: With each game round, the player receives experience points depending on the size of the bet. A higher bet results in a greater amount of experience points. When the player reaches a new level, they receive a reward in form of coins.

Money rain: If the player receives a very large payout, i.e., three times the size of the bet, coins start to rain for 3 seconds (see Fig. 1).

Music: Background music is a relaxing underwater ambient music during the regular gameplay. When the multiplier rises, a fast and exciting music begins to play. Each event triggers a different sound effect.

3.3 Technology

The two slot machine versions were developed with Unity 2018.1.1f [67] using the SteamVR plugin in the version 1.2.2 [68]. For the VE, we used the 3D asset *Aquarium* [55]. For symbols, we used the 2D icon pack *Sealife* [25].

Both versions implement the HTC Vive controller as input device. Pressing the touchpad on the left or the right side adjusts the bet. Pulling the trigger button starts a game round. The controller is only displayed inside the VE in the VR version using its 3D asset. This decision was made to provide players of the VR version with the position of the input device. This is not necessary for desktop 3D.

The static interface elements used to display relevant information, i.e., coins, win and experience, have a slightly bigger text size in the VR version to ensure readability (see Fig. 2). All other UI elements, e.g., bet, bet-level and payout animations, do not differ between the two versions.

Aside from the technology itself, the other main difference is the output device used. The desktop 3D version is played on a regular computer screen. The VR version is played using the HTC Vive Pro.

4 STUDY

Due to the indications discussed in Sect. 2, we assume the following hypotheses (H):

H1: The immersive VR version of our slot machine causes more dissociation than its desktop 3D counterpart.

H2: The immersive VR version of our slot machine causes more urge to gamble than its desktop 3D counterpart.

H3: The immersive VR version of our slot machine causes more dark flow than its desktop 3D counterpart.

H4: The immersive VR version of our slot machine causes more illusion of control than its desktop 3D counterpart.

To answer our hypotheses and to compare the two slot machine versions in respect to the identified harm-inducing factors, we conducted a within-subjects experiment. All participants played both versions, i.e., the *VR* condition and the *desktop* condition, in counterbalanced order.

Players begin each condition with a total amount of 2500 coins. The lowest possible bet is 20 coins and highest possible bet is 1000 coins. A player can modify the bet size in steps of 100 coins and reaches a new level after betting 1500 coins. The reward for a new level is 300 coins.

To achieve comparability between the two game versions, we implemented a seed for each playing session (see Table 1). The first session is played with the first seed and the second session with the second seed. Both seeds have the same hit frequency (HF), real hit frequency (RHF), a nearly similar return to player (RTP) value and include one money rain. This ensures a similar game experience for every participant.

Table 1: Overview of the seeds used.

Round	RTP Session 1	RTP Session 2
1	0.15	2.65
2	0	0
3	1	2.9
4	6.6	1
5	0	3.95
6	0.15	0.7
7	0	0
8	0.15	0
9	0	0.15
10	2.65	0
11	0	0.2
12	1.25	0
13	0	1.55
14	1.25	0
15	1.5	1.3
RTP	0.98	0.96
HF	0.66	0.66
RHF	0.33	0.33

4.1 Task

To create an initial incentive for the participants to play the game, we gave them the task to maximize their virtual money. They were not told the number of game rounds per playing session. Each session ended after 15 game rounds.

4.2 Apparatus

The experimental setup (see Fig. 6) consisted of a desk, a computer (CPU: Intel Xeon E31230v5@3.40GHz, RAM: 16GB, GPU: NVIDIA GeForce GTX 980 Ti), two screens (resolution: 1920x1080), a mouse and a keyboard. Both versions of the slot machine were played on the same computer using the same HTC Vive controller. Participants sat on a chair during the two playing sessions. The gameplay of the VR version was rendered to an HTC Vive Pro (2160x1200 resolution per eye). Inside the VE, symbols had a size of 1m x 1m and the player was positioned 7m away from the grid. The gameplay of the desktop version was displayed on a 24” screen. In this way, the apparent size of the symbols and the UI was similar for both versions.

4.3 Measures

Participants filled in questionnaires before the experiment and after each experimental condition. We used the questionnaires in their original language along with a translated version matching the common language of the study’s location. The demography questionnaire and the orally communicated single-item questions were only presented in the common language of the study’s location. Questionnaires were selected in alignment with our theoretical considerations of harm-inducing factors as risk indicators in Sect. 2.2. Here, we target all identified harm-inducing factors.

4.3.1 Demographics

We asked for demographic information, i.e., age, gender, gaming experience, VR experience, attitude towards gambling and slot machine knowledge. As a control variable, the study included the Immersive Tendency Questionnaire (ITQ) [70].

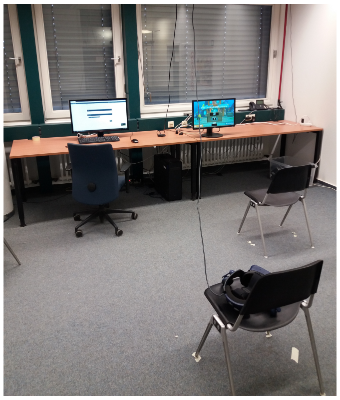


Figure 6: Study room setup: the left screen presents the questionnaires, the right screen displays the gameplay of the desktop version. While playing the desktop version, the participant sits on the rightmost chair. For playing the VR version, the player sits on the foremost chair.

4.3.2 Presence

The Mid Immersion Presence Questionnaire (MIPQ) is a single-item questionnaire assessing a person’s current presence [11, 12]. The MIPQ consists of the orally presented question ”How far do you feel present in the virtual environment at this moment?”. Rating is done on a scale from 0 to 10. Higher scores indicate higher presence. The MIPQ was assessed after the eighth game round in session 1 and after the ninth game round in session 2 (see Table 1). This decision was made as we thus assessed the presence in the fourth game round after a big win, i.e., a money rain event.

4.3.3 Dissociation

The Clinician Administered Dissociative States Scale (CADSS) is a 23-item questionnaire measuring the current dissociation [13]. The items are answered on a 5-point Likert scale ranging from 0 to 4 (4 = highest degree of dissociation). The questions refer to the current state of the participant as assessed after the stimulus.

4.3.4 Urge to gamble

The Gambling Urge Scale (GUS) is a 6-item questionnaire measuring the current urge to gamble [54]. Participants rate statements about their current urge to gamble on a 7-point Likert scale ranging from 1 to 7 (7 = strong urge to gamble).

Also, we assessed a participant’s motivation to play our type of gambling game again using a single-item questionnaire [36]: “To what extent would you be motivated to go elsewhere to play the same game, either today or another day?” The questionnaire uses a 10-point Likert scale ranging from 0 to 9 (9 = high motivation).

4.3.5 Game Experience

The Game Experience Questionnaire (GEQ) is a 42-item questionnaire with the subscales immersion, flow, competence, tension, challenge, positive affect and negative affect [45]. We used the GEQ to measure *dark flow* using the subscales of flow and positive affect [21]. The competence subscale provided insights into the illusion of control. The GEQ uses a 5-point Likert scale ranging from 1 to 5, higher scores indicate a higher experience.

4.4 Procedure

Each experimental session lasted about 45 minutes and consisted of the following stages:

(1.) Welcome: Each participant receives a short introduction to the experiment as well as to the health and safety rules and signs a consent form.

(2.) Pre-Questionnaire: The participant fills in the demographics questionnaire and the ITQ.

(3.) Introduction: The participant receives an explanation of the game and the respective game controls.

(4.) Playing Session 1: The participant plays the slot machine for 15 game rounds. After the 8th game round, we assessed the MIPQ.

(5.) Post-Questionnaire: The participant completes the CADSS, the GEQ, the current motivation to play again, and the GUS.

(6.) Playing Session 2: The participant plays the slot machine for 15 game rounds. After the 9th game round, we assessed the MIPQ.

(7.) Post-Questionnaire: The participant completes the CADSS, the GEQ, the current motivation to play again, and the GUS.

(8.) End: The participant receives information about the dangers of real gambling games and watches a short information video about gambling addiction.

Studies demonstrated that players gamble less risky when they are observed by others [43,56]. The presence of the experimenter could cause a confounding effect. For safety reasons, the experimenter could not leave the room entirely. Thus, to limit this influence, we told each participant that the experimenter would work during the playing sessions. The experimenter then sat at a table which was positioned at the opposite side of the room (about 4 meters behind the participant) facing towards a wall.

4.5 Ethics

An ethics proposal was submitted for this study and was approved by the institutional review board of Human-Computer-Media at the University of Würzburg. To limit the risk of playing a gambling game during this study, we implemented the following measures: (1) The participants had to be of age 18 and older. (2) They showed a score of 0 on the Problem Gambling Severity Index before the study. (3) No real money was used in this study. (4) We informed the participants about the risks of gambling after the study. The participants had to watch a short information video about gambling addiction. We also provided further educational material.

4.6 Participants

In total, 48 participants (34 females, 14 males) were recruited from the undergraduate students who were enrolled at the University of Würzburg using an online participant recruitment system that rewards students with credits mandatory for obtaining their bachelor's degrees. The participants had a mean age of 20.92 years ($SD = 2.23$) and reported a score of 0 on the Problem Gambling Severity Index. None of them had severe visual impairments. 26 participants used an HTC Vive or Oculus Rift ($M = 5.14$ hours, $SD = 7.40$) before and 26 participants reported a previous computer game experience with a mean weekly playtime of 6.27 hours ($SD = 7.41$). The participants' mean slot machine knowledge was 1.22 (1 = no knowledge, 5 = expert knowledge, $SD = 0.47$) and mean attitude towards gambling was -0.23 (-2 = very negative, 2 = very positive, $SD = 0.67$) based on self-report. Their mean ITQ score was 4.29 ($SD = 0.62$).

5 RESULTS

To compare the two conditions, we calculated paired-samples t-tests [48]. For determining the effect size, we calculated Cohen's d. We used rmcorr to check for a correlation between factors at the intra-individual level [5]. Fig. 7 provides a graphical comparison of our measurements.

5.1 Presence

Presence was significantly higher ($t(47) = 14.79$, $p < 0.01$) in the VR condition ($M = 5.90$, $SD = 2.07$) compared to the desktop condition ($M = 3.04$, $SD = 1.85$) with a very large effect size ($d = 1.46$). All harm-inducing factors and presence were positively correlated (see Table 2).

Table 2: Overview of correlations between presence and the measured harm-inducing factors.

Harm-inducing Factor	$r_m(47)$	p	95% CI
Dissociation	0.57	< 0.01	$[0.34, 0.74]$
Urge to gamble	0.35	0.01	$[0.07, 0.58]$
Motivation	0.56	< 0.01	$[0.33, 0.73]$
Dark Flow	0.77	< 0.01	$[0.61, 0.86]$
Competence	0.30	0.03	$[0.02, 0.54]$

5.2 Dissociation

Dissociation was significantly higher ($t(47) = 6.27$, $p < 0.01$) in the VR condition ($M = 0.48$, $SD = 0.39$) compared to the desktop condition ($M = 0.17$, $SD = 0.17$) with a large effect size ($d = 1.10$).

5.3 Urge to gamble

The urge to gamble was significantly higher ($t(47) = 1.89$, $p = 0.03$) in the VR condition ($M = 1.37$, $SD = 0.72$) compared to the desktop condition ($M = 1.20$, $SD = 0.45$) with a small effect size ($d = 0.29$).

The motivation to play the game again was significantly higher ($t(47) = 4.97$, $p < 0.01$) in the VR condition ($M = 4.54$, $SD = 2.83$) compared to the desktop condition ($M = 3.06$, $SD = 2.35$) with a medium effect size ($d = 0.57$).

5.4 Dark Flow

The dark flow was significantly higher ($t(47) = 7.23$, $p < 0.01$) in the VR condition ($M = 2.96$, $SD = 0.82$) compared to the desktop condition ($M = 2.35$, $SD = 0.63$) with a large effect size ($d = 0.85$).

5.5 Illusion of Control

The competence subscale of the GEQ was not significantly different ($t(47) = 1.34$, $p = 0.09$) in the VR condition ($M = 2.46$, $SD = 0.81$) compared to the desktop condition ($M = 2.32$, $SD = 0.74$).

6 DISCUSSION

The study was designed to compare two versions of a virtual slot machine in respect to identified harm-inducing factors. Both versions differed in the technology used, i.e., desktop 3D and immersive VR, but implemented the same game mechanics and provided the same information. In this way, we investigated the influence of immersive VR on identified harm-inducing factors and thus the risk potential of VR-based gambling.

Compared to other current approaches, e.g., AsTERiG [53], our approach is independent of the game mechanics used. AsTERiG would have determined the same risk potential for both tested versions. In contrast, our approach of measuring the identified harm-inducing factors revealed differences between the two versions. This provides a first indication that measuring the identified harm-inducing factors allows for a comparison of EGMs in respect to their risk potentials. However, future research is needed to validate this approach.

6.1 Effects of Immersive VR on Harm-Inducing Factors

As intended, the full visual immersion of the VR slot machine resulted in a significantly higher presence in comparison to the desktop version. The results of our study show a significant correlation between presence and all tested harm-inducing factors. The factors

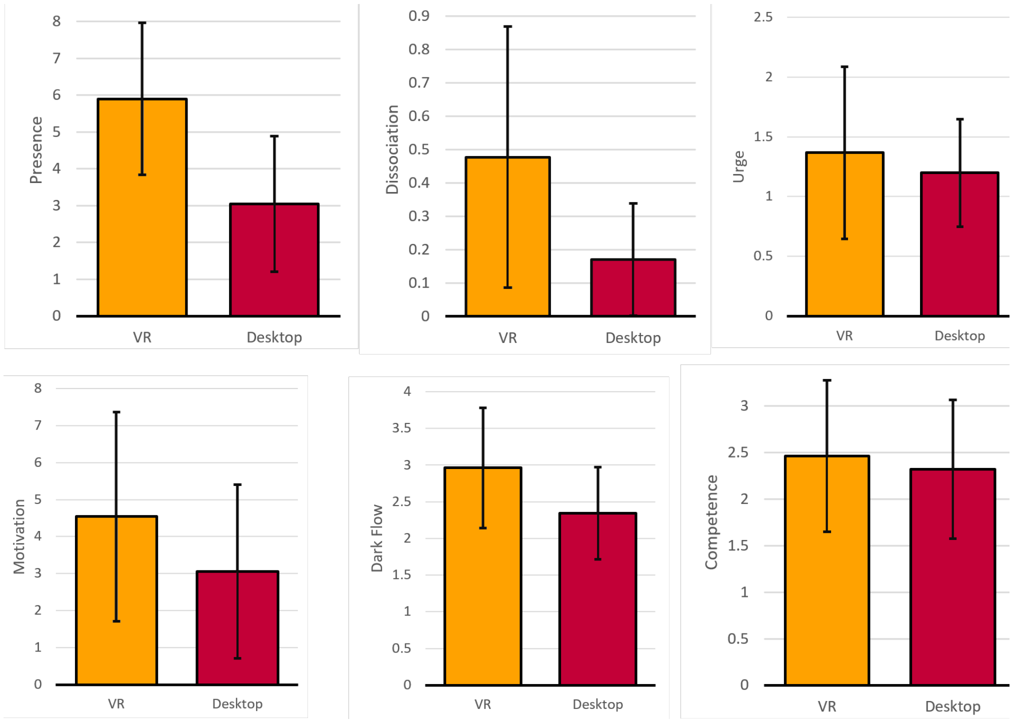


Figure 7: Comparison of the harm-inducing factor measurements between the two versions of our slot machine. Error bars indicate standard deviations.

dissociation, urge to gamble, motivation and illusion of control show a weak to moderate linear correlation. Dark flow has a clear linear relationship.

