Evaluating Learning Outcomes and Intrinsic Motivation: A Case Study of DS-Hacker 3D

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Abstract. This paper presents a comprehensive evaluation of an educational video game, *DS-Hacker 3D*, that incorporates analogies to enhance the learning of conceptual knowledge in computer science, specifically Binary Search Tree (BST) concepts. The study addresses the challenges students face in understanding complex computer science topics and the limited availability of well-evaluated educational video games in the field. *DS-Hacker 3D* targets undergraduate students and follows a constructivist learning approach, establishing connections between new information and familiar knowledge through analogies. The evaluation includes validated assessment tools to measure learning outcomes and intrinsic motivation. The results demonstrate the effectiveness of the educational video game in facilitating the acquisition of BST conceptual knowledge and promoting intrinsic motivation. The study contributes to the development of educational video games for teaching computer science concepts.

Keywords: Analogies · Binary Search Tree · Digital Game-Based Learning · Educational Video Games

1 Introduction

Computer science is a vast field filled with complex concepts and models, often posing challenges for students to comprehend and grasp [18, 29]. Research focusing on misconceptions and learning difficulties in computer science indicates that novice learners commonly encounter difficulties in understanding various topics, including logic [29, 41], programming concepts [11, 13, 18, 37, 38], data structures [4, 10, 46], and computer architecture conceptual knowledge [29, 41]. Consequently, even upon completing introductory computer science courses, students may still struggle to grasp the basic principles of programming or to write simple code [25].

In a literature review on programming misconceptions conducted by Qian and Lehman [29], six factors contributing to learning difficulties were identified: (1) the complexity of learning activities, (2) misconceptions arising from natural language, (3) students' lack of mathematical knowledge, (4) inaccurate mental models, (5) inadequate strategies for solving abstract problems, (6) environmental factors including students'

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existing knowledge, and (7) ineffective instructional approaches. These findings highlight the significance of students' prior knowledge, communication methods (e.g., how learning content is presented), task complexity, and learning strategies in the acquisition of computer science knowledge.

Furthermore, according to constructivist learning theories, the process of acquiring knowledge and comprehending a new subject requires establishing connections with previously acquired knowledge [3]. From this perspective, learning becomes a process of relearning, whereby learners modify or utilize their past experiences, beliefs, and knowledge as a foundation for constructing new knowledge [20]. Additionally, active engagement of learners in the learning process is crucial [5]. As a result, effective learning strategies should consider learners' prior knowledge and facilitate their active involvement to promote the effective integration of new knowledge.

In this paper, we propose that analogies and digital game-based learning (DGBL) are effective approaches for teaching complex conceptual knowledge in computer science, particularly Binary Search Tree (BST) conceptual knowledge. Analogies involve comparing structures of two domains that share symmetrical relations among their components [12]. Their purpose is to transfer ideas and concepts from a familiar domain (source) to an unfamiliar one (target) [15]. Analogies have been widely used in educational settings to establish connections between non-intuitive concepts and familiar knowledge [28], especially in science teaching [12].

DGBL, on the other hand, is a flexible and interactive learning approach that can effectively represent and facilitate understanding of abstract and complex knowledge. Video games, as a form of DGBL, utilize various narrative elements such as text, audio, images, and simulations [14, 39]. Simulations are operating representations based on models or abstractions of real-world processes or systems [16]. In educational video games, simplified models can aid in comprehending the learning content [39]. This enables players to engage with and perceive the models from different perspectives, surpassing the limitations of purely narrative depictions. Additionally, the game designer can employ the video games' operative model to construct analogies conveyed through narrative elements that can facilitate learning new information.

When it comes to DGBL for computer science education, numerous video games have been developed and studied. However, many of these games have not undergone thorough rigorous evaluation. For example, in a systematic literature review conducted by Petri and Gresse von Wangenheim [27] covering the period from 1995 to 2015, they identified 117 evaluation studies and 106 educational games. The review's findings revealed that over 81% of the studies "did not utilize any well-defined model or method for conducting the evaluation" [27]. Similarly, in another review focusing on video games for learning data structures and recursion, Rojas-Salazar and Haahr [32] discovered 15 video games and 2 bundles of mini-games. The results indicated that 35% of the games lacked a theoretical foundation on how people learn, 35% did not employ a well-defined evaluation method, and 24% of the games were not evaluated at all. Hence, there is a clear need for thorough evaluations to enhance our understanding of the effectiveness of educational video games in the field of computer science, particularly in the context of data structures such as BST.

