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RESEARCH ARTICLE

A Virtual Reality Application and an Interactive Board Game for Students Learning to Program

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ABSTRACT This study investigates the pedagogical effectiveness of three instructional formats for teaching block-based programming: an immersive virtual reality (VR) environment, a tactile board game (BG), and a traditional digital manual. Two interactive prototypes (VR and BG) were developed and validated to ensure functional and educational reliability. A three-way experimental design was employed to evaluate learner engagement, conceptual understanding, and satisfaction. Results revealed that both VR and BG significantly outperformed the traditional digital format across all metrics, with VR showing slightly higher engagement due to its immersive features. However, the BG demonstrated comparable learning outcomes and stronger accessibility. These findings validate the study's hypotheses, emphasizing the value of interactivity in education. The BG emerges as an effective, low-tech alternative in contexts where VR access is limited, reinforcing the importance of well-designed physical tools in programming education.

INDEX TERMS Board games, block programming, computational thinking, education technology, interactive learning, virtual reality.

I. INTRODUCTION

In recent years, the field of education has seen a growing emphasis on the importance of teaching programming and computational thinking from an early age [1]. This trend is driven by the recognition that these skills are not only crucial for careers in technology but also enhance problem-solving and logical reasoning abilities applicable across various domains [2], [3]. However, traditional programming education often presents significant barriers to beginners, particularly due to the complexities of syntax and abstract concepts [4].

In response to these challenges, the e-DIPLOMA project (project number 101061424) was launched to enhance online learning through advanced technologies like Augmented Reality, Virtual Reality, Artificial Intelligence, chatbots, and gamification, all tailored to the educational context. Using a co-creation methodology, the project engages key stakeholders to ensure that inclusive learning is accessible [5].

As part of this initiative, two innovative prototypes have been developed to teach block programming, each tailored to different educational contexts. The first prototype is a board game (BG) that introduces programming principles through a hands-on, individual gameplay experience. It allows students to learn at their own pace while actively applying programming concepts. The second prototype uses virtual reality (VR) to offer an immersive learning environment, enabling students to interact with programming constructs in a simulated 3D space.

The development of both prototypes was informed by comprehensive co-design processes involving students, educators, parents, and domain experts. The BG prototype prioritized accessibility and adaptability, resulting in a tangible and flexible tool applicable in a variety of educational settings.

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In contrast, the VR prototype concentrated on the design of an intuitive user interface and interactive scenarios aligned with pedagogical objectives, aiming to facilitate a seamless and cognitively engaging virtual learning experience.

Although emerging technologies like virtual reality demonstrate significant potential to improve computational thinking, this study emphasizes how traditional tools, when carefully designed, can achieve comparable educational outcomes. As a baseline control, a static PDF manual is included to validate the necessity of interactivity and engagement in learning efficacy, with the expectation that this noninterventional format will underperform relative to both BG and the VR. The study is guided by three key objectives:

- **O1:** To design and develop two distinct educational prototypes for block programming: a tactile BG and an immersive VR environment.
- **O2:** To evaluate their effectiveness in engagement, conceptual comprehension, and learner satisfaction, comparing them against the static PDF limitations.
- **O3:** To compare how BG and VR bridge gaps in programming education, with the PDF serving as a control to isolate the advantages of interactivity.

Based on these objectives, the following hypotheses are proposed to explore the potential impacts of both VR and BG prototypes on programming education.

- **H1:** VR will result in significantly higher engagement and computational thinking gains compared to the BG and PDF formats, with the BG showing a closer approximation to VR effectiveness.
- **H2:** The BG prototype, although a traditional tool, will demonstrate learning gains in understanding programming principles similar to those of VR, significantly outperforming PDF in terms of teaching fundamental concepts.
- **H3:** The BG's superior accessibility and user-centered design will make it especially effective for learners who do not have access to VR, while the non-interactive format of PDF will limit its effectiveness in fostering learning outcomes.

II. LITERATURE REVIEW

As part of the evolving educational landscape, innovative tools such as Game-based Learning (GBL), Block Programming and VR are playing a key role in bringing programming concepts to life. Both GBL and VR, when applied to block programming, enhance critical thinking, problem-solving skills and engagement [6], [7], [8], [9], [10]. GBL, through digital and traditional games, fosters interactive learning environments that reinforce computational thinking, while VR immerses students in dynamic, visual environments that make abstract block programming concepts more tangible. Together, these approaches create a comprehensive learning experience that simplifies programming education and motivates students to actively engage with technology.