We found significantly higher values in dissociation, urge to gamble, dark flow and motivation. The competence subscale of the GEQ and hence the illusion of control did not differ significantly between the two conditions. This is explainable by the lack of a game mechanic potentially evoking an illusion of control. For instance, the implementation of a stop button has demonstrated to cause this effect in the context of gambling [20].

H1 **More Dissociation:** The results of our user study show a significant difference between the two conditions in respect to dissociation. We found a significant correlation between presence and dissociation. Thus, H1 is *supported*.

H2 **More Urge to Gamble:** Our study shows a significantly higher urge to gamble and motivation to gamble again in the VR condition. We found significant correlations between presence and the two factors. Thus, H2 is *supported*.

H3 **More Dark Flow:** The results show a significant difference in dark flow between the two conditions. We found a significant correlation between presence and dark flow. Thus, H3 is *supported*.

H4 **More Illusion of Control:** The results revealed no significant difference between the two conditions in respect to the competence subscale. However, we found a significant correlation between presence and the competence subscale. Thus, we cannot confirm H4 and need to *reject* it.

Our ethical considerations might have resulted in a confounding effect. Winning money is the main motivation when playing gambling games [6]. By not winning or losing real money, a player's engagement could have been compromised. However, gambling games often try to achieve a *suspension of judgement* by using virtual currencies [28]. This breaks the connection between real money and virtual money and makes the players place higher bets despite still playing with real money [38]. Thus, although no real money was used, the present study's results are of high relevance, especially for online gambling.

As dissociation is the most dangerous factor [34], our results are critical for assessing the general risk potential of VR-based gambling. High values in harm-inducing factors indicate a high risk potential. Here, we found higher harm-inducing factor values when playing the VR slot machine. Thus, we provide first insights of immersive VR *increasing* the *risk potential* of slot machines. We only used healthy individuals. Considering this, the present study indicates the dangerousness of VR-based gambling, especially for new players. As our participants represent the target group of immersive VR gambling games [29], our results are of *high relevance*.

6.2 Recommendations

Therefore, we recommend to regulate and to control the development of VR-based EGMs. One potential approach would be to require the implementation of harm-minimization strategies aiming at the tested harm-inducing factors [8, 31]. In respect to VR-based gambling, even new harm-minimization strategies might be possible [26]. However, harm-minimization strategies have not yet been tested in immersive VR. This raises the need to analyze the effectiveness of these strategies in an immersive VR gambling scenario.

However, we merely analyzed two versions of a slot machine.

Other types of EGMs or an aspect of social gambling might result in different effects on harm-inducing factors. Thus, it is critical to conduct further research to analyze a wider range of EGMs. Also, an analysis of other factors, e.g., the provision of an illusion of virtual body ownership or social presence, is of high importance. It would not only provide further insights into the risk potential of VR-based gambling, but also reveal potential dangers of games like PokerStars VR [39] that already provide embodied social virtual gambling.

While gambling in VR indicates to have a higher risk potential, the outcomes of the present study are of high importance for gambling addiction therapy [9]. Evoking higher harm-inducing factors could be beneficial for treatment methods of cue exposure therapy [17]. Cue exposure therapy aims at a desensitization of patients by an over-saturation. By providing an immersive VR gambling treatment, the therapy could create stronger stimuli and hence be more effective.

7 CONCLUSION

This paper analyzes the effects of immersive VR on the risk potential of gambling. In this paper, we present two different versions of a virtual slot machine: a desktop 3D version and an immersive VR version. Both versions are identical in their game design. For evaluating the games' risk potential, we identify relevant harm-inducing factors as an assessment tool. In particular, we compare the two versions in respect to dissociation, urge to gamble, dark flow, and illusion of control. Overall, higher values in these factors indicate a higher risk potential.

In a novel user study, we measured significantly higher values of dissociation, dark flow, and urge to gamble when playing the VR slot machine. The illusion of control, however, did not differ between the two versions. The study revealed a significant correlation between presence and all assessed harm-inducing factors. Thus, our contribution is twofold: 1) We show that immersive VR increases the risk potential of virtual slot machines. 2) We demonstrate that measuring harm-inducing factors allows for a comparison of EGMs in respect to their risk potential.

Future research is needed to analyze further VR-based EGMs as well as to compare them to their physical counterparts in respect to the risk potential. Also, evaluating effects of other factors, such as the illusion of virtual body ownership and social gambling, presents an important research goal. Another research direction is the analysis of harm-minimization strategies for VR-based gambling. Finally, it is necessary to validate our approach of measuring the risk potential by analyzing harm-inducing factors.

REFERENCES

[1] F. Aardema, K. O'Connor, S. Côté, and A. Taillon. Virtual reality induces dissociation and lowers sense of presence in objective reality. *Cyberpsychology, Behavior, and Social Networking*, 13(4):429–435, 2010.

[2] E. Adams and J. Dormans. *Game Mechanics*. Advanced Game Design. New Riders, Berkeley, 2012.

[3] T. Armstrong, M. Rockloff, N. Greer, and P. Donaldson. Rise of the machines: A critical review on the behavioural effects of automating traditional gambling games. *Journal of gambling studies*, 33(3):735–767, 2017.

[4] A. Association. *Diagnostic and Statistical Manual of Mental Disorders (DSM-5®)*. American Psychiatric Publishing, 2013.

[5] J. Z. Bakdash and L. R. Marusich. Repeated measures correlation. *Frontiers in psychology*, 8:456, 2017.

[6] M. Banz and P. Lang. Glücksspielverhalten und glücksspielsucht in deutschland. ergebnisse des surveys 2017 und trends. bzga-forschungsbericht. *Bundeszentrale für gesundheitliche Aufklärung. doi: 10.17623/BZGA:225-GS-SY17-1.0*, 2017.

[7] Barcrest. Monopoly Big Event. `https://www.vegasslotsonline.com/barcrest/monopoly-big-event/`, 2015. Last accessed 2018-11-15.

[8] A. Blaszczynski, E. Cowley, C. Anthony, and K. Hinsley. Breaks in play: Do they achieve intended aims? *Journal of gambling studies*, 32(2):789–800, 2016.

[9] S. Bouchard, C. Loranger, I. Giroux, C. Jacques, and G. Robillard. Using virtual reality to provide a naturalistic setting for the treatment of pathological gambling. In *The Thousand Faces of Virtual Reality*. InTech, 2014.

[10] S. Bouchard, G. Robillard, I. Giroux, C. Jacques, C. Loranger, M. St-Pierre, M. Chrétien, and A. Goulet. Using virtual reality in the treatment of gambling disorder: The development of a new tool for cognitive behavior therapy. *Frontiers in psychiatry*, 8:27, 2017.

[11] S. Bouchard, G. Robillard, J. St-Jacques, S. Dumoulin, M.-J. Patry, and P. Renaud. Reliability and validity of a single-item measure of presence in vr. In *Haptic, Audio and Visual Environments and Their Applications, 2004. HAVE 2004. Proceedings. The 3rd IEEE International Workshop on*, pp. 59–61. IEEE, 2004.

[12] S. Bouchard, J. St-Jacques, G. Robillard, and P. Renaud. Anxiety increases the feeling of presence in virtual reality. *Presence*, 17(4):376–391, 2008.

[13] J. D. Bremner, J. H. Krystal, F. W. Putnam, S. M. Southwick, C. Marmar, D. S. Charney, and C. M. Mazure. Measurement of dissociative states with the clinician-administered dissociative states scale (cadss). *Journal of Traumatic Stress: Official Publication of The International Society for Traumatic Stress Studies*, 11(1):125–136, 1998.

[14] Bundeszentrale für gesundheitliche Aufklärung (BZgA). Total verzock?! infos zur glücksspielsucht für jugendliche und junge erwachsene. Bundeszentrale für gesundheitliche Aufklärung (BZgA), Köln, Apr. 2009.

[15] F. Calado and M. D. Griffiths. Problem gambling worldwide: An update and systematic review of empirical research (2000–2015). *Journal of Behavioral Addictions*, 5(4):592–613, 2016.

[16] K. Caler, J. R. V. Garcia, and L. Nower. Assessing problem gambling: a review of classic and specialized measures. *Current Addiction Reports*, 3(4):437–444, 2016.

[17] B. L. Carter and S. T. Tiffany. Meta-analysis of cue-reactivity in addiction research. *Addiction*, 94(3):327–340, 1999.

[18] M. Cloutier, R. Ladouceur, and S. Sévigny. Responsible gambling tools: Pop-up messages and pauses on video lottery terminals. *The Journal of Psychology*, 140(5):434–438, 2006.

[19] M. Csikszentmihalyi and I. Csikszentmihalyi. *Beyond boredom and anxiety*, vol. 721. Jossey-Bass San Francisco, 1975.

[20] M. J. Dixon, C. J. Larche, M. Stange, C. Graydon, and J. A. Fugelsang. Near-misses and stop buttons in slot machine play: An investigation of how they affect players, and may foster erroneous cognitions. *Journal of Gambling Studies*, 34:161–180, 2018. doi: 10.1007/s10899-017-9699-x

[21] M. J. Dixon, M. Stange, C. J. Larche, C. Graydon, J. A. Fugelsang, and K. A. Harrigan. Dark flow, depression and multiline slot machine play. *Journal of gambling studies*, 34(1):73–84, 2018.

[22] J. A. Ferris and H. J. Wynne. *The Canadian problem gambling index*. Canadian Centre on Substance Abuse Ottawa, ON, 2001.

[23] K. Finlay-Gough, H. Marmurek, V. Kanetkar, and J. Londerville. The influence of casino architecture and structure on problem gambling behaviour: An examination using virtual reality technology. In *European Conference on Research Methodology for Business and Management Studies*, p. 187. Academic Conferences International Limited, 2015.

[24] K. Floyd, J. P. Whelan, and A. W. Meyers. Use of warning messages to modify gambling beliefs and behavior in a laboratory investigation. *Psychology of Addictive Behaviors*, 20(1):69, 2006.

[25] Freepik. Sealife. `https://www.flaticon.com/packs/sealife-3`, 2017. Last accessed 2018-11-15.

[26] S. M. Gainsbury and A. Blaszczynski. Virtual reality gambling: Public policy implications for regulation and challenges for consumer protection. *Gaming Law Review*, 21(4):314–322, 2017.

[27] C. Graydon, M. J. Dixon, K. A. Harrigan, J. A. Fugelsang, and M. Jarick. Losses disguised as wins in multiline slots: using an educational animation to reduce erroneous win overestimates. *International Gambling Studies*, 17(3):442–458, 2017.

[28] M. Griffiths. Fruit machine gambling: The importance of structural characteristics. *Journal of gambling studies*, 9(2):101–120, 1993.

[29] M. Griffiths. The psychosocial impact of gambling in virtual reality. *Casino & Gaming International*, (29):51–54, 2017.

[30] M. Griffiths, R. Wood, J. Parke, and A. Parke. Dissociative states in problem gambling. *Current issues related to dissociation*, pp. 27–37, 2006.

[31] A. Harris and M. D. Griffiths. A critical review of the harm-minimisation tools available for electronic gambling. *Journal of gambling studies*, 33(1):187–221, 2017.

[32] W. A. IJsselsteijn, Y. A. W. de Kort, and A. Haans. Is this my hand I see before me? The rubber hand illusion in reality, virtual reality, and mixed reality. *Presence: Teleoperators and Virtual Environments*, 15(4):455–464, 2006.

[33] D. F. Jacobs. Evidence for a common dissociative-like reaction among addicts. *Journal of Gambling Behavior*, 4(1):27–37, 1988.

[34] N. B. Kuley and D. F. Jacobs. The relationship between dissociative-like experiences and sensation seeking among social and problem gamblers. *Journal of Gambling Behavior*, 4(3):197–207, 1988.

[35] R. Ladouceur, M. Mayrand, and Y. Tourigny. Risk-taking behavior in gamblers and non-gamblers during prolonged exposure. *Journal of Gambling Behavior*, 3(2):115–122, 1987.

[36] R. Ladouceur and S. Sevigny. The impact of video lottery game speed on gamblers. *Journal of Gambling Issues*, (17), 2006.

[37] E. J. Langer. The illusion of control. *Journal of personality and social psychology*, 32(2):311, 1975.

[38] J. Lapuz, M. D. Griffiths, et al. The role of chips in poker gambling: An empirical pilot study. *Gambling Research: Journal of the National Association for Gambling Studies (Australia)*, 22(1):34, 2010.

[39] Lucky VR Inc. PokerStars VR. `https://www.pokerstars.eu/de/poker/ps-vr/?no_redirect=1`, 2018. Last accessed 2018-11-15.

[40] G. Makransky and L. Lilleholt. A structural equation modeling investigation of the emotional value of immersive virtual reality in education. *Educational Technology Research and Development*, 2018. doi: 10.1007/s11423-018-9581-2

[41] D. R. Mestre, C. Maïano, V. Dagonneau, and C.-S. Mercier. Does virtual reality enhance exercise performance, enjoyment, and dissociation? an exploratory study on a stationary bike apparatus. *Presence: Teleoperators and Virtual Environments*, 20(1):1–14, 2011.

[42] G. Meyer and M. Bachmann. *Spielsucht: Ursachen und Therapie*. Springer-Verlag, 2005.

[43] H. Molde, R. Mentzoni, D. Hanss, D. Sagoe, S. Andersen, and S. Pallesen. People around you–do they matter? an experimental gambling study. *International Gambling Studies*, 17(3):349–365, 2017.

[44] C. D. Murray, J. Fox, and S. Pettifer. Absorption, dissociation, locus of control and presence in virtual reality. *Computers in Human Behavior*, 23(3):1347–1354, 2007.

[45] L. Nacke. *Affective ludology: Scientific measurement of user experience in interactive entertainment*. PhD thesis, Blekinge Institute of Technology, 2009.

[46] NetEnt AB. Gonzo's Quest. `https://games.netent.com/video-slots/gonzos-quest/#`, 2011. Last accessed 2018-11-15.

[47] NetEnt AB. Gonzo's Quest VR. `https://www.netent.com`, 2018. Last accessed 2018-11-15.

[48] G. Norman. Likert scales, levels of measurement and the "laws" of statistics. *Advances in Health Sciences Education*, 15:625–632, 2010. doi: 10.1007/s10459-010-9222-y

[49] S. Oberdörfer and M. E. Latoschik. Gamified knowledge encoding: Knowledge training using game mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games 2018)*. Würzburg, Germany, September 2018.

[50] C.-B. Park, J.-S. Choi, S. M. Park, J.-Y. Lee, H. Y. Jung, J.-M. Seol, J. Y. Hwang, A. R. Gwak, and J. S. Kwon. Comparison of the effectiveness of virtual cue exposure therapy and cognitive behavioral therapy for nicotine dependence. *Cyberpsychology, Behavior, and Social Networking*, 17(4):262–267, 2014.

[51] C.-B. Park, S. M. Park, A. R. Gwak, B. K. Sohn, J.-Y. Lee, H. Y. Jung, S.-W. Choi, J.-S. Choi, et al. The effect of repeated exposure to virtual gambling cues on the urge to gamble. *Addictive behaviors*, 41:61–64, 2015.

[52] S. Partington, E. Partington, and S. Olivier. The dark side of flow: A qualitative study of dependence in big wave surfing. *The Sport Psychologist*, 23(2):170–185, 2009.

[53] F. W. Peren. Assessment tool to measure and evaluate the risk potential of gambling products: Asterig. *Gaming Law Review and Economics*, 15(11):671–679, 2011.

[54] N. Raylu and T. P. Oei. The gambling urge scale: development, confirmatory factor validation, and psychometric properties. *Psychology of Addictive Behaviors*, 18(2):100, 2004.