This paper aims to conduct a comprehensive evaluation of an educational video game that incorporates analogies to enhance the learning of conceptual knowledge in computer science, specifically BST concepts, through a case study. Data structures and algorithms form a crucial foundation in computer science and find extensive application in the software industry, significantly improving the efficiency of computational systems [35]. However, BST knowledge presents challenges inherent in complex scientific fields, making it difficult for novice students to develop a deep understanding of advanced data structures and their associated algorithms. In this regard, our study proposes that educational video games have the potential to facilitate the acquisition of abstract knowledge, thereby improving learning outcomes and intrinsic motivation. The results of the case study demonstrate that our educational video game successfully establishes connections between the video game's model and the abstract BST concepts through analogies, while also highlighting the greater intrinsic motivation associated with DGBL compared to traditional digital learning approaches, such as video tutorials.

1.1 Related Work

This section presents works related to educational video games about trees data structures. The section only covers games described in short and full papers published in peer-reviewed journals and conference proceedings. Peer-reviewed journal and conference articles assure good quality research as well as the availability of the papers. Other educational games about data structures published in other mediums (e.g., websites) are not included.

Our review has found five significant examples. The first game, called *Elemental: The Recurrence* [9], stands out as a 3D puzzle-coding game that teaches the recursive depth-first search (DFS) algorithm within a binary tree context. Players assume the role of Ele, a programmable avatar, navigating through a binary tree-inspired game world. By coding the missing sections of the DFS algorithm, players advance in the game.

The second game is an adaptation of the classic game *Mario* and focuses on Adelson-Velsky and Landis (AVL) trees [43]. This adaptation presents five distinct levels, each devoted to a different AVL tree concept: BST structure (level one), AVL tree rotations (level two), AVL tree search algorithm (level three), add algorithm (level four), and delete algorithm (level five).

The third game, named the *AVL Tree Game* [40], focus exclusively on AVL tree rotations and the add algorithm. It takes the form of a mobile puzzle game, providing an interactive platform for players to engage with and comprehend AVL trees.

Concerning the fourth game, Shabanah et al. [36] designed a game prototype that focuses on teaching the BST add algorithm. In this game, players are challenged to construct a BST as fast as possible using the given nodes.

Lastly, *Tree Legends with UnityChan* [17] is an action-adventure game designed to foster understanding of tree traversal and search algorithms. Featuring binary, ternary, and quaternary trees, this game encompasses three levels, each concentrating on a specific type of tree data structure. Players navigate through tree-based game world, encountering enemies and helpful non-player characters who offer essential insights to surmount the game's challenges.

The present study makes several contributions based on the reviewed works related to games for learning tree data structures. Firstly, it highlights the limited availability of games dedicated to teaching tree data structures and their algorithms in peer-reviewed academic literature, with only five such games identified. This scarcity underscores the need for further exploration and development in this area.

Secondly, our study focuses on the learning aspects of educational video games, emphasizing the importance of incorporating a well-defined learning theory, learning objectives, and appropriate learning activities in any learning tool [5, 23]. By providing a strong theoretical foundation, clear learning objectives, and suitable learning activities aligned with the learning theory, our study aims to fill the gap left by previous works that lack explicit information in these crucial areas. This comprehensive approach enables a better understanding of the game's scope and facilitates the evaluation process, including the analysis of game design decisions, hypotheses, and experimental results.

Furthermore, our study emphasizes the importance of educational game evaluation aspect, addressing limitations observed in previous works that focus on games for learning tree data structures. Specifically, three out of the five reviewed works [36, 40, 43] either did not evaluate the game or conducted only informal evaluations, such as brief interviews without a structured protocol. Additionally, the remaining two works [9, 17] employed parametric inferential statistics on ordinal data, which violates parametric assumptions and compromises result analysis. To overcome these limitations, our evaluation approach employs validated assessment tools with scale properties to measure learning outcomes and intrinsic motivation, ensuring reliable and meaningful data. By employing these measurement tools and employing nonparametric statistical methods when parametric assumptions are not met, our study ensures robust data analysis while avoiding common statistical analysis and measurement tool problems [30, 34].