A. BLOCK PROGRAMMING APPROACHES

The promotion of personalized learning has led to a significant acceleration in the development of educational tools aimed at enhancing computational thinking, particularly among younger learners [4], [11]. These tools advance in parallel with technological progress, providing increasingly accessible means to engage with programming concepts while accommodating diverse learning styles and aligning with the fundamental principles of interactive, autonomous and personalized education [12].

Within this paradigm, block programming is instrumental in fostering a digital culture within educational institutions [12]. By rendering programming more intuitive and visually appealing, it bolsters crucial computational thinking skills essential for problem-solving and system design, thereby empowering students to become active creators of technology. To sustain student interest, it is imperative to implement teaching strategies that encourage motivation [13]. Furthermore, the integration of block programming with emerging technologies enhances student engagement, thereby enriching the overall educational experience [14].

Logo, introduced in the late 1960s, was one of the first educational programming platforms, using turtle graphics to engage children with abstract programming concepts through text-based commands [15]. This system laid the foundation for child-centred programming education, promoting problem-solving and logical thinking. Building on this, the MIT Media Lab introduced Scratch in 2007, a block-based programming language that provided a visual interface for creating logical sequences, offering a more intuitive and accessible alternative to text-based programming for young learners [16], [17], [18]. In parallel, Google developed Blockly, a JavaScript library that enables the creation of customizable block-based programming environments, where users can drag and drop visual blocks to generate programs in languages like JavaScript and Python, bridging the gap between visual programming and traditional coding [19].

Another significant platform is Snap!, which builds upon Scratch by offering a more advanced block-based programming environment. Designed for both children and adult learners, Snap! facilitates deeper exploration of computer science concepts [20]. While maintaining a user-friendly interface, it supports more complex programming constructs, making it suitable for higher-level programming education, including university-level courses. Similarly, App Inventor, developed at MIT, focuses on block-based programming specifically for mobile app development [21], [22]. By using a drag-and-drop interface, users can quickly create functional mobile applications without traditional coding, democratizing app development and enabling rapid prototyping.

Nextblocks represents a recent addition to the field of block-based programming, incorporating familiar features such as a drag-and-drop workspace and a categorized block toolbox [23]. It allows students to immediately run their programs and view results, creating a real-time feedback loop, while also including safeguards to prevent incompatible block combinations. This progression from Logo's text-based simplicity to visual and interactive environments highlights a broader trend toward accessible, creative, and collaborative programming education.

With our study, we aim to enrich the current landscape of basic programming education through innovative technological and methodological tools. Our project includes the design of a virtual reality application and an interactive BG, both developed to facilitate the understanding of fundamental block programming instructions. Beyond the direct educational benefits, we hope to identify key factors related to immersion, interactivity and motivation across different formats.

B. GAME-BASED APPROACHES TO PROGRAMMING EDUCATION

GBL has become a highly effective educational strategy, particularly with the rise of digital games that integrate interactive and immersive learning experiences. Digital GBL environments provide a dynamic platform for students to develop critical skills such as computational thinking and problem-solving.

Recent research highlights the significant impact of digital games on developing computational thinking. Liu [6] and Kuo and Hsu [7] emphasize how games can be used to assess and teach these skills. Liu shows that Zoombinis, a logic puzzle game, can assess computational thinking by analyzing factors such as accuracy and actions during gameplay, providing valuable information on the progress of students [6]. Kuo and Hsu demonstrates how Robot City engages students in collaborative problem solving, fostering computational participation, and teaching structural programming concepts [7]. Tsai et al. explore the integration of game mechanics through the GAME model in block-based programming courses, finding that such approaches significantly boost students' self-efficacy and understanding of programming. [8].

Further supporting these findings, Thammabut et al. [24] and Chen et al. [25] emphasize the educational benefits of game-based learning. Thammabut et al. developed a game to enhance AI and programming skills among industrial students, resulting in improved problem decomposition and pattern recognition [24]. Similarly, Chen's research highlights how both digital and non-digital games improve engagement with programming concepts, leading to better outcomes in computational thinking [25].

While digital games offer significant advantages for the advancement of computational thinking and programming education, traditional non-digital games, particularly BGs, also serve as effective educational tools. Yen and Liao examined the influence of cognitive styles on learning outcomes and game behavior within BG programming, demonstrating that such games can function as a valuable medium for programming education by adapting to diverse learning preferences and promoting game behaviors that facilitate skill acquisition [26]. Wangenheim et al. [27] introduced SplashCode BG to enhance algorithmic thinking. Their findings revealed that the students not only perceived the game as enjoyable, but also experienced increased motivation and social interaction, evidencing that BGs can successfully impart basic programming concepts [27]. Further research by Thammabut et al. evaluated the use of BGs to enhance programming and artificial intelligence competencies among industrial students, indicating that traditional games can markedly improve educational outcomes in a nondigital setting [24].