[55] Rik van den Biggelaar. Aquarium. `https://sketchfab.com/models/7b04425c2f0f48c5a07d634431f93e02`, 2016. Last accessed 2018-11-15.

[56] M. J. Rockloff and N. Greer. Audience influence on egm gambling: The protective effects of having others watch you play. *Journal of Gambling Studies*, 27(3):443–451, 2011.

[57] M. J. Schuemie, P. Van Der Straaten, M. Krijn, and C. A. Van Der Mast. Research on presence in virtual reality: A survey. *CyberPsychology & Behavior*, 4(2):183–201, 2001.

[58] N. D. Schull. Digital gambling: The coincidence of desire and design. *The Annals of the American Academy of Political and Social Science*, 597(1):65–81, 2005.

[59] S. Sharman, M. R. Aitken, and L. Clark. Dual effects of 'losses disguised as wins' and near-misses in a slot machine game. *International Gambling Studies*, 15(2):212–223, 2015.

[60] M. Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 364(1535):3549–3557, 2009.

[61] M. Slater, V. Linakis, M. Usoh, and R. Kooper. Immersion, presence, and performance in virtual environments: An experiment with tri-dimensional chess. In *ACM Virtual Reality Software and Technology (VRST)*, pp. 163–172, 1996.

[62] M. Slater, D. Perez-Marcos, H. H. Ehrsson, and M. V. Sanchez-Vives. Inducing illusory ownership of a virtual body. *Frontiers in neuroscience*, 3(2):214, 2009.

[63] M. Slater and S. Wilbur. A framework for immersive virtual environments (five): Speculations on the role of presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, 6(6):603–616, 1997.

[64] J. A. Stevens and J. P. Kincaid. The relationship between presence and performance in virtual simulation training. *Open Journal of Modelling and Simulation*, 3:41–48, 2015.

[65] M. J. Stewart and M. J. Wohl. Pop-up messages, dissociation, and craving: How monetary limit reminders facilitate adherence in a session of slot machine gambling. *Psychology of Addictive Behaviors*, 27(1):268, 2013.

[66] N. Turner and R. Horbay. How do slot machines and other electronic gambling machines actually work? *Journal of Gambling Issues*, (11), 2004.

[67] Unity. unity 2018.1.1f1. available at https://unity3d.com/get-unity/download/archive, February 2018.

[68] Valve Coorperation. Steamvr plugin. `https://www.assetstore.unity3d.com/en/#!/content/32647`, 2015–2017.

[69] T. Waltemate, D. Gall, D. Roth, M. Botsch, and M. E. Latoschik. The impact of avatar personalization and immersion on virtual body ownership, presence, and emotional response. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1643–1652, 2018.

[70] B. G. Witmer and M. J. Singer. Measuring presence in virtual environments: A presence questionnaire. *Presence*, 7(3):225–240, 1998.

[71] M. J. Wohl, A. Parush, H. A. S. Kim, and K. Warren. Building it better: Applying human–computer interaction and persuasive system design principles to a monetary limit tool improves responsible gambling. *Computers in Human Behavior*, 37:124–132, 2014.

[72] World Health Organization. *ICD-10 Classification of Mental and Behavioural Disorders (The): Diagnostic Criteria for Research*. ICD-10 classification of mental and behavioural disorders / World Health Organization. World Health Organization, 1993.

[73] World Health Organization. *ICD-11 for Mortality and Morbidity Statistics*. World Health Organization, 2018.

[74] M. M. Young and M. J. Wohl. The gambling craving scale: Psychometric validation and behavioral outcomes. *Psychology of Addictive Behaviors*, 23(3):512, 2009.

8.2 Discussion

The results of the user study not only revealed a significant effect of immersion on harm-inducing factors, i.e., dissociation, urge to game, and dark flow, but also demonstrated how game mechanics realize a virtual gambling game with a potentially high risk potential. The game mechanics used for encoding the actual gambling knowledge were realized in a way that users could not learn the underlying principles. Also, the majority of the used game mechanics were implemented to evoke erroneous beliefs in the users. For instance, the slot machine provided a losses-disguised-as-wins game mechanic. While fulfilling a similar purpose, i.e., increasing the motivation to continue using an application, the game mechanics simultaneously increase the overall risk potential of virtual gambling games. This user study demonstrated the importance of continuing the research of game mechanics. Future work needs to be aimed at developing a comprehensive understanding of game mechanics and their various contexts of use. This could either lead to further guidelines for the design of effective applications, to new concepts for using gamification in other contexts, e.g., for therapy, or to recommendations for regulations.

9 Discussion

Without action, games remain only in the pages of an abstract rule book. Without the active participation of players and machines, video games exist only as static computer code. Video games come into being when the machine is powered up and the software is executed; they exist when enacted.
– Alexander R. Galloway (2006)

This thesis approached the analysis of knowledge encoding and knowledge learning using gamification in three different ways. At first, the theoretical background was analyzed. The assumptions made were tested an expert review of *World of Warcraft*. The analysis showed that an active participation in a gameplay results in an acquisition and practice of knowledge (RQ1). Based on the theoretical considerations and the review's results, the Gamified Knowledge Encoding was proposed. The model defines how any knowledge can be encoded in game mechanics (RQ3), i.e., by transforming a learning content into game rules and mapping it to interacting game mechanics, and how the resulting learning process is structured (RQ2). The resulting gamification metaphors create learning affordances requiring the application of the knowledge and demonstrating its underlying principles. During the gameplay, players compile mental models for the learning content which allow for a training transfer from the game to a real world context. Then, the Gamified Knowledge Encoding was applied to develop *GEtiT* and *GEtiT VR*, thus demonstrating its effectiveness as a design guideline. A usability study validated the serious game's design and the knowledge encoding process as defined by the proposed model. Finally, four learning effectiveness studies validated the Gamified Knowledge Encoding's definition of the gamified learning process. Three studies evaluated *GEtiT* and one used the Gamified Knowledge Encoding to analyze and predict the learning outcomes of *Kerbal Space Program*. The studies's results show that the gamification of learning achieves a similar learning outcome to traditional learning methods, but also a higher learning quality (RQ4). The core findings of this thesis were summarized and published in two scientific papers (see subsection 6.2 and subsection 7.2). This thesis further provides an outlook on future work, i.e., the analysis of further contexts of use of game mechanics. The importance of this outlook is supported by a first user study analyzing the harmful effects of using game mechanics in a virtual gambling scenario.

The four learning effectiveness studies focussed on the evaluation of transfer-oriented learning. Instead of assessing the learning outcome directly inside a serious game, participants were challenged to complete paper-based exercises. They had to transfer the knowledge learned from the 3D game environments to paper-based exercises consisting of 2D pre-post-images as well as written mathematical expression representations. The results presented in this thesis indicate the effectiveness and satisfaction of using a gamification of learning approach for a typical learning scenario at university level. All four studies showed that using a game-based approach resulted in a similar learning outcome to a traditional approach, but also in a higher learning quality. This not only validates the Gamified Knowledge Encoding model, but also supports the overall feasibility of game-based learning targeting a learning transfer to a different context.

However, the game groups had to overcome a greater transfer threshold than the paper groups. The paper groups practiced with assignments similar to the exercises used in the final exam. The game groups played serious games and thus had to develop an understanding for the 2D representations and text-based exercises while completing the knowledge assessment test. The test results of the game groups might have been negatively affected by this transfer process. Despite the additional learning transfer challenge, the game groups yielded a similar outcome to the paper groups. Therefore, playing serious games could provide a better learning effectiveness. Future work is needed to either measure an in-context learning outcome or to conduct the measurements using an approach that requires a learning transfer for all conditions.

As already indicated in subsection 6.3 and subsection 7.2, the evaluation of *GEtiT VR* might have been confounded by the experimental goal to compare different visualization methods for the same gamification metaphor. By working with the Gamified Knowledge Encoding to design a non-experimental version of *GEtiT VR*, the serious game's efficiency and thus the overall learning outcome could be improved.

While the Gamified Knowledge Encoding provides a general definition of knowledge learning using game mechanics, it was only validated using two distinct learning contents, i.e., affine transformations and orbital mechanics. Both learning contents, however, base on mathematical approaches that produce unambiguous results. For a comprehensive validation, it is important to further research the overall applicability of the model for other learning contents. This would require a continuation of the research presented in this thesis. A different type of learning content, e.g., interpreting poems, has to be encoded in game mechanics and subsequently evaluated in a learning effectiveness study. Alternatively, computer games already targeting the learning of specific non-mathematical knowledge, e.g., *Never Alone* (E-Line Media, 2016), could be analyzed using the Gamified Knowledge Encoding model following the approach described in subsection 7.3. Subsequently, the learning predictions and learning outcomes need to be tested in a user study.

Finally, it is important for future research to analyze other contexts of use of game mechanics. For instance, as discussed in subsection 8.1, gambling games provide game mechanics to create disbeliefs about the chances of success when playing. The presented user study merely was a first step towards the continuation of the analysis of game mechanics to compile a comprehensive definition. Future research could not only lead to the identification of further dangerous contexts of use, but also reveal potential benefits for therapy applications.

10 Conclusion

It's a dangerous business, Frodo, going out of your door. You step into the Road, and if you don't keep your feet, there's no knowing where you might be swept off to. – J.R.R. Tolkien (2012)

Computer games are used in various ways to achieve knowledge acquisition. Game-based learning, serious games, and gamification represent the main three approaches of using computer games as learning tools. However, the actual process of encoding knowledge in computer games as well as the process of acquiring knowledge while playing them has not been defined, yet. This thesis presents the development of the Gamified Knowledge Encoding model and discusses its application to overcome these shortcomings.

The Gamified Knowledge Encoding model utilizes game mechanics to encode, require, and demonstrate specific learning contents. For encoding a particular knowledge, it is transformed into clear rules that subsequently are mapped to interacting game mechanics as their internal rules. The interaction between the game mechanics not only creates the gameplay, but also requires the application of the encoded knowledge and demonstrates its underlying principles. The game mechanics create gamification metaphors for the learning content. A gamification metaphor represents a knowledge's gamified metamodel which can be fully internalized in form of mental models during the gameplay. These mental models ultimately allow for a training transfer from the gamified learning environment to a real world context. The Gamified Knowledge Encoding model not only provides a guideline for an effective encoding of specific knowledge in computer games, but also describes the process of acquiring knowledge using game mechanics. This thesis provides a first comprehensive definition of the gamification of learning and the educational effects of game mechanics in general. The definition of the comprehensive model answers the first three RQs by explaining the acquisition and training of knowledge using computer games, knowledge application as well as knowledge demonstration during the gameplay, and knowledge encoding in game mechanics.

For validating the Gamified Knowledge Encoding, the model was used to 1) develop *GEtiT* as well as *GEtiT VR* and to 2) predict the learning outcome of playing *Kerbal Space Program*. *GEtiT*'s development and evaluation demonstrated the model's applicability to create effective serious games. In user studies, *GEtiT*'s usability and learning effectiveness were measured. The results revealed a similar learning outcome to traditional learning methods and a higher learning quality when playing the serious games. The Gamified Knowledge Encoding-driven analysis of *Kerbal Space Program* further validated the model by effectively identifying the encoded orbital mechanics knowledge rules. Executing the relevant game mechanics during the gameplay led to the predicted learning effect. Overall, the studies validated the educational effects of game mechanics and hence the Gamified Knowledge Encoding model. The user studies' results answer the last RQ by demonstrating an effective transfer-oriented knowledge learning that yields a similar learning outcome to a traditional training method but also a higher learning quality.

The comparison of both *GEtiT* versions demonstrated the importance of a good usability. Except for the necessary adjustments to allow for an execution of the player-bound game mechanics when playing *GEtiT VR*, both versions provided the same game mechanics. However, these adjustments led to changes in the interaction patterns that negatively affected *GEtiT VR*'s efficiency. The reduced efficiency resulted in a significantly lower number of solved levels in the learning effectiveness study, thus demonstrating the effects of a lower usability for learning environments. This is a critical insight for educators and developers. Also, this thesis contributes to the ongoing research of educational potentials of immersive VR as well as the research of VR interaction techniques by presenting and evaluating *GEtiT VR*. In particular, this thesis analyzed the effects of three different transition techniques allowing for an immediate transition between two individual VEs. The respective study further contributed to the ongoing research of evoking the illusion of virtual body ownership. As a first look at future directions, this thesis evaluated the effects of playing gambling games in immersive VR in respect to the overall risk potential. Gambling games implement game mechanics to hide the underlying principles of the game knowledge and to evoke erroneous beliefs in the players. The study revealed an effect of immersive VR on harm-inducing factors, thus showing a higher risk potential of VR gambling games. This result supports the importance of this research, as it not only identifies dangers, but also new opportunities, e.g., for realizing effective therapy applications using game mechanics.

In conclusion, this thesis not only provided the first comprehensive definition of the gamification of learning, but also significantly contributed to other areas of Human-Computer Interaction. Future work should focus on developing and evaluating serious games targeting non-mathematical learning contents to advance the validation of the Gamified Knowledge Encoding model. Also, as demonstrated by the analysis of VR gambling games, a continuation of the analysis of different contexts of use is of high importance to generate a comprehensive understanding and taxonomy of game mechanics.

Learning by gaming: Game on!

A Publications

Section 3): Oberdörfer, S. and Latoschik, M. E. Develop your strengths by gaming: Towards an inventory of gamificationable skills. In Horbach, M., editor, *Informatik 2013 – Informatik angepasst an Mensch, Organisation und Umwelt*, pages 2346–2357, Koblenz, Germany, September 2013. Gesellschaft für Informatik e.V

Subsection 4.1): Oberdörfer, S. and Latoschik, M. E. Gamified Knowledge Encoding: Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games '18)*, Würzburg, Germany, September 2018a. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493425

Subsection 5.1): Oberdörfer, S. and Latoschik, M. E. Interactive gamified 3D-training of affine transformations. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*, pages 343–344, Munich, Germany, 2016. ACM. doi: 10.1145/2993369.2996314

Subsection 5.2): Oberdörfer, S., Heidrich, D., and Latoschik, M. E. Interactive Gamified Virtual Reality Training of Affine Transformations. In Ullrich, C. and Wessner, M., editors, *Proceedings of DeLFI and GMW Workshops 2017*, Chemnitz, Germany, 2017

Subsection 6.1): Oberdörfer, S., Fischbach, M., and Latoschik, M. E. Effects of VE Transition Techniques on Presence, IVBO, Efficiency, and Naturalness. In *Proceedings of the 6th Symposium on Spatial User Interaction (SUI '18)*, pages 89–99, Berlin, Germany, October 2018. ACM. doi: 10.1145/3267782.3267787

Subsection 6.2): Oberdörfer, S., Heidrich, D., and Latoschik, M. E. Usability of Gamified Knowledge Learning in VR and Desktop-3D. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*, pages 175:1–175:13, Glasgow, Scotland UK, May 2019. ACM. doi: 10.1145/3290605.3300405

Subsection 7.1): Oberdörfer, S. and Latoschik, M. E. Effectivity of Affine Transformation Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games '18)*, Würzburg, Germany, September 2018b. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493418

Subsection 7.2): Oberdörfer, S. and Latoschik, M. E. Knowledge Encoding in Game Mechanics: Transfer-Oriented Knowledge Learning in Desktop-3D and VR. *International Journal of Computer Games Technology*, 2019, 2019. doi: 10.1155/2019/7626349

Subsection 7.3): Oberdörfer, S. and Latoschik, M. E. Effective Orbital Mechanics Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games '18)*, Würzburg, Germany, September 2018c. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493417

Subsection 8.1): Heidrich, D., Oberdörfer, S., and Latoschik, M. E. The Effects of Immersion on Harm-Inducing Factors in Virtual Slot Machines. In *Proceedings of the 26th IEEE Virtual Reality conference (VR '19)*, Osaka, Japan, March 2019. IEEE, ©2019 IEEE. Reprinted, with permission

B Materials

B.1 GEtiT

Used in:

- 5.1, 5.2, 6.2, 7.1, 7.2

GEtiT is available at *http://www.hci.uni-wuerzburg.de/projects/getit/*

As *GEtiT* is an ongoing research project, it was tested in various developmental stages as presented in this thesis. The USB flash drive only includes the latest version of the serious game in */materials/getit/*.