2 Methods

We performed an evaluation of *DS-Hacker 3D* during August and September of 2020 at Universidad de Costa Rica (UCR). Due to the Covid-19 pandemic, UCR was placed on lockdown, and classes were taught online. For this reason, the experiment was performed virtually, and all materials and tests were distributed and completed using a custom-made web application.

2.1 Materials and Participants

Educational Video Game. *DS-Hacker 3D* (Fig. 1) is an immersive third-person adventure PC game created using the Unity engine. *DS-Hacker 3D* targets bachelor students of engineering, computer science, data science, or mathematics schools that have programming courses. The selection of game content aligns with the guidelines for undergraduate degree programs [2], making it a suitable complement to introductory programming or data structures courses found in many curricula.

In terms of learning aspects, *DS-Hacker 3D* was designed based on a constructivist approach that emphasizes the learner's active construction of knowledge by connecting new information with existing experiences. This approach is informed by Kolb's experiential learning theory and the experiential learning cycle [20], which provide the foundation for how learning occurs within the game. As a result, the game's learning experience closely follows this cycle and establishes connections between new information and familiar knowledge and experiences with analogies between the game world and the BST structure. These analogies are integrated into the game mechanics and narrative elements, facilitating the acquisition of BST conceptual knowledge.

Fig. 1. Screenshot of DS-Hacker 3D – Level 1.

DS-Hacker 3D primarily covers essential concepts related to the BST data structure, which serves as a fundamental topic taught in introductory computer science courses [2]. The game's learning objectives (LOs) specifically focus on BSTs. However, since BSTs are a specific instance of Binary Trees (BTs), it becomes imperative to include BT concepts as well to effectively impart BST conceptual knowledge. The learning objectives are outlined in Table 1, providing a comprehensive overview of the specific areas targeted for learning within the game.

Concerning the game aspects, *DS-Hacker 3D* is a cyberpunk science fiction game that follows the narrative structure of the Hero's Journey [8]. Set in a future where corrupt corporations threaten society, players assume the role of a robotic hacker. Guided by the non-player character Anonymous, they embark on a mission to infiltrate and extract information from the corporations' computational systems. The game features interlinked mazes and immersive visuals, music, and sound effects, aiming to enhance player immersion and motivation. The narrative elements, delivered through Anonymous' monologues, introduce challenges and missions while teaching BST concepts. Analogies between the game environment and BST structures facilitate understanding and the creation of new knowledge based on familiar concepts.

DS-Hacker 3D consists of four levels, each offering distinct challenges and learning opportunities. Level one serves as a tutorial where players are acquainted with the game's controllers, user interface (UI), game world, and overarching story. This introductory level does not encompass specific LOs but focuses on exploration and familiarization with game mechanics. Moving on to the second level, players are introduced to the concept of BTs and the structure of nodes. Level three delves deeper into the BT structure, reinforcing understanding and familiarizing players with the terminology associated with its various components. Finally, in the fourth level, players are introduced to the BST

Table 1. Levels, topics, learning objectives (LOs), and learning activities (LAs) of DS-Hacker 3D.

Level	Topics	LOs	Learning Activities
Level 1	No topic	No LOs	No learning activities
Level 2	Binary Tree node	LO1. The student should describe the concept of BT LO2. The student should define the basic elements that compose a BT node	LA1. Read and listen the BT definition LA2. Read and listen the node definition and its basic components LA3. Read and listen the link definition (reference/pointers) LA4. Relate the portals (links) with the concept of reference/pointers LA5. Relate the chambers of the game environment with the BT node structure and components
Level 3	Binary Tree structure	LO3. The student should identify BTs LO4. The student should identify the BT's components	LA6. Read and listen the definition of the left and right child LA7. Read and listen the definition of the parent node LA8. Read and listen the definition of a sub-tree LA9. Identify the left and right child of the BT represented by the game environment LA10. Identify the root node of the BT represented by the game environment
Level 4	Binary Search Tree	LO5. The student should explain the BST property LO6. The student should identify the BSTs LO7. The student should solve problems using the BST property LO8. The student should determine whether the BST property is unfulfilled	LA11. Read and listen the definition of the basic components of a BST LA12. Read and listen the definition of the BST property LA13. Apply the BST property to search for specific nodes

data structure, gaining knowledge about its distinct components and the crucial BST property (Table 1).