In this study, the application of GBL principles will be explored through both digital and traditional game formats to support the learning of programming concepts. Building on previous research that highlights the effectiveness of digital games in fostering computational thinking and problem solving skills [6], [7], we will investigate the potential of these interactive environments to improve programming education. Furthermore, we will examine the educational value of traditional BGs, as demonstrated in previous studies [24], [27], which show that non-digital games can similarly promote algorithmic thinking and student engagement. By integrating these two formats, the study aims to assess the broader impact of game-based learning in programming education.

C. THE IMPACT OF VIRTUAL REALITY ON LEARNING PROGRAMMING

The use of VR for educational purposes, particularly in teaching programming, has gained increasing attention due to its immersive and interactive nature, which enhances user engagement and learning outcomes. Several studies have explored how VR environments can provide novel approaches to teaching programming concepts, ranging from block-based programming interfaces to frameworks that address common learning challenges in programming [28], [29].

Hedlund et al. [30] presented BlocklyVR, a virtual reality adaptation of the widely-used block-based programming platform Blockly, which explored the potential for programming to become a physically interactive endeavor. The findings indicated that programming performance remained unaffected by the VR interface, despite incorporating physical movements, and participants reported negligible virtual reality sickness. Additionally, the study identified four interaction types within VR that transformed traditionally static programming tasks into a more dynamic and immersive experience [30]. Similarly, Segura et al. [9] developed VR-OCKS, a virtual reality system designed to teach foundational programming concepts through puzzle-based challenges. This system introduces users —primarily children and adolescents— to programming in a 3D environment, where they issue commands to control a humanoid character. Experimental results with both children and adults revealed high levels of engagement and educational potential [9].

In an additional investigation into the application of virtual reality for programming education, Vincur et al. [31]

introduced Cubely, a virtual reality programming environment that employs a block-based methodology. This system enables novice programmers to engage in solving puzzles through the manipulation of cubes that symbolize program instructions. These puzzles are seamlessly integrated into a virtual world that provides an immersive experience. This methodological approach capitalizes on the game-like nature inherent in block-based programming to encourage creativity and experimentation, thereby enhancing the educational experience [31].

Finally, Wee et al. [10] introduced iProgVR, a virtual reality framework specifically constructed to tackle the inherent abstractness of programming as well as the prevalent misconceptions encountered by students. The VR intervention demonstrated a marked improvement in students' understanding of programming concepts and effectively addressed misconceptions when compared to conventional video lectures. Participants also found the VR environment to be significantly more engaging [10].

Building on the insights provided by these studies, our project aims to further expand the applications of VR in programming education by addressing and identifying new opportunities for engagement. By combining the immersive nature of VR with carefully designed instructional strategies, we aim to create an environment that not only simplifies the understanding of block-based programming concepts but also provides actionable insights into how VR can be effectively integrated into diverse educational contexts. Our approach emphasizes not only learning outcomes but also the broader aspects of accessibility, adaptability and student motivation, which are critical for scaling VR-based educational tools.

III. PROTOTYPES DEVELOPMENT

This section explains the development of the prototypes designed for the project. The prototypes aim to provide engaging and effective educational tools that enhance the understanding of block programming.

A. BLOCK DRIVE RESCUE: BOARD GAME

Block Drive Rescue is an interactive BG designed to teach fundamental programming principles through block-based pedagogy. It aims to foster problem-solving and computational thinking by immersing players in hands-on, meaningful challenges. The design process, gameplay mechanics, and technical components that shape this educational experience are described in the subsections below.

1) PRELIMINARY GAME DESIGN

The development of *Block Drive Rescue* began with an initial game design aimed at exploring how core programming concepts could be effectively conveyed through a tangible, rule-based system. This preliminary version served as a foundation for iterative refinement and user testing throughout the co-design process.

The game is structured around a series of levels set within a 6 × 6 grid environment, where players must guide a blue arrow to specific grid squares containing plants in order to measure humidity. To achieve this, players use a set of blocks that represent programming instructions (as illustrated in Figure 1). The gameplay challenges take into account the arrow's orientation, navigable paths, and obstacles, encouraging players to apply logical reasoning and strategic planning. Each level progressively increases in difficulty, introducing core programming concepts such as sequencing, movement commands (e.g., *Move Forward*, *Turn*), conditionals (e.g., *If obstacle ahead do:*), loops (e.g., *Repeat N times do:*), and functions (e.g., *Get Humidity*).

As shown in Figure 2, the initial setup of the six exercises followed a consistent structure. Each task provided a predefined number of blocks, and when a new concept was introduced, a partial configuration was