B.2 VR Transition Techniques Experiment System

Used in:

- 6.1

The VR Transition Techniques Experiment System can be found on the USB flash drive in */materials/vr-tt/*.

B.3 Kerbal Space Program

Used in:

- 7.3

Kerbal Space Program is available at *https://www.kerbalspaceprogram.com*

Since the end of the experiment presented in subsection 7.3, the development of *Kerbal Space Program* was continued. As a result, the version 0.18.3 demo version of the game is no longer available. The latest demo version (version 1.0.0.813 Demo) can be found on the USB flash drive in */materials/ksp/*.

B.4 Virtual Slot Machine

Used in:

- 8.1

The Virtual Slot Machine can be found on the USB flash drive in */materials/slot-machine/*.

C Research Instruments

C.1 Standardized Questionnaires

Table 14: Overview of used standardized questionnaires

Questionnaire	Used in
Alpha IVBO (Roth et al., 2017)	6.1
Clinician Administered Dissociative States Scale (Bremner et al., 1998)	8.1
Gambling Motivation (Ladouceur and Sevigny, 2006)	8.1
Gambling Urge Scale (Raylu and Oei, 2004)	8.1
Game Experience Questionnaire (Nacke, 2009)	8.1
Flow Short Scale (Rheinberg et al., 2003)	6.2
Immersive Tendency Questionnaire (Witmer and Singer, 1998)	8.1
Mid Immersion Presence Questionnaire (Bouchard et al., 2004)	6.1, 8.1
NASA Task Load Index (Hart and Staveland, 1988)	6.1, 6.2
Presence Questionnaire - version 3.0 (Witmer et al., 2005)	6.1
QUESI (Naumann and Hurtienne, 2010)	6.1, 6.2
Simulator Sickness Questionnaire (Kennedy et al., 1993)	6.1, 6.2, 7.2

C.2 GEtiT: Learning Quality Questionnaire

Used in:

- 7.1 (only Q1 - 14), 7.2

Description: The learning quality of *GEtiT* (see subsection 7.1 and subsection 7.2) was measured using a self-designed questionnaire (Oberdörfer and Latoschik, 2018b, 2019). The questionnaire uses a 5-point Likert scale (1 = disagree; 5 = agree). The *Learning Quality* subcategory consists of nine questions (Q1 - Q9) and the system specific *Motivational Aspects* subcategory consists of six questions (Q10 - 16). Q17 and Q18 were added to analyze the audiovisual encoding of *GEtiT*. Q19 and Q20 were designed to assess the achievement system and the debriefing system added to the system. For evaluating the results, the overall mean for the sum of a subcategory's questions is computed.

Learning Quality:

Q1 Did you enjoy playing GEtiT / solving the paper-based assignments?

Q2 Did GEtiT's puzzles / the assignments help you to develop a better understanding of ATs?

Q3 Did you notice a knowledge gain while you were solving the GEtiT puzzles / the assignments?

Q4 Did the raise in the difficulty match your knowledge gain?

Q5 Were the tasks of the GEtiT puzzles / the assignments easy to understand?

Q6 Was the difficulty of the GEtiT puzzles / the assignments well adjusted?

Q7 Were you motivated by new challenges due to a raise in the difficulty?

Q8 Did you enjoy the class that was based on GEtiT / the paper-based assignments?

Q9 Was it interesting to solve the GEtiT puzzles / the assignments by using AT operations?

Motivational Aspects:

Q10 Was the serious game-based learning method more enjoyable than traditional learning methods, e.g., paper-based assignments?

Q11 Would you prefer to utilize a serious game instead of visiting a regular class?

Q12 Did you notice a higher motivation to play GEtiT to practice your knowledge in contrast to other learning methods?

Q13 Were you motivated by the additional feedback mechanisms, such as highscores and the amount of used operations?

Q14 Did the feedback mechanisms motivate you to try a particular level again to improve your performance?

Q15 Were you motivated by the indication of the needed time?

Q16 Were you motivated by the ranking system?

Audiovisual Encoding:

Q17 Did the color(s) of the AT cards help you to internalize the different AT operation types?

Q18 Did the sound effects of the AT cards help you to internalize the different AT operation types?

Achievements & Debriefing:

Q19 Did you find the possibility of unlocking achievements motivating?

Q20 Did the mathematical representation of your solution at the end of each level help you to develop a better understanding of ATs?

C.3 Kerbal Space Program: Joy of Use

Used in:

- 7.3

Description: The experiment discussed in subsection 7.3 consisted of two phases. At the end of each phase, the joy of use of playing *Kerbal Space Program* (Phase 1) and utilizing the game for learning purposes (Phase 2) was measured using a self-designed questionnaire.

Phase 1:

1. Did you enjoyed play Kerbal Space Program?
2. Did you learn new facts about orbital mechanics during the gameplay?
3. Did you do additional research to understand a specific rocket part or to complete the assignments?
4. Did you do additional research to build more efficient rockets or to solve the assignments in a more efficient way?

Phase 2:

1. Did you enjoy playing Kerbal Space Program?
2. Did you learn new facts about orbital mechanics during the gameplay?
3. Did you use Kerbal Space Program to visualize or test certain facts presented in the lecture?
4. Was the Kerbal Space Program-based class interesting?
5. Would you like to see Kerbal Space Program being implemented as a learning environment in future classes?
6. Were the Kerbal Space Program-based assignment more engaging than traditional paper-based assignments?
7. Do you think that Kerbal Space Program 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).

C.4 Affine Transformations Knowledge Test v1

Used in:

- 7.1

Description: The learning outcome of *GEtiT* was measured with an exam assessing the AT knowledge of the participants. The exam consisted of 15 multiple choice assignments that were designed to be of equal difficulty to the assignments normally used in the final exam of an Interactive Computer Graphics lecture.

Exam

Test Affine Transformation Training Game Studie

SS 2015 (1), Studie ATTG

Prof. Dr. Marc Erich Latoschik, University of Würzburg
June 23, 2015 12:00

Student	
Name:	
Mat Nr.:	

Result																	
Exercise:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	$\sum$
Max:	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	30
Points:																	
Grade:																	

Instructions

Carefully read and understand the following directions before you start:

- Check completeness of exam documents. You should have received:
  - One front page including these directions.
  - **10 exercise sheets with 16 exercises.**
- Put your student **number** on **all sheets** of paper (filling in your name is optional).
- Read the exercises **carefully**. First **understand**, then **solve**!
- Write legible, what cannot be read cannot be given credit.
- Multiple choice questions **may** have **several** correct **answers**.
- **No** additional **resources** are allowed.
- The maximum number of points to achieve is **30**.
- The points per exercise are calculated as follows: $\frac{c}{a} \cdot max$ where
  - max is the maximum number of points for that exercise.
  - a is the overall number of possible alternative answers provided for that exercise.
  - c is the number of correct answers given, that is, all answers which are selected where correct and left unselected where not correct.
  - Selecting none or all boxes of an exercise will result in a score of 0 points for that exercise

Good luck!

Exercise 1: Gruppenzugehörigkeit in der Studie [0 Points]

In welcher Gruppe waren Sie während der Studie eingeteilt?

- ☐ **Gruppe 1 (Zettelgruppe)**
- ☐ **Gruppe 2 (Computerspielgruppe Freitags 14-16)**
- ☐ **Gruppe 3 (Computerspielgruppe Freitags 16-18)**
- ☐ **Gruppe 4 (Computerspielgruppe freie Zeitwahl)**
- ☐ **Nicht an der Studie teilgenommen**

Exercise 2: Scaling a rectangle [2 Points]

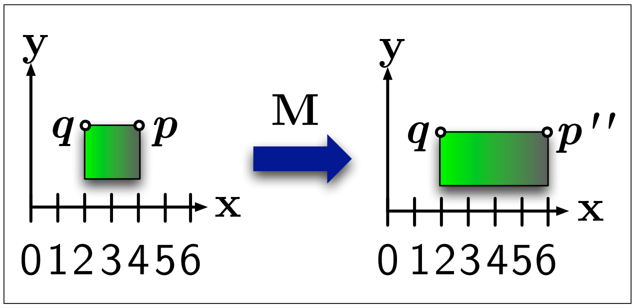


Figure 1: Scaling of a simple rectangle.

Be $\boldsymbol{p}$ and $\boldsymbol{q}$ two points of a simple polygon (a square) which has to be transformed as illustrated in Figure 1. Which of the following transformation matrices are correct for $\mathbf{M}$?

☒ $\begin{bmatrix} 2 & 0 & 0 & -2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☐ $\begin{bmatrix} 2 & 0 & 0 & q_x \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☐ $\begin{bmatrix} -2 & 0 & 0 & 2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☒ $\begin{bmatrix} 2 & 0 & 0 & -q_x \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☐ $\begin{bmatrix} 2 & 0 & 0 & 2 \\ 0 & 2 & 0 & 2 \\ 0 & 0 & 2 & 2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Exercise 3: Composite Transformations [2 Points]

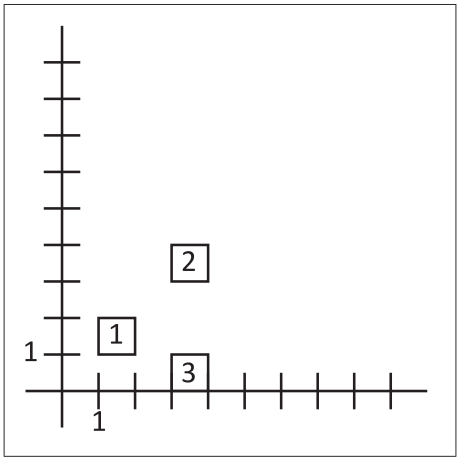


Figure 2: Composite Transformation

Complex transformations can be represented by composition of simple transformations. Have a look at figure 2. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☒ $T = T(0, -3, 0)T(2, 2, 0)$
- ☐ $T = R_Z(-45°)R_Z(-45°)T(-1, 2, 0)$
- ☒ $T = T(0, -3, 0)R_Z(180°)T(-5, -5, 0)$

Exercise 4: Rotation around z-axis [2 Points]

Given a rotation matrix $\mathbf{R}$ which rotates 90 degrees around the z-axis in a right handed coordinate frame. Which transformation matrix specifies the correct rotation?

- ☒ $\mathbf{R} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
- ☐ $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
- ☐ $\mathbf{R} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

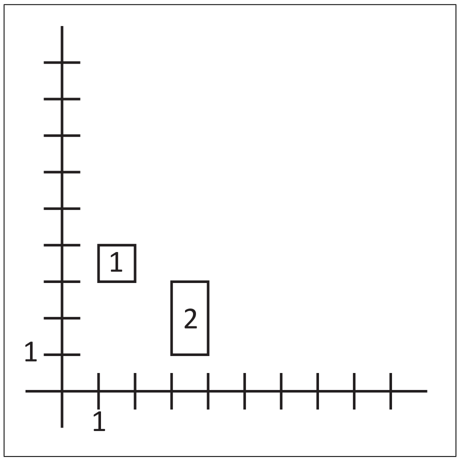


Figure 3: Composite Transformation

Exercise 5: Composite Transformations [2 Points]

Complex transformations can be represented by composition of simple transformations. Have a look at figure 3. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = S(0,1,0)T(2,-2,0)$
- ☒ $T = T(4,1,0)R_Z(90°)S(2,1,1)T(-1,-3,0)$
- ☐ $T = T(3,1,0)R_Z(90°)S(2,1,1)T(-1,-3,0)$

Exercise 6: Compensate rotation around y-axis [2 Points]

$$\mathbf{R} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Consider the rotation matrix shown above. How does the inverse transformation $\mathbf{R}^{-1}$ look like which compensates $\mathbf{R}$?

$$\mathbf{R}^{-1} = \begin{bmatrix} \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \end{bmatrix}$$

Answer: $\mathbf{R}^{-1} = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Exercise 7: Composite Transformations [2 Points]

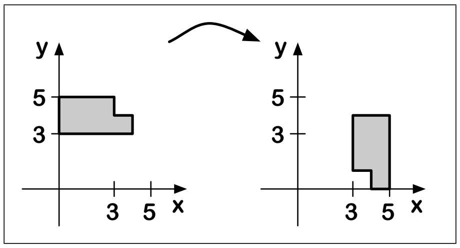


Figure 4: Transformation eines Körpers.

Complex transformations can be represented by composition of simple transformations. Have a look at figure 4. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = R_Z(-\frac{\pi}{2})$
- ☐ $T = R_Z(-\frac{\pi}{2})S(-1,1,1)$
- ☐ $T = S(1,1,-1)T(-4,8,0)R_X(-\frac{\pi}{2})$
- ☒ $T = T(8,4,0)S(1,-1,1)R_Z(\frac{\pi}{2})$

Exercise 8: Translating a cube [2 Points]

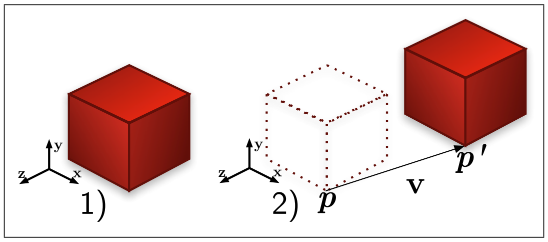


Figure 5: Translating a cube along a vector.

Be $\boldsymbol{p}$ with components p_x, p_y, p_z one point of a cube. Translate the cube along a vector $\mathbf{v}$ with components v_x, v_y, v_z as illustrated in Figure 10. How does the corresponding homogeneous transformation matrix $\mathbf{T}$, with $\boldsymbol{p}' = \mathbf{T}\boldsymbol{p}$ look like? (Assume column vector representation).

$$\mathbf{T} = \begin{bmatrix} \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \end{bmatrix}$$

Answer: $\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & v_x \\ 0 & 1 & 0 & v_y \\ 0 & 0 & 1 & v_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Exercise 9: Composite Transformations [2 Points]

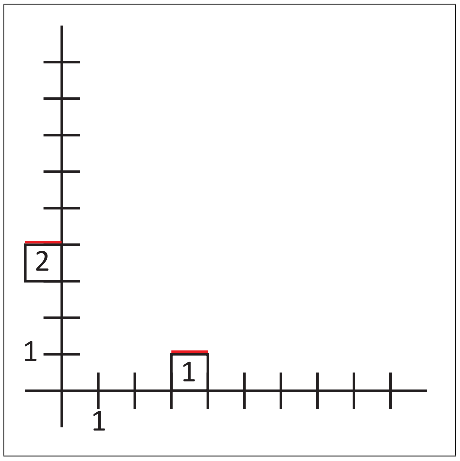


Figure 6: Composite Transformation

Complex transformations can be represented by composition of simple transformations. Have a look at figure 6. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = R_Z(90°)$
- ☒ $T = T(-1, 3, 0)R_Z(-90°)T(0, -3, 0)R_Z(90°)$
- ☐ $T = T(-1, 3, 0)R_Z(-90°)R_Z(90°)$

Exercise 10: Properties of Rotations [2 Points]

Let A denote one of the base coordinate frame's axes X, Y und Z. Let α denote an arbitrary angle of rotation around this axis.