Table 2. Descriptive statistics of the pre-test and post-test scores of the control and experimental groups.

	Pre-Test Control	Post-Test Control	Pre-Test Experimental	Post-Test Experimental
Number of values	28	28	27	27
Median	5	8	5	9
Mean	4.27	7.82	4.85	8.89
Variance	4.51	3.86	3.98	1.03
Standard Deviation	2.12	1.96	1.99	1.01

Table 1 also lists the learning activities associated with each level of the game that players must engage in during their gaming sessions. A detailed description of the game can be found in [31]. A video of *DS-Hacker 3D* gameplay can be accessed through the following link: https://www.dropbox.com/s/eoecefxjqx3pnr2/Gameplay%20DS-Hacker%203D.mkv?dl=0.

Video Tutorials. Video tutorials were used as the "traditional" digital learning approach that was used in the control activity. Two video tutorials developed by the School of Mathematics at the Open State University of Costa Rica (UNED) were used. These tutorials cover all the LOs taught by *DS-Hacker 3D* and are available in the official YouTube channel of the school. The first video covers fundamental concepts of the BT data structure the second video focuses on fundamental concepts of the BST data structure.

Data Collection Tools. The measurement of changes in BST conceptual knowledge was conducted using a custom-made test specifically designed for this purpose. The test comprised 10 multiple-choice questions, each having three distractors and one correct answer. It was carefully aligned with the content and learning objectives of *DS-Hacker 3D*, drawing inspiration from well-known textbooks on data structures such as "Data Structure and Algorithms" by Aho [1] and "Algorithms" by Sedgewick and Wayne [35]. To ensure the validity of the test content, it underwent rigorous verification by two undergraduate professors specializing in data structures and algorithms from Trinity College Dublin, as well as six professors specializing in programming, data structures, and algorithms from the UCR. The consistency of the test was assessed using psychometric techniques within Item Response Theory and the Rasch model, involving a sample of 220 computer science bachelor students from UCR and the National University of Costa Rica. The reliability of the test, as measured by Cronbach's alpha, was found to be 0.76.

To evaluate participants' intrinsic motivation, we used a Spanish translation of the Intrinsic Motivation Inventory (IMI) survey [33]. The IMI is a well-known survey used to assess six factors: enjoyment, perceived competence, effort, usefulness, felt pressure and tension, and perceived choice, where enjoyment is considered the self-reported measure of intrinsic motivation [24].

Participants. Students from the bachelor programme of the Industrial Engineering Department at UCR were selected to participate in the evaluation. In total, 54 students participated in the experiment and completed all the surveys and tests. Participants were randomly assigned to a control or an experimental group. The control group had 28 participants (50.9%), and the experimental group had 27 participants (49.1%). Regarding their demographic background, 33 participants (61.1%) were female, and 21 participants (38.9%) were male.

2.2 Evaluation Design

An independent repeated measures design, also known as pre-test post-test experiment, was conducted with randomly assigned students. The experiment was facilitated through a web application, which also served as the platform for completing surveys and tests. Initially, students were presented with a consent form and agreement checkbox, and upon agreement, they were randomly allocated to one of two learning activities by the web application. General instructions for the experiment were then provided, followed by a demographic survey. Upon completion of the survey, participants proceeded to the pre-test section, where instructions and questions were presented. Subsequently, the web application delivered the learning activity instructions and materials, which participants completed before advancing to the next section. Following the learning activities, students were given the post-test and the IMI scale. Upon answering all the questions, participants submitted their surveys and tests, with the data being stored in a Firebase database.

3 Results

Tables 3 and 4 present a comprehensive summary of the descriptive analysis of the pre-test, post-test, and IMI scores, and the differences between the post-test and pre-test scores. The tables include the median, mean, variance and standard deviation.

Table 3. Descriptive statistics of the differences between the post-test and pre-test and the IMI scores of the control and experimental group.