Which of the following properties apply to rotations $\mathbf{R}_A(\alpha)$ of angle α around A?

- ☒ $\mathbf{R}_A(0) = I$ (identity element)
- ☒ $\mathbf{R}_A(\alpha)^{-1} = \mathbf{R}_A(-\alpha)$
- ☐ $\mathbf{R}_A(\alpha)^{-1} = \mathbf{R}_{-A}(-\alpha)$
- ☐ $\mathbf{R}_A(\alpha)\mathbf{R}_A(\beta) = \mathbf{R}_A(\alpha\beta)$
- ☒ $\mathbf{R}_A(\alpha)\mathbf{R}_A(\beta) = \mathbf{R}_A(\beta)\mathbf{R}_A(\alpha)$
- ☐ $\mathbf{R}_A(\alpha)\mathbf{R}_B(\beta) = \mathbf{R}_B(\beta)\mathbf{R}_A(\alpha)$
- ☒ $\mathbf{R}_A(\alpha)^{-1} = \mathbf{R}_{-A}(\alpha)$

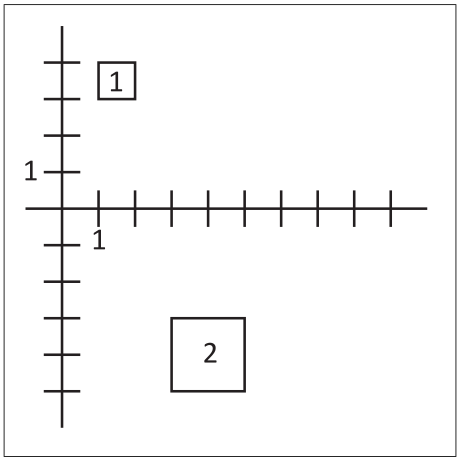


Figure 7: Composite Transformation

Exercise 11: Composite Transformations [2 Points]

Complex transformations can be represented by composition of simple transformations. Have a look at figure 7. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☒ $T = T(1, -10, 0)S(2, 2, 2)$
- ☒ $T = T(1, 3, 0)R_X(180°)S(2, 2, 2)$
- ☒ $T = T(-1, -5, -2)S(2, 2, 2)T(1, -3, 1)$
- ☐ $T = T(1, -3, 1)T(1, -4, 1)S(2, 2, 2)$
- ☐ $T = R_X(-180°)T(-2, 0, 0)S(2, 2, 2)$

Exercise 12: Rotation around y-axis [2 Points]

Given a rotation matrix $\mathbf{R}$ which rotates 90 degrees around the y-axis in a right handed coordinate frame. Which transformation matrix specifies the correct rotation?

☐ $\mathbf{R} = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☐ $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☒ $\mathbf{R} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Exercise 13: Properties of Translations [2 Points]

Let x, y, z be the displacement components given a base coordinate system with axes X, Y, Z.

Which of the following properties apply to translations $T(x, y, z)$?

- ☒ $T(0, 0, 0) = I$ (Identity element)
- ☐ $T(x, y, z) = T(z, y, x)$
- ☐ $T(x_1, y_1, z_1)T(x_2, y_2, z_2) = T(x_1x_2, y_1y_2, z_1z_2,)$
- ☒ $T^{-1}(x, y, z) = T(-x, -y, -z)$
- ☐ $T^{-1}(x, y, z) = T(\frac{1}{x}, \frac{1}{y}, \frac{1}{z})$
- ☒ $T(x_1, y_1, z_1)T(x_2, y_2, z_2) = T(x_2, y_2, z_2)T(x_1, y_1, z_1)$

Exercise 14: Transforming a triangle [2 Points]

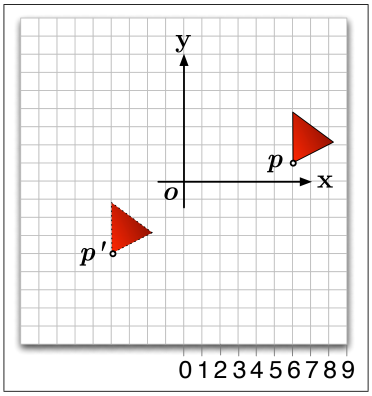


Figure 8: A triangle has to be translated from position $\boldsymbol{p}$ to position $\boldsymbol{p}'$.

Figure 8 illustrates a triangle with a given point $\boldsymbol{p}$ which has to be transformed to position $\boldsymbol{p}'$. Specify the acording transformation matrix $\mathbf{M}$ given a column representation of vectors and points. (Note that both $\boldsymbol{p}$ and $\boldsymbol{p}'$ have integer coordinates x and y.)

$$\mathbf{T} = \begin{bmatrix} \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \end{bmatrix}$$

Answer: $\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & -10 \\ 0 & 1 & 0 & -5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Exercise 15: Composite Transformations [2 Points]

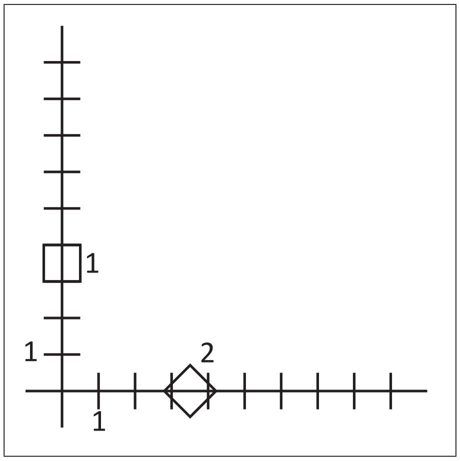


Figure 9: Composite Transformation

Complex transformations can be represented by composition of simple transformations. Have a look at figure 9. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

☐ $T = T(3, 0, 0)R_Z(45°)T(0, -3.5, 0)$

☐ $T = R_Z(-90°)R_Z(-45°)$

☒ $T = T(3.5, 0, 0)R_Z(45°)T(0, -3.5, 0)$

Exercise 16: Translating a cube backwards [2 Points]

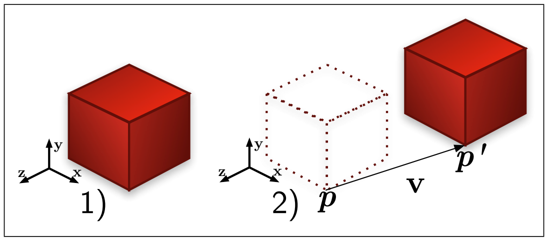


Figure 10: Translating a cube along a vector.

Be $\boldsymbol{p}$ with components p_x, p_y, p_z one point of a cube. Assuming a transformation matrix $\mathbf{T}$ which translates the cube along vector $\mathbf{v}$ with components v_x, v_y, v_z as illustrated in Figure 10. How does the corresponding inverse homogeneous transformation matrix $\mathbf{T}^{-1}$, with $\boldsymbol{p} = \mathbf{T}^{-1}\boldsymbol{p}'$ look like? (Assume column vector representation).

$$\mathbf{T} = \begin{bmatrix} \_\_\_\_ & \_\_\_\_ & \_\_\_\_ & \_\_\_\_ \\ \_\_\_\_ & \_\_\_\_ & \_\_\_\_ & \_\_\_\_ \\ \_\_\_\_ & \_\_\_\_ & \_\_\_\_ & \_\_\_\_ \\ \_\_\_\_ & \_\_\_\_ & \_\_\_\_ & \_\_\_\_ \end{bmatrix}$$

Answer: $\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & -v_x \\ 0 & 1 & 0 & -v_y \\ 0 & 0 & 1 & -v_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$

C.5 Affine Transformations Knowledge Test v2

Used in:

- 7.2

Description: The learning outcome was measured using a 16-assignment pen-and-paper exam assessing the participants' overall AT knowledge. The assignments were designed to be of similar difficulty to the assignments given in a regular final exam of the interactive computer graphics lecture.

Exam

Test "Gamified Training Environment for Affine Transformation" Studie

SS 2017 (1), Studie GEtIT

Prof. Dr. Marc Erich Latoschik, University of Würzburg

July 10, 2017 14:00

Student	
Name:	
Mat Nr.:	

Result																	
Exercise:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	$\sum$
Max:	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	30
Points:																	
Grade:																	

Instructions

Carefully read and understand the following directions before you start:

- Check completeness of exam documents. You should have received:
  - One front page including these directions.
  - **8 exercise sheets with 16 exercises.**
- Put your student **number** on **all sheets** of paper (filling in your name is optional).
- Read the exercises **carefully**. First **understand**, then **solve**!
- Write legible, what cannot be read cannot be given credit.
- Multiple choice questions **may** have **several** correct **answers**.
- **No** additional **resources** are allowed.
- The maximum number of points to achieve is **30**.
- The points per exercise are calculated as follows: $\frac{c}{a} \cdot max$ where
  - max is the maximum number of points for that exercise.
  - a is the overall number of possible alternative answers provided for that exercise.
  - c is the number of correct answers given, that is, all answers which are selected where correct and left unselected where not correct.
  - Selecting none or all boxes of an exercise will result in a score of 0 points for that exercise

Good luck!

Exercise 1: Gruppenzugehörigkeit in der Studie [0 Points]

In welcher Gruppe waren Sie während der Studie eingeteilt?

- ☐ **Gruppe 1 (GEtiT VR)**
- ☐ **Gruppe 2 (GEtiT Desktop)**

Exercise 2: Scaling a rectangle [2 Points]

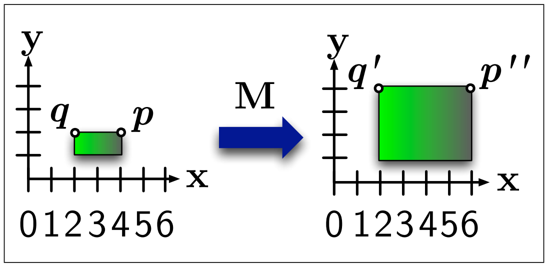


Figure 1: A small green rectangle is scaled in two dimensions.

Be $\boldsymbol{p}$ and $\boldsymbol{q}$ two points of a simple polygon (a green rectangle) which has to be transformed as illustrated in Figure 1. Which of the following transformation matrices is/are correct for $\mathbf{M}$?

☐ $\begin{bmatrix} 2 & 0 & 0 & -2 \\ 0 & 3 & 0 & -2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☐ $\begin{bmatrix} 3 & 0 & 0 & -2 \\ 0 & 2 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☐ $\begin{bmatrix} 2 & 0 & 0 & -2 \\ 0 & 3 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Exercise 3: Composite Transformations [2 Points]

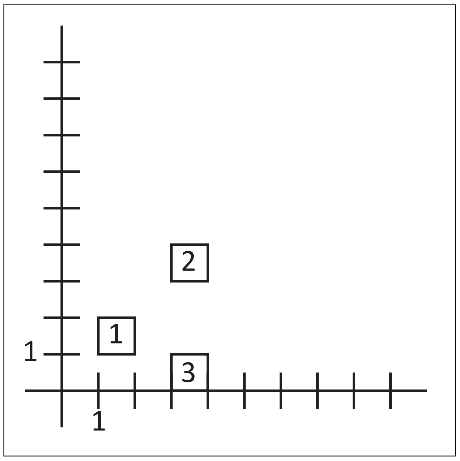


Figure 2: Composite Transformation

Complex transformations can be represented by composition of simple transformations. Have a look at figure 2. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = T(0, -3, 0)T(2, 2, 0)$
- ☐ $T = R_Z(-45°)R_Z(-45°)T(-1, 2, 0)$
- ☐ $T = T(0, -3, 0)R_Z(180°)T(-5, -5, 0)$

Exercise 4: Rotation around x-axis [2 Points]

Given a rotation matrix $\mathbf{R}$ which rotates 90 degrees around the x-axis in a right handed coordinate frame. Which transformation matrix specifies the correct rotation?

☐ $\mathbf{R} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☐ $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

☐ $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Exercise 5: Composite Transformations [2 Points]

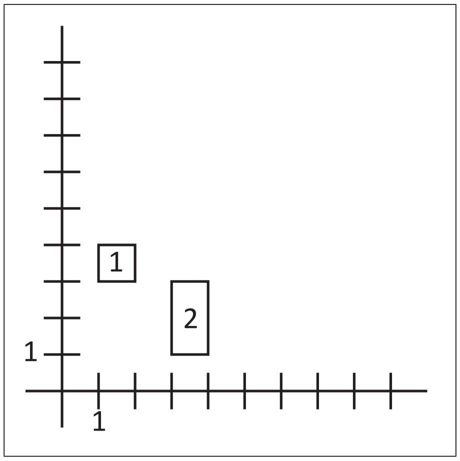


Figure 3: Composite Transformation

Complex transformations can be represented by composition of simple transformations. Have a look at figure 3. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = S(0,1,0)T(2,-2,0)$
- ☐ $T = T(4,1,0)R_Z(90°)S(2,1,1)T(-1,-3,0)$
- ☐ $T = T(3,1,0)R_Z(90°)S(2,1,1)T(-1,-3,0)$

Exercise 6: Compensate rotation around y-axis [2 Points]

$$\mathbf{R} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Consider the rotation matrix shown above. How does the inverse transformation $\mathbf{R}^{-1}$ look like which compensates $\mathbf{R}$?

$$\mathbf{R}^{-1} = \begin{bmatrix} \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \end{bmatrix}$$

Exercise 7: Composite Transformations [2 Points]

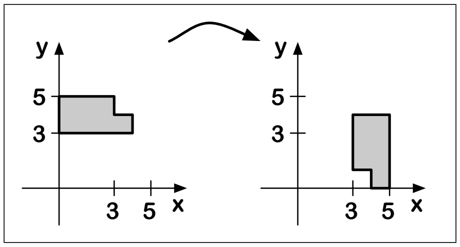


Figure 4: Transformation eines Körpers.

Complex transformations can be represented by composition of simple transformations. Have a look at figure 4. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = R_Z(-\frac{\pi}{2})$
- ☐ $T = R_Z(-\frac{\pi}{2})S(-1,1,1)$
- ☐ $T = S(1,1,-1)T(-4,8,0)R_X(-\frac{\pi}{2})$
- ☐ $T = T(8,4,0)S(1,-1,1)R_Z(\frac{\pi}{2})$

Exercise 8: Translating a cube [2 Points]

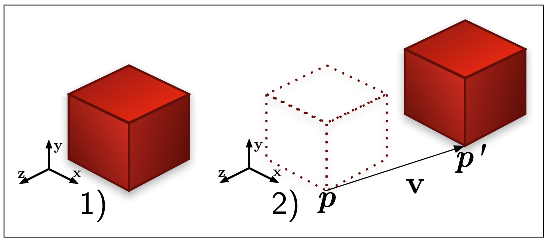


Figure 5: Translating a cube along a vector.

Be $\boldsymbol{p}$ with components p_x, p_y, p_z one point of a cube. Translate the cube along a vector $\mathbf{v}$ with components v_x, v_y, v_z as illustrated in Figure 5. How does the corresponding homogeneous transformation matrix $\mathbf{T}$, with $\boldsymbol{p}' = \mathbf{T}\boldsymbol{p}$ look like? (Assume column vector representation).

$$\mathbf{T} = \begin{bmatrix} \_\_\_\_ & \_\_\_\_ & \_\_\_\_ & \_\_\_\_ \\ \_\_\_\_ & \_\_\_\_ & \_\_\_\_ & \_\_\_\_ \\ \_\_\_\_ & \_\_\_\_ & \_\_\_\_ & \_\_\_\_ \\ \_\_\_\_ & \_\_\_\_ & \_\_\_\_ & \_\_\_\_ \end{bmatrix}$$

Exercise 9: Composite Transformations [2 Points]

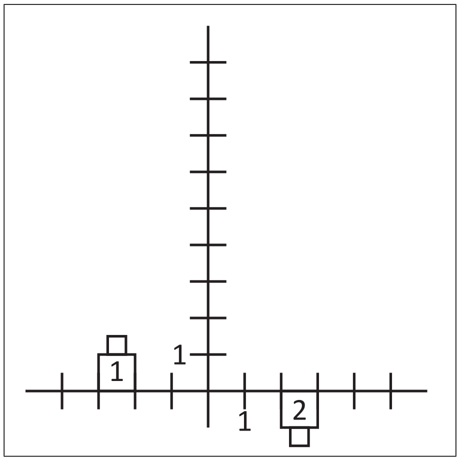


Figure 6: Composite Transformation

Complex transformations can be represented by composition of simple transformations. Have a look at figure 6. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = R_Z(-180°)$
- ☐ $T = T(3,0,0)R_Z(90°)R_Z(90°)T(2,0,0)$
- ☐ $T = T(2,0,0)R_Z(90°)R_Z(90°)T(2,0,0)$

Exercise 10: Properties of Rotations [2 Points]

Let A denote one of the base coordinate frame's axes X, Y und Z. Let α denote an arbitrary angle of rotation around this axis.

Which of the following properties apply to rotations $\mathbf{R}_A(\alpha)$ of angle α around A?

- ☐ $\mathbf{R}_A(0) = I$ (identity element)
- ☐ $\mathbf{R}_A(\alpha)^{-1} = \mathbf{R}_A(-\alpha)$
- ☐ $\mathbf{R}_A(\alpha)^{-1} = \mathbf{R}_{-A}(-\alpha)$
- ☐ $\mathbf{R}_A(\alpha)\mathbf{R}_A(\beta) = \mathbf{R}_A(\alpha\beta)$
- ☐ $\mathbf{R}_A(\alpha)\mathbf{R}_A(\beta) = \mathbf{R}_A(\beta)\mathbf{R}_A(\alpha)$
- ☐ $\mathbf{R}_A(\alpha)\mathbf{R}_B(\beta) = \mathbf{R}_B(\beta)\mathbf{R}_A(\alpha)$
- ☐ $\mathbf{R}_A(\alpha)^{-1} = \mathbf{R}_{-A}(\alpha)$

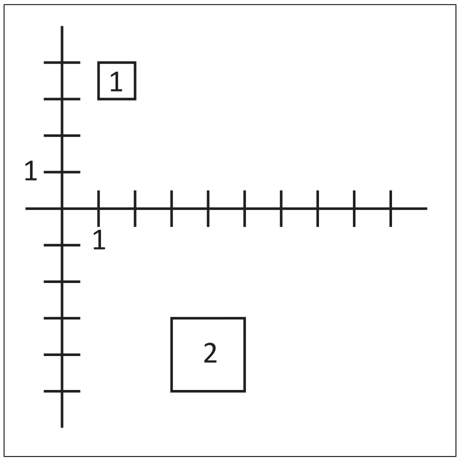


Figure 7: Composite Transformation

Exercise 11: Composite Transformations [2 Points]

Complex transformations can be represented by composition of simple transformations. Have a look at figure 7. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = T(1, -10, 0)S(2, 2, 2)$
- ☐ $T = T(1, 3, 0)R_X(180°)S(2, 2, 2)$
- ☐ $T = T(-1, -5, -2)S(2, 2, 2)T(1, -3, 1)$
- ☐ $T = T(1, -3, 1)T(1, -4, 1)S(2, 2, 2)$
- ☐ $T = R_X(-180°)T(-2, 0, 0)S(2, 2, 2)$

Exercise 12: Rotation around y-axis [2 Points]

Given a rotation matrix $\mathbf{R}$ which rotates 90 degrees around the y-axis in a right handed coordinate frame. Which transformation matrix specifies the correct rotation?

- ☐ $\mathbf{R} = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
- ☐ $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
- ☐ $\mathbf{R} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Exercise 13: Properties of Shears [2 Points]

Let a and b denote two of the axes X, Y, Z of a base coordinate system and let v a number.

Which of the following properties apply to shear transformations $H_{ab}(v)$?

- ☐ $H_{ab}(0) = I$ (Identity element)
- ☐ $H_{ab}(v) = H_{ba}(v)$
- ☐ $H_{ab}(1)H_{ab}(-1) = H_{ab}(0)$
- ☐ $H_{ab}^{-1}(v) = H_{ab}(-v)$
- ☐ $H_{ab}^{-1}(v) = H_{ab}(\frac{1}{x}, \frac{1}{y}, \frac{1}{z})$

Exercise 14: Composite Transformations [2 Points]

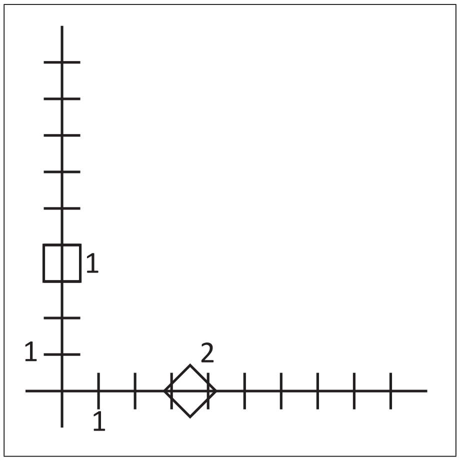


Figure 8: Composite Transformation

Complex transformations can be represented by composition of simple transformations. Have a look at figure 8. Which of the following transformation(s) T transform the object as shown in the figure? Assume a right-handed 3 dimensional coordinate system.

- ☐ $T = T(3, 0, 0)R_Z(45°)T(0, -3.5, 0)$
- ☐ $T = R_Z(-90°)R_Z(-45°)$
- ☐ $T = T(3.5, 0, 0)R_Z(45°)T(0, -3.5, 0)$

Exercise 15: Properties of Translations [2 Points]

Let x, y, z be the displacement components given a base coordinate system with axes X, Y, Z.

Which of the following properties apply to translations $T(x, y, z)$?

- ☐ $T(0, 0, 0) = I$ (Identity element)
- ☐ $T(x, y, z) = T(z, y, x)$
- ☐ $T(x_1, y_1, z_1)T(x_2, y_2, z_2) = T(x_1x_2, y_1y_2, z_1z_2,)$
- ☐ $T^{-1}(x, y, z) = T(-x, -y, -z)$
- ☐ $T^{-1}(x, y, z) = T(\frac{1}{x}, \frac{1}{y}, \frac{1}{z})$
- ☐ $T(x_1, y_1, z_1)T(x_2, y_2, z_2) = T(x_2, y_2, z_2)T(x_1, y_1, z_1)$

Exercise 16: Transforming a triangle [2 Points]

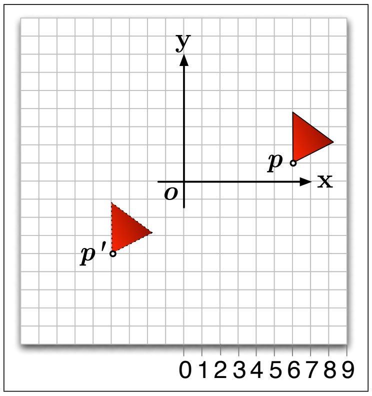


Figure 9: A triangle has to be translated from position $\boldsymbol{p}$ to position $\boldsymbol{p}'$.

Figure 9 illustrates a triangle with a given point $\boldsymbol{p}$ which has to be transformed to position $\boldsymbol{p}'$. Specify the acording transformation matrix $\mathbf{M}$ given a column representation of vectors and points. (Note that both $\boldsymbol{p}$ and $\boldsymbol{p}'$ have integer coordinates x and y.)

$$\mathbf{T} = \begin{bmatrix} \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \\ \text{----} & \text{----} & \text{----} & \text{----} \end{bmatrix}$$

C.6 Orbital Mechanics Knowledge Test - Phase 1

Used in:

- 7.3

Description: The effectiveness of Kerbal Space Program 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.

Raumfahrt-Fachkenntnisse - Part 1

Bitte beachten Sie, dass bei einigen Fragen mehrere Antworten korrekt sein können.

1. Was verursacht eine retrograde-orientierte Zündung des Triebwerks an der Periapsis?

☐ Ansteigen der Apoapsis
☐ Absinken der Apoapsis
☐ Ansteigen der Periapsis
☐ Absinken der Periapsis

2. Wie sieht ein Raketenaufstieg aus?

____
____
____
____

3. Welche Elemente beschreiben einen Orbit?

☐ Periapsis
☐ Apoapsis
☐ delta V
☐ Inklination

4. Der Prograde-Vektor während eines Orbitalflugs zeigt in welche Richtung?

☐ Nach Norden
☐ In Richtung des Orbits
☐ In die entgegengesetzte Richtung des Orbits
☐ Auf den Mittelpunkt des zentralen Körpers
☐ Auf den Äquator

5. Welche Bedingungen muss ein geostationärer Orbit erfüllen?

____
____
____
____

6. Was befindet sich an der Apoapsis?

☐ Höchster Punkt des Orbits
☐ Niedrigster Punkt des Orbits
☐ Aufsteigender Knoten
☐ Der Punkt, an dem der Orbit den Äquator kreuzt

7. Wovon hängt die Geschwindigkeit an der Apoapsis ab?

☐ Masse des Himmelskörpers
☐ Schubkraft des Triebwerks
☐ Höhe der Apoapsis
☐ Masse des Raumfahrzeugs
☐ Exzentrizität des Orbits

8. Welche Werte müssen für die Geschwindigkeitsvorratsberechnung bekannt sein?

☐ Leermasse, Treibstoffmasse, Spezifischer Impuls
☐ Startmasse, Treibstoffmasse, Spezifischer Impuls
☐ Gewicht der Nutzlast, Treibstoffmasse, Spezifischer Impuls
☐ Gewicht der Nutzlast, Startmasse, Spezifischer Impuls

9. Zwei Planeten mit dem selben Radius haben unterschiedliche Massen. Was stimmt?

☐ Das Raumschiff hat eine höhere Geschwindigkeit bei dem massiveren Planeten
☐ Das Raumschiff hat eine höhere Geschwindigkeit bei dem leichteren Planeten
☐ Die minimale Höhe für einen Orbit ist beim schwereren Planeten höher
☐ Die minimale Höhe für einen Orbit ist beim leichteren Planeten höher

Raumfahrt-Fachkenntnisse - Part 2

Bitte beachten Sie, dass bei einigen Fragen mehrere Antworten korrekt sein können.

1. Was verursacht eine prograde-orientierte Zündung des Triebwerks bei der Apoapsis?

☐ Ansteigen der Höhe der Periapsis
☐ Absinken der Höhe der Periapsis
☐ Veränderung der Inklination des Orbits
☐ Veränderung der Exzentrizität des Orbits
☐ Absinken der Höhe der Apoapsis
☐ Ansteigen der Höhe der Apoapsis

2. Warum ist ein Raketenstart in Richtung Osten in der Nähe des Äquators sehr günstig für einen äquatorialen Orbit?

____
____
____
____

3. Welche dieser Elemente gehören zu den Bahnelementen, die einen Orbit beschreiben?

☐ Exzentrizität
☐ Große Halbachse
☐ Apoapsis
☐ Masse des zentralen Himmelskörpers
☐ Hill-Sphäre

4. Der Retrograde-Vektor zeigt in welche Richtung?

☐ Nach Süden
☐ In Richtung des Orbits
☐ In die entgegengesetzte Richtung der Flugbahn
☐ Auf den Mittelpunkt des zentralen Himmelskörpers

5. Was unterscheidet einen geosynchronen Orbit von einem geostationären Orbit? Was haben beide Flugbahnen gemeinsam?

6. Was befindet sich an der Periapsis?

☐ Höchster Punkt des Orbits
☐ Niedrigster Punkt des Orbits
☐ Absteigender Knoten
☐ Wiedereintrittspunkt

7. Wovon hängt die Geschwindigkeit an der Periapsis ab?

☐ Masse des zentralen Himmelskörpers
☐ Schubkraft des Triebwerks
☐ Höhe der Apoapsis
☐ Masse des Raumfahrzeugs
☐ Exzentrizität des Orbits

8. Welche Werte müssen für die Geschwindigkeitsvorratsberechnung bekannt sein?

☐ Spezifischer Impuls des Triebwerks, Masse der Nutzlast, Startmasse, Leermasse
☐ Spezifischer Impuls des Triebwerks, Masse der Nutzlast, Startmasse, Masse des Treibstoffs, Schubkraft des Triebwerks
☐ Spezifischer Impuls des Triebwerks, Masse der Nutzlast, Startmasse, Flugdauer für einen Orbit, Schubkraft des Triebwerks
☐ Spezifischer Impuls des Triebwerks, Masse der Nutzlast, Masse des Treibstoffs, Leermasse

9. Was muss für die Berechnung der Flugzeit für einen kompletten kreisförmigen Orbit bekannt sein?

☐ Radius des Orbits, Masse des zentralen Himmelskörpers

☐ Radius des Orbits, Masse des zentralen Himmelskörpers, Schubkraft des Triebwerks

☐ Radius des Orbits, Masse des zentralen Himmelskörpers, Inklination des Orbits

☐ Radius des Orbits, Masse des zentralen Himmelskörpers, Geschwindigkeit des Raumschiffes

C.7 Orbital Mechanics Knowledge Test - Phase 2

Used in:

- 7.3

Description: The effectiveness of Kerbal Space Program 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.

Raumfahrt-Fachkenntnisse - Test

Aufgabe 1 - Geschwindkeitsbedarf

Sie starten auf einem kreisförmigen $300km$ Erdorbit mit 5° Inklination. Das Ziel ist ein kreisförmiger $1000km$ Orbit mit 10° Inklination.

a) Beschreiben Sie die hierfür nötigen Manöver. (Punkte, an denen diese ausgeführt werden, Fachbegriffe, Richtung, ...)

b) Berechnen Sie den nötigen Geschwindigkeitsbedarf.

Aufgabe 2 - Geschwindkeitsvorrat

Gegeben ist eine 2-stufige Trägerrakete:
1. Stufe: $20t$ Struktur, $230t$ Treibstoff, $ce = 3000\frac{m}{s}$
2. Stufe: $1t$ Struktur, $14t$ Treibstoff, $ce = 4000\frac{m}{s}$
Nutzlast: $5t$

a) Berechnen Sie den Geschwindigkeitsvorrat der gesamten Trägerrakete.

b) Wie viel Treibstoff muss die Nutzlast der Rakete bei einer Ausströmgeschwindigkeit von $3000\frac{m}{s}$ enthalten, damit ein Geschwindigkeitsbedarf der gesamten Mission von $13000\frac{m}{s}$ erfüllt werden kann?

Aufgabe 3 - Geostationärer Orbit

a) Was ist ein geostationärer Orbit? Welche Eigenschaften hat er?

b) Berechnen Sie die Höhe des stationären Mars-Orbits.

Benötigte Konstanten

$G = 6.674 * 10^{-11} \frac{m^3}{kg\, s^2}$
$M_{Erde} = 5.974 * 10^{24}\, kg$
$R_{Erde} = 6.371 * 10^{6}\, m$
$M_{Mars} = 6.419 * 10^{23}\, kg$
$R_{Mars} = 3.386 * 10^{6}\, m$
Rotationsperiode des Mars: $T = 24h,\ 37min = 88620s$

Bibliography

Adams, E. and Dormans, J. *Game Mechanics*. Advanced Game Design. New Riders, Berkeley, 2012.

Ambrose, S. H. Coevolution of Composite-Tool Technology, Constructive Memory, and Language. *Current Anthropology*, 51(1):135–147, 2010. doi: 10.1086/650296.