	Difference Control	Difference Experimental	IMI Score Control	IMI Score Experimental
Number of values	28	27	28	27
Median	3.5	4	105.5	117
Mean	3.54	4.04	101.21	115.59
Variance	5.89	3.11	276.55	140.71
Standard Deviation	2.43	1.77	16.63	11.86

Figure 2 presents the boxplots which also summarize the results of the descriptive analysis.

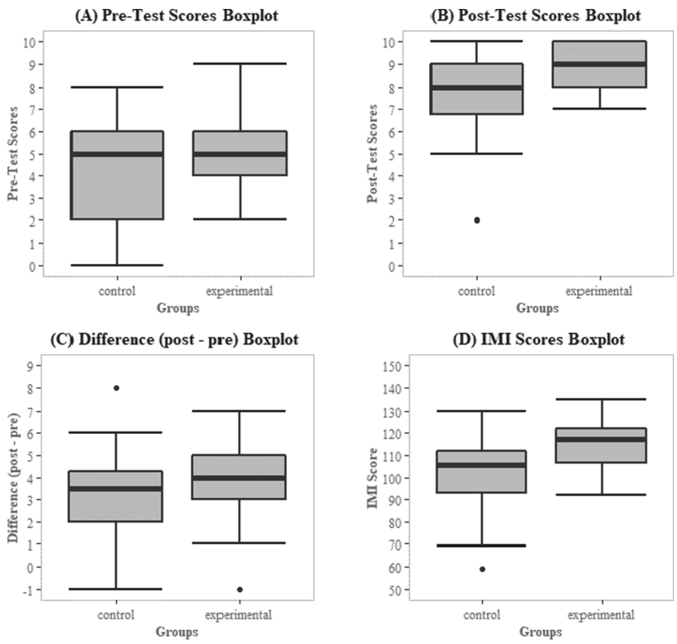

Fig. 2. Boxplots of the (A) pre-test, (B) post-test, (C) difference between the pre- and post-test, and (D) IMI scores.

Results of the t-test performed on the pre-test scores suggest that the difference between the control and experimental groups were not significant, $t(53) = -1.02$, *p-value* $= 0.31$ (*p-value* >0.05). Results of a Mann-Whitney U test on the post-test scores suggest that the differences between the control and experimental group was statistically significant, $W = 259.5$, *p-value* $= 0.04$. However, results of the t-test performed on the differences of scores between the post-test and pre-test scores (post-test score minus pre-test score; the learning gains) show that the difference between the control and experimental group was not significant, $t(53) = -0.87$, *p-value* $= 0.39$. Results of the t-test performed on the IMI scores indicates that the difference between the control and experimental group was statistically significant, $t(53) = -3.68$, *p-value* $= 0.001$. Table 4 summarizes the results of the inferential analysis between groups.

Table 4. Results of the inferential analysis between groups.

	Statistic	df	p-value	95% confidence interval	Effect size
Pre-test scores	−1.02	53	0.31	[−1.68, 0.55]	−0.28
Post-test scores	259.5		0.04		0.28
Differences	−0.87	53	0.39	[−1.65, 0.65]	−0.24
IMI scores	−3.68	53	0.001	[−22.22, −6.54]	−1

4 Discussion

Regarding the learning outcomes, our findings indicate that *DS-Hacker 3D* is an effective educational tool for teaching conceptual knowledge about BSTs. The results of the statistic descriptive analysis demonstrate that students who engaged with the game experienced significant improvements in their learning. This suggests that the act of playing the game facilitated the construction of new conceptual knowledge. Based on the pedagogical design of *DS-Hacker 3D* and the results obtained, we suggest that the presence of analogies within the narrative elements and game mechanics effectively conveyed the BST concepts to the students. We can confidently assert that *DS-Hacker 3D* holds great potential for integration into formal educational settings.

In terms of comparing the learning efficacy between the video tutorials and *DS-Hacker 3D*, our study revealed that both approaches were equally effective. The experimental group, on average, achieved a higher score on the post-test, and this difference was statistically significant. However, when considering the learning gains (post-test score minus pre-test score), there was no statistically significant difference between the two groups. These results indicate that well-designed educational video games, such as *DS-Hacker 3D*, have the potential to be just as effective as video tutorials in teaching conceptual knowledge.