Amory, A., Naicker, K., Vincent, J., and Adams, C. The use of computer games as an educational tool: identification of appropriate game types and game elements. *British Journal of Educational Technology*, 30(4):311–321, 1999. doi: 10.1111/1467-8535.00121.

Anderson, E. F., McLoughlin, L., Liarokapis, F., Peters, C., Petridis, P., and de Freitas, S. Serious Games in Cultural Heritage. In *Proceedings of the 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST*, pages 29–48, Valletta, Malta, September 2009.

Anderson, J. R. *Cognitive Psychology and Its Implications*. Worth Publishers, 8th edition, 2015.

Andrews, S. F. *The Guild Leader's Handbook: Strategies and Guidance from a Battle-Scarred MMO Veteran*. No Starch Press, San Francisco, 1st edition, 2010.

Annetta, L. A., Minogue, J., Holmes, S. Y., and Cheng, M.-T. Investigating the impact of video games on high school students' engagement and learning about genetics. *Computers & Education*, 53:74–85, 2009. doi: 10.1016/j.compedu.2008.12.020.

Arnab, S., Lim, T., Carvalho, M. B., Bellotti, F., de Freitas, S., Louchart, S., Suttie, N., Berta, R., and De Gloria, A. Mapping learning and game mechanics for serious games analysis. *British Journal of Educational Technology*, 46(2): 391–411, 2015. doi: 10.1111/bjet.12113.

Bartle, R. A. Hearts, Clubs, Diamonds, Spades: Players Who Suit MUDs. *Journal of MUD Research*, 1(1), 1996.

Blizzard Entertainment. World of Warcraft. available at https://www.blizzard.com, 2004–2019.

Bouchard, S., Robillard, G., St-Jacques, J., Dumoulin, S., Patry, M.-J., and Renaud, P. Reliability and Validity of a Single-Item Measure of Presence in VR. In *Proceedings of the 3rd IEEE International Workshop on Haptic, Audio and Visual Environments and Their Applications - HAVE 2004*, pages 59–61. IEEE, 2004. doi: 10.1109/HAVE.2004.1391882.

Bowman, D. A., McMahan, R. P., and Ragan, E. D. Questioning Naturalism in 3D User Interfaces. *Communications of the ACM*, 55(9):78–88, 2012. doi: 10.1145/2330667.2330687.

Bremner, J. D., Krystal, J. H., Putnam, F. W., Southwick, S. M., Marmar, C., Charney, D. S., and Mazure, C. M. Measurement of Dissociative States with the Clinician-Administered Dissociative States Scale (CADSS). *Journal of Traumatic Stress*, 11(1):125–136, 1998. doi: 10.1023/A:1024465317902.

Brophy, J. *Teaching*, volume 1 of *Educational Practices Series*. International Academy of Education & International Bureau of Education, Brussels, 2000.

Brown, E. and Cairns, P. A Grounded Investigation of Game Immersion. In *CHI '04 Extended Abstracts on Human Factors in Computing Systems*, pages 1297–1300, Vienna, Austria, April 2004. ACM. doi: 10.1145/985921.986048.

Caillois, R. *Man, Play and Games*. University of Illinois Press, Champaign, 1st edition, 2001.

Charsky, D. From Edutainment to Serious Games: A Change in the Use of Game Characteristics. *Games and Culture*, 5(2):177–198, 2010. doi: 10.1177/1555412009354727.

Cheng, M. T., Shet, H. C., and Annetta, L. A. Game immersion experience: its hierarchical structure and impact on game-based science learning. *Journal of Computer Assisted Learning*, 31:232–253, 2014. doi: 10.1111/jcal.12066.

Cherney, I. D. Mom, Let Me Play More Computer Games: They Improve My Mental Rotation Skills. *Sex Roles*, 59(11-12):776–786, 2008. doi: 10.1007/s11199-008-9498-z.

Chi, M. T. H., Feltovich, P. J., and Glaser, R. Categorization and Representation of Physics Problems by Experts and Novices. *Cognitive Science*, 5(2):121–152, 1981.

Colzato, L. S., van den Wildenberg, W. P. M., Zmigrod, S., and Hommel, B. Action video gaming and cognitive control: playing first person shooter games is associated with improvement in working memory but not action inhibition. *Psychological Research*, 77:234–239, 2013. doi: 10.1007/s00426-012-0415-2.

Craik, F. I. M. and Tulving, E. Depth of Processing and the Retention of Words in Episodic Memory. *Journal of Experimental Psychology*, 104(3):268–294, 1975. doi: 10.1037/0096-3445.104.3.268.

Csikszentmihalyi, M. *Flow: The Psychology of Optimal Experience*. Harper-Perennial, New York, NY, USA, 1990.

Dalgarno, B. and Lee, M. J. W. What are the learning affordances of 3-D virtual environments? *British Journal of Educational Technology*, 41(1):10–32, 2010. doi: 10.1111/j.1467-8535.2009.01038.x.

de Freitas, S. and Liarokapis, F. Serious Games: A New Paradigm for Education? In Ma, M., Oikonomou, A., and Jain, L. C., editors, *Serious Games and Edutainment Applications*, pages 9–23. Springer-Verlag, London, 2011. doi: 10.1007/978-1-4471-2161-9_2.

Debeauvais, T., Nardi, B., Schiano, D. J., Ducheneaut, N., and Yee, N. If You Build It They Might Stay: Retention Mechanisms in World of Warcraft. In *Proceedings of the 6th International Conference on Foundations of Digital Games (FDG '11)*, pages 180–187, Bordeaux, France, June & July 2011. ACM. doi: 10.1145/2159365.2159390.

Dede, C. J. Immersive Interfaces for Engagement and Learning. *Science*, 323, 2009.

Dede, C. J., Jacobson, J., and Richards, J. Introduction: Virtual, Augmented, and Mixed Realities in Education. In Liu, D., Dede, C. J., Huang, R., and Richards, J., editors, *Virtual, Augmented, and Mixed Realities in Education*, Smart Computing and Intelligence. Springer, Singapoore, 2017.

Deterding, S., Dixon, D., Khaled, R., and Nacke, L. From game design elements to gamefulness: defining "gamification". In *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments (MindTrek '11)*, pages 9–15, Tampere, Finland, September 2011. ACM. doi: 10.1145/2181037.2181040.

Driscoll, M. P. *Psychology of Learning for Instruction*. Pearson Education Limited, 3rd edition, 2013.

E-Line Media. Never Alone. available at http://neveralonegame.com, 2016.

Ericsson, K. A., Krampe, R. T., and Tesch-Römer, C. The Role of Deliberate Practice in the Acquisition of Expert Performance. *Psychological Review*, 100(3):363–406, 1993. doi: 10.1037/0033-295X.100.3.363.

Fitts, P. M. and Posner, M. I. *Human performance*. Brooks Cole, 1967.

Foley, J., van Dam, A., Feiner, S., and Hughes, J. *Computer Graphics: Principles and Practice*. Addison-WesleySystems Programming Series. Addison-Wesley, Reading, MA, USA, 1990.

Freina, L. and Ott, M. A Literature Review on Immersive Virtual Reality in Education: State Of The Art and Perspectives. In *Proceedings of the 11th eLearning and Software for Education (eLSE '15)*, Bucharest, Romania, April 2015.

Fu, K. S., Gonzalez, R., and Lee, C. S. G. *Robotics: Control, Sensing, Vision and Intelligence*. McGraw-Hill Education, New York, 1987.

Gagné, R. M. Learning Outcomes and Their Effects: Useful Categories of Human Performance. *American Psychologist*, 39(4):377–385, 1984. doi: 10.1037/0003-066X.39.4.377.

Galloway, A. R. *Gaming: Essays on algorithmic culture*, volume 18. U of Minnesota Press, 2006.

Gee, J. P. *What video games have to teach us about learning and literacy*. Palgrave Macmillan, New York, 1st edition, 2007.

Gibson, J. J. *The Ecological Approach to Visual Perception*. Houghton Mifflin, Boston, 1979.

Gittler, G. and Glück, J. Differential Transfer of Learning: Effects of Instruction in Descriptive Geometry on Spatial Test Performance. *Journal of Geometry and Graphics*, 2(1):71–84, 1998.

Gladwell, M. *Outliers: The Story of Success.* Penguin, 2008.

Glass, B. D., Maddox, W. T., and Love, B. C. Real-Time Strategy Game Training: Emergence of a Cognitive Flexibility Trait. *PLoS ONE*, 8(8):e70350, 2013. doi: 10.1371/journal.pone.0070350.

Goh, S. H. and Wasko, M. M. Leadership in MMOGS: Emergent and Transformational Leadership Candidates. In *Proceedings of the 15th Americas Conference on Information Systems (AMCIS '09)*, San Francisco, California, USA, 2009.

Green, C. S. and Bavelier, D. Action video game modifies visual selective attention. *Nature*, 423(6939):534–537, 2003. doi: 10.1038/nature01647.

Green, C. S. and Bavelier, D. Action-Video-Game Experience Alters the Spatial Resolution of Vision. *Psychological Science*, 18(1):88–94, 2007. doi: 10.1111/j.1467-9280.2007.01853.x.

Gurr, A. Video Games and the Challenge of Engaging the 'Net' Generation. In Kaufman, D. and Sauvé, L., editors, *Educational Gameplay and Simulation Environments: Case Studies and Lessons Learned*, chapter 8, pages 119–131. Information Science Reference, Hershey, PA, USA, 2010. doi: 10.4018/978-1-61520-731-2.ch008.

Hart, S. G. and Staveland, L. E. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In Hancock, P. A. and Meshkati, N., editors, *Human Mental Workload*, pages 139–183. Elsevier Science Publishers B.V., Amsterdam, 1988.

Heidrich, D., Oberdörfer, S., and Latoschik, M. E. The Effects of Immersion on Harm-Inducing Factors in Virtual Slot Machines. In *Proceedings of the 26th IEEE Virtual Reality conference (VR '19)*, Osaka, Japan, March 2019. IEEE, ©2019 IEEE. Reprinted, with permission.

Hoffmann, J. and Engelkamp, J. *Lern- und Gedächtnispsychologie*. Springer-Verlag, 2013.

Jennett, C., Cox, A., Cairns, P., Dhoparee, S., Epps, A., Tijs, T., and Walton, A. Measuring and defining the experience of immersion in games. *International Journal of Human-Computer Studies*, 66:641–661, 2008. doi: 10.1016/j.ijhcs.2008.04.004.

Johnson-Laird, P. N. *Mental Models. Towards a Cognitive Science of Language, Inference, and Consciousness*. Harvard University Press, 1983.

Joorabchi, M. E. and El-Nasr, M. S. Measuring the Impact of Knowledge Gained from Playing FPS and RPG Games on Gameplay Performance. In *Entertainment Computing – ICEC 2011*, pages 300–306, Vancouver, BC, Canada, October 2011. Springer. doi: 10.1007/978-3-642-24500-8_33.

Kaptelinin, V. and Nardi, B. A. Affordances in HCI: Toward a Mediated Action Perspective. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*, pages 967–976, Austin, TX, USA, May 2012. ACM. doi: 10.1145/2207676.2208541.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, 3(3):203–220, 1993. doi: 10.1207/s15327108ijap0303_3.

Kerres, M. *Mediendidaktik: Konzeption und Entwicklung digitaler Lernangebote*. De Gruyter, Berlin/Boston, 5th edition, 2018.

Klisch, Y., Miller, L. M., Beier, M. E., and Wang, S. Teaching the Biological Consequences of Alcohol Abuse through an Online Game: Impacts among Secondary Students. *CBE - Life Sciences Education*, 11(1):94–102, 2012. doi: 10.1187/cbe.11-04-0040.

Krzywinska, T. Arachne Challenges Minerva: The Spinning Out of Long Narrative in World of Warcraft and Buffy the Vampire Slayer. In Harrigan, P. and Wardrip-Fruin, N., editors, *Third person: Authoring and Exploring Vast Narratives*, pages 385–398. MIT Press, Cambridge, Massachusetts, 2009.

Ladouceur, R. and Sevigny, S. The impact of video lottery game speed on gamblers. *Journal of Gambling Issues*, (17), 2006. doi: 10.4309/jgi.2006.17.12.

Lombard, M. and Ditton, T. At the Heart of It All: The Concept of Presence. *Journal of Computer-Mediated Communication*, 3(2), 1997. doi: 10.1111/j.1083-6101.1997.tb00072.x.

Lugrin, J.-L., Latoschik, M. E., Habel, M., Roth, D., Seufert, C., and Grafe, S. Breaking Bad Behaviours: A New Tool for Learning Classroom Management using Virtual Reality. *Frontiers in ICT*, 3:26, 2016. doi: 10.3389/fict.2016.00026.

Lugrin, J.-L., Charles, F., Habel, M., Dudaczy, H., Oberdörfer, S., Matthews, J., Porteous, J., Wittmann, A., Seufert, C., Grafe, S., and Latoschik, M. E. Benchmark Framework for Virtual Students' Behaviours. In *Proceedings of the 17th International Conference on Autonomous Agents, Multiagent Systems (AAMAS '18)*, pages 2236–2238, Stockholm, Sweden, 2018a. International Foundation for Autonomous Agents and Multiagent Systems.

Lugrin, J.-L., Oberdörfer, S., Latoschik, M. E., Wittmann, A., Seufert, C., and Grafe, S. VR-Assisted vs Video-Assisted Teacher Training. In *Proceedings of the 25th IEEE Virtual Reality conference (VR '18)*, pages 625–626, Reutlingen, Germany, 2018b. IEEE. doi: 10.1109/VR.2018.8446312.

Lv, Z., Tek, A., Da Silva, F., Empereur-mot, C., Chavent, M., and Baaden, M. Game On, Science - How Video Game Technology May Help Biologists Tackle Visualization Challenges. *PLoS ONE*, 8(3):e57990, 2013. doi: 10.1371/journal.pone.0057990.

Lynam, T., Mathevet, R., Etienne, M., Stone-Jovicich, S., Leitch, A., Jones, N., Ross, H., Du Toit, D., Pollard, S., Biggs, H., and Perez, P. Waypoints on a Journey of Discovery: Mental Models in Human-Environment Interactions. *Ecology and Society*, 17(3), 2012. doi: 10.5751/ES-05118-170323.

Makransky, G. and Lilleholt, L. A structural equation modeling investigation of the emotional value of immersive virtual reality in education. *Educational Technology Research and Development*, 2018. doi: 10.1007/s11423-018-9581-2.

Martin, A. The Representation of Object Concepts in the Brain. *Annual Review of Psychology*, 58:25–45, 2007. doi: 10.1146/annurev.psych.57.102904.190143.

Martín-Gutiérrez, J., Mora, C. E., Añorbe-Díaz, B., and González-Marrero, A. Virtual Technologies Trends in Education. *EURASIA Journal of Mathematics Science and Technology Education*, 13(2):469–486, 2017. doi: 10.12973/eurasia.2017.00626a.

McGonigal, J. *Reality is Broken: Why Games Make Us Better and How They Can Change the World*. Penguin Press, New York, 1st edition, 2011.

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., and Davis, T. J. Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education*, 70:29–40, 2014. doi: 10.1016/j.compedu.2013.07.033.

Mestre, J. *Transfer of Learning: Issues and Research Agenda*. National Science Foundation, Washington, D.C., 2002.

Miller, L. M., Chang, C.-I., Wang, S., Beier, M. E., and Klisch, Y. Learning and motivational impacts of a multimedia science game. *Computers & Education*, 57(1):1425–1433, 2011. doi: 10.1016/j.compedu.2011.01.016.

Moser, A., dos Santos, N., and Corcini, L. F. Immersive 3D Virtual and Gamified Environment: The Learner Model Approach. *Journal of Research & Method in Education*, 7(3):26–35, 2017. doi: 10.9790/7388-0703012635.

Nacke, L. E. *Affective Ludology: Scientific Measurement of User Experience in Interactive Entertainment*. PhD thesis, Blekinge Institute of Technology, School of Computing, 2009.

Naumann, A. and Hurtienne, J. Benchmarks for Intuitive Interaction with Mobile Devices. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '10)*, pages 401–402, Lisboa, Portugal, September 2010. ACM. doi: 10.1145/1851600.1851685.

Nickols, F. The Knowledge in Knowledge Management. *The Knowledge Management Yearbook 2000-2001*, pages 12–21, 2000.

Norman, D. A. *The Psychology of Everyday Things*. Basic Books, New York, 1988.

Norman, D. A. Affordance, Conventions, and Design. *interactions*, 6(3):38–42, 1999. doi: 10.1145/301153.301168.

Oberdörfer, S. and Latoschik, M. E. Develop your strengths by gaming: Towards an inventory of gamificationable skills. In Horbach, M., editor, *Informatik 2013 – Informatik angepasst an Mensch, Organisation und Umwelt*, pages 2346–2357, Koblenz, Germany, September 2013. Gesellschaft für Informatik e.V.

Oberdörfer, S. and Latoschik, M. E. Interactive gamified 3D-training of affine transformations. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*, pages 343–344, Munich, Germany, 2016. ACM. doi: 10.1145/2993369.2996314.

Oberdörfer, S. and Latoschik, M. E. Gamified Knowledge Encoding: Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games '18)*, Würzburg, Germany, September 2018a. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493425.

Oberdörfer, S. and Latoschik, M. E. Effectivity of Affine Transformation Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applica-*

tions (VS Games '18), Würzburg, Germany, September 2018b. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493418.

Oberdörfer, S. and Latoschik, M. E. Effective Orbital Mechanics Knowledge Training Using Game Mechanics. In *Proceedings of the 10th International Conference on Virtual Worlds and Games for Serious Applications (VS Games '18)*, Würzburg, Germany, September 2018c. ©2018 IEEE. Reprinted, with permission. doi: 10.1109/VS-Games.2018.8493417.

Oberdörfer, S. and Latoschik, M. E. Knowledge Encoding in Game Mechanics: Transfer-Oriented Knowledge Learning in Desktop-3D and VR. *International Journal of Computer Games Technology*, 2019, 2019. doi: 10.1155/2019/7626349.

Oberdörfer, S., Heidrich, D., and Latoschik, M. E. Interactive Gamified Virtual Reality Training of Affine Transformations. In Ullrich, C. and Wessner, M., editors, *Proceedings of DeLFI and GMW Workshops 2017*, Chemnitz, Germany, 2017.

Oberdörfer, S., Fischbach, M., and Latoschik, M. E. Effects of VE Transition Techniques on Presence, IVBO, Efficiency, and Naturalness. In *Proceedings of the 6th Symposium on Spatial User Interaction (SUI '18)*, pages 89–99, Berlin, Germany, October 2018. ACM. doi: 10.1145/3267782.3267787.

Oberdörfer, S., Heidrich, D., and Latoschik, M. E. Usability of Gamified Knowledge Learning in VR and Desktop-3D. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*, pages 175:1–175:13, Glasgow, Scotland UK, May 2019. ACM. doi: 10.1145/3290605.3300405.

Oei, A. C. and Patterson, M. D. Enhancing Cognition with Video Games: A Multiple Game Training Study. *PLoS ONE*, 8(3):e58546, 2013. doi: 10.1371/journal.pone.0058546.

Palmunen, L.-M., Pelto, E., Paalumäki, A., and Lainema, T. Formation of Novice Business Students' Mental Models Through Simulation Gaming. *Simulation & Gaming*, 44(6):846–868, 2013. doi: 10.1177/1046878113513532.

Perry, D. and DeMaria, R. *David Perry on Game Design: A Brainstorming Toolbox*. Course Technology, Boston, MA, USA, 2009.

Pezzulo, G. Grounding Procedural and Declarative Knowledge in Sensorimotor Anticipation. *Mind & Language*, 26(1):78–114, 2011. doi: 10.1111/j.1468-0017.2010.01411.x.

Pittalis, M. and Christou, C. Types of reasoning in 3D geometry thinking and their relation with spatial ability. *Educational Studies in Mathematics*, 75(2): 191–212, 2010. doi: 10.1007/s10649-010-9251-8.

Power, M. and Langlois, L. Designing a Simulator for Teaching Ethical Decision-Making. In Kaufman, D. and Sauvé, L., editors, *Educational Gameplay and Simulation Environments: Case Studies and Lessons Learned*, chapter 10, pages 146–158. Information Science Reference, Hershey, PA, USA, 2010. doi: 10.4018/978-1-61520-731-2.ch010.

Prax, P. Leadership Style in World of Warcraft Raid Guilds. In *Proceedings of the 2010 International DiGRA Nordic Conference: Experiencing Games: Games, Play, and Players (DiGRA Nordic '10)*, Stockholm, Sweden, 2010. DiGRA.

Pugh, L. *21 Yaks and a Speedo*. Our Blue Future, London, UK, 2013.

Qiu, L., Tay, W. W., and Wu, J. The Impact of Virtual Teamwork on Real-world Collaboration. In *Proceedings of the International Conference on Advances in Computer Enterntainment Technology (ACE '09)*, pages 44–51, Athens, Greece, October 2009. ACM. doi: 10.1145/1690388.1690396.

Rasmussen, J. Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. *IEEE Transactions on Systems, Man, and Cybernetics*, 13(3):257–266, 1983. doi: 10.1109/TSMC.1983.6313160.

Raylu, N. and Oei, T. P. S. The Gambling Urge Scale: Development, Confirmatory Factor Validation, and Psychometric Properties. *Psychology of Addictive Behaviors*, 18(2):100–1005, 2004. doi: 10.1037/0893-164X.18.2.100.

Reber, A. S. Implicit Learning and Tacit Knowledge. *Journal of Experimental Psychology*, 118(3):219–235, 1989. doi: 10.1037/0096-3445.118.3.219.

Reeves, B., Malone, T. W., and O'Discoll, T. Leadership's Online Labs. *Harvard Business Review*, 86(5):58–66, 2008.

Rheinberg, F., Vollmeyer, R., and Engeser, S. Die Erfassung des Flow-Erlebens. In Stiensmeier-Pelster, J. and Rheinberg, F., editors, *Diagnostik von Motivation und Selbstkonzept*, pages 261–279. Hogrefe, Göttingen, 2003.

Richter, S. and Lechner, U. Communication Content Relations to Coordination and Trust over Time: A Computer Game Perspective. In *Proceedings of the 5th International Conference on Communities and Technologies (C&T '11)*, pages 60–68, Brisbane, Australia, June & July 2011. ACM. doi: 10.1145/2103354.2103363.

Riegle, R. P. and Matejka, W. A. The Learning Guild: MMORPGs as Educational Environments. In *Proceedings of the 22nd Annual Conference on Distance Teaching and Learning*, 2006.

Ritterfeld, U. and Weber, R. Video Games for Entertainment and Education. In Vorderer, P. and Bryant, J., editors, *Playing Video Games: Motives, Responses, and Consequences*, chapter 26, pages 399–413. Lawrence Erlbaum Associates Inc, 2006.

Rogers, C. B., El-Mounaryi, H., Wasfy, T., and Satterwhite, J. Assessment of STEM e-Learning in an Immersive Virtual Reality (VR) Environment. *Computers in Education Journal*, 8(4), 2017.

Rosser, J. C., Jr, Lynch, P. J., Cuddihy, L., Gentile, D. A., Klonsky, J., and Merrell, R. The Impact of Video Games on Training Surgeons in the 21st Century. *Archives of Surgery*, 142(2):181–186, 2007. doi: 10.1001/archsurg.142.2.181.

Roth, D., Lugrin, J.-L., Latoschik, M. E., and Huber, S. Alpha IVBO - Construction of a Scale to Measure the Illusion of Virtual Body Ownership. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '17)*, pages 2875–2883, Denver, Colorado, USA, May 2017. ACM. doi: 10.1145/3027063.3053272.

Salomoni, P., Prandi, C., Roccetti, M., Casanova, L., and Marchetti, L. Assessing the Efficacy of a Diegetic Game Interface with Oculus Rift. In *Proceedings of the 13th IEEE Annual Consumer Communications & Networking Conference (CCNC '16)*, pages 387–392, Las Vegas, Nevada, USA, January 2016. IEEE. doi: 10.1109/CCNC.2016.7444811.

Sauvé, L. Effective Educational Games. In Kaufman, D. and Sauvé, L., editors, *Educational Gameplay and Simulation Environments: Case Studies and Lessons Learned*, chapter 2, pages 27–50. Information Science Reference, Hershey, PA, USA, 2010. doi: 10.4018/978-1-61520-731-2.ch002.

Schroeder, R. *Being There Together: Social Interaction in Virtual Environments*. Oxford University Press, New York, 1st edition, 2011.

Schulzke, M. Moral Decision Making in Fallout. *The International Journal of Computer Game Research*, 9(2), 2009.

Seaborn, K. and Fels, D. I. Gamification in theory and action: A survey. *International Journal of Human-Computer Studies*, 74:14–31, 2015. doi: 10.1016/j.ijhcs.2014.09.006.

Seel, N. M. *Psychologie des Lernens*. Reinhardt Verlag, 2nd edition, 2003.

Sherry, J. L. Flow and Media Enjoyment. *Communication Theory*, 14(4):328–347, 2004. doi: 10.1111/j.1468-2885.2004.tb00318.x.

Shute, V. J., Ventura, M., and Ke, F. The power of play: The effects of Portal 2 and Lumosity on cognitive and noncognitive skills. *Computers & Education*, 80:58–67, 2015. doi: http://dx.doi.org/10.1016/j.compedu.2014.08.013.

Sicart, M. Defining Game Mechanics. *The International Journal of Computer Game Research*, 8(2), 2008.

Siewiorek, A. and Gegenfurtner, A. Leading to Win: The Influence of Leadership Styles on Team Performance During a Computer Game Training. In *Proceedings of the 9th International Conference of the Learning Sciences (ICLS '10)*, pages 524–531, Chicago, IL, USA, June & July 2010. International Society of the Learning Sciences.

Simon, H. and Chase, W. Skill in Chess. *American Scientist*, 61(4):394–403, 1973.

Slater, M. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B*, 364:3549–3557, 2009. doi: 10.1098/rstb.2009.0138.

Slater, M. Implicit Learning Through Embodiment in Immersive Virtual Reality. In Liu, D., Dede, C. J., Huang, R., and Richards, J., editors, *Virtual, Augmented, and Mixed Realities in Education*, Smart Computing and Intelligence. Springer, Singapoore, 2017.

Slater, M. and Wilbur, S. A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. *Presence*, 6(6):603–616, 1997. doi: 10.1162/pres.1997.6.6.603.

Slater, M., Linakis, V., Usoh, M., and Kooper, R. Immersion, Presence, and Performance in Virtual Environments: An Experiment with Tri-Dimensional Chess. In *Proceedings of the ACM Symposium on Virtual Reality Software* *and Technology (VRST '96)*, pages 163–172, Hong Kong, July 1996. ACM. doi: 10.1145/3304181.3304216.

Squire, L. R. Declarative and Nondeclarative Memory: Multiple Brain Systems Supporting Learning and Memory. *Journal of Cognitive Neuroscience*, 4(3): 232–243, 1992. doi: 10.1162/jocn.1992.4.3.232.

Squire, L. R. Memory systems of the brain: A brief history and current perspective. *Neurobiology of Learning and Memory*, 82:171–177, 2004. doi: 10.1016/j.nlm.2004.06.005.

Stevens, J. A. and Kincaid, J. P. The Relationship between Presence and Performance in Virtual Simulation Training. *Open Journal of Modelling and Simulation*, 3:41–48, 2015. doi: 10.4236/ojmsi.2015.32005.

Take-Two Interactive, Inc. Kerbal Space Program. available at https://kerbalspaceprogram.com, 2011–2019.

Tang, S., Hanneghan, M., and Carter, C. A Platform Independent Game Technology Model for Model Driven Serious Games Development. *The Electronic Journal of e-Learning*, 11(1):61–79, 2013.

ten Berge, T. and van Hezewijk, R. Procedural and Declarative Knowledge - An Evolutionary Perspective. *Theory & Psychology*, 9(5):605–624, 1999. doi: 10.1177/0959354399095002.

Tobinski, D. A. *Kognitive Psychologie - Problemlösen, Komplexität und Gedächtnis*. Springer-Verlag, 2017.

Tolkien, J. R. R. *The Lord of the Rings*. Houghton Mifflin Harcourt, 50th anniversary edition, 2012.

Tulodziecki, G., Herzig, B., and Grafe, S. *Medienbildung in Schule und Unterricht*. Julius Klinkhardt, 2010.

Ur, P. *A Course in Language Teaching*. Cambridge University Press, 1996.

Voiskounsky, A. E., Mitina, O. V., and Avetisova, A. A. Playing Online Games: Flow Experience. *PsychNology*, 2(3):259–281, 2004.

Weibel, D. and Wissmath, B. Immersion in Computer Games: The Role of Spatial Presence and Flow. *International Journal of Computer Games Technology*, 2011, 2011. doi: 10.1155/2011/282345.

Weidenmann, B. Multimedia, Multicodierung und Multimodalität beim Online-Lernen. In Issing, L. J. and Klimsa, P., editors, *Online Lernen. Handbuch für Wissenschaft und Praxis*, chapter 5, pages 73–86. Oldenbourg, 2009.

Weir, A. *The Martian*. Crown Publishers, 1st edition, 2014.

Wen, Z. A., Lin, Z., Chen, R., and Andersen, E. What.Hack: Engaging Anti-Phishing Training Through a Role-playing Phishing Simulation Game. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*, pages 108:1–108:12, Glasgow, Scotland UK, May 2019. ACM. doi: 10.1145/3290605.3300338.

Williams, D., Ducheneaut, N., Xiong, L., Zhang, Y., Yee, N., and Nickell, E. From Tree House to Barracks: The Social Life of Guilds in World of Warcraft. *Games and Culture*, 1(4):338–361, 2006. doi: 10.1177/1555412006292616.

Wirth, W., Hartmann, T., Böcking, S., Vorderer, P., Klimmt, C., Schramm, H., Saari, T., Laarni, J., Ravaja, N., Gouveia, F. R., Biocca, F., Sacau, A., Jäncke, L., Baumgartner, T., and Jäncke, P. A Process Model of the Formation of Spatial Presence Experiences. *Media Psychology*, 9(3):493–525, 2007. doi: 10.1080/15213260701283079.

Witmer, B. G. and Singer, M. J. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence*, 7(3):225–240, 1998. doi: 10.1162/105474698565686.

Witmer, B. G., Jerome, C. J., and Singer, M. J. The Factor Structure of the Presence Questionnaire. *Presence*, 14(3):298–314, 2005. doi: 10.1162/105474605323384654.

Woltz, D. J. and Shute, V. J. Individual Difference in Repetition Individual Difference in Repetition Priming and Its Relationship to Declarative Knowledge Acquisition. *Intelligence*, 17:333–359, 1993. doi: 10.1016/0160-2896(93)90004-O.

Yee, N. The Demographics, Motivations, and Derived Experiences of Users of Massively Multi-User Online Graphical Environments. *Presence*, 15(3): 309–329, 2006. doi: 10.1162/pres.15.3.309.

Yee, N. Befriending Ogres and Wood-Elves: Relationship Formation and The Social Architecture of Norrath. *The International Journal of Computer Game Research*, 9(1), 2009.