The positive results of the post-test scores in *DS-Hacker 3D* may be attributed to its pedagogical aspects and alignment with learning theory. The game ensures that the LOs and LAs are well-aligned and framed by Kolb's experiential learning theory. By applying the alignment principle, *DS-Hacker 3D* aims to guarantee that all students can achieve the LOs. Furthermore, the game elements, such as narrative mechanics, challenges, environment, and user interface, were designed to engage students actively and facilitate the learning process. For example, the game incorporates analogies, facts, and terminology related to the BST data structure, allowing players to recall and apply concepts through gameplay. The puzzles and traversal of the game environment structured as a BST further reinforce the understanding of fundamental BST concepts. These game features aim to ensure that all players are motivated to achieve the learning objectives, leading to effective learning outcomes.

Our findings regarding intrinsic motivation revealed that students who played *DS-Hacker 3D* exhibited higher levels of intrinsic motivation compared to those who watched the video tutorials. Intrinsic motivation is a desirable characteristic for effective learning experiences as it enhances students' willingness to actively engage in the learning process [19, 42]. *DS-Hacker 3D* outperformed the video tutorials in this regard. The results indicated that nearly all the students experienced a sense of enjoyment while playing the game, and simultaneously, they perceived their participation as meaningful and relaxing. This discovery is particularly encouraging as it contrasts with previous studies suggesting that a significant proportion of adults in higher education are not motivated by video games [44].

The game's higher scores in intrinsic motivation may be attributed to its motivating elements. The game narrative, including the plot and character story, enhance immersion, curiosity, and engagement [7, 22, 45]. The appealing cyberpunk and sci-fi theme may also contribute to maintaining high levels of intrinsic motivation. The inclusion of challenges and goals within the game further may boost players' motivation. Achievement of challenges, task-related goals, and progression are known techniques to increase motivation [6, 7, 22]. *DS-Hacker 3D* offers multiple levels with increasing difficulty, each accompanied by tasks and cognitive puzzles. The game ensures that the provided BST concepts align with the players' skill level, allowing for successful completion of tasks and puzzles. Overall, *DS-Hacker 3D* effectively matches challenges and tasks to players' skills, providing motivation and a sense of progression throughout the game.

4.1 Limitations

While we aimed to conduct a comprehensive evaluation and analysis, it is important to acknowledge the limitations of this study. Firstly, the sample size used for assessing human psychological features was relatively small. Human constructs such as learning and intrinsic motivation exhibit significant variability, necessitating larger samples to enhance the reliability of measurements and the statistical power [21, 26]. Furthermore, our evaluation focused on a specific population with similar characteristics, namely students from the same year and school. Replicating the study with a diverse population may yield different results. Another limitation is the assumption that the Spanish translation of the IMI survey possesses equivalent psychometric properties as the original English version. Although we conducted inferential statistical analysis using parametric methods based on this assumption, it is advisable to verify the psychometric properties of the Spanish version following best practices. Lastly, our methodology primarily confirms *that* learning occurred without delving into the specifics of *how* individuals were learning. To address this gap, future research should employ qualitative studies and appropriate methodologies to explore the learning process in depth.

5 Conclusion

This study has evaluated a DGBL tool with embedded analogies in its narrative elements and game mechanics to facilitate learning computer science conceptual knowledge, specifically BST conceptual knowledge. The game, called *DS-Hacker 3D*, was tested with university students. Our results show that video games can be efficient learning tools that facilitate the learning process of abstract conceptual knowledge. Additionally, our results show that our video game increases the students' intrinsic motivation, a desirable characteristic that learning experiences should have. These results demonstrated that DGBL approaches have great potential in higher education environments to support classes.

While we have shown that video games can be used for learning complex data structures, there is potential for using video games for learning many other types of science knowledge through the combination of analogies, narrative elements, and game mechanics. For example, abstract models that explain complex phenomena, such as electricity, atoms, or the immune system, can be represented through a game's operative model allowing the player to interact through the game mechanics. Analogies in conjunction with the game's narrative elements can be used to explain the relation between the game's model and the phenomenon studied. For this reason, we expect the approach described in this paper to generalise to many domains, in particular within science learning. Future work will explore this potential further.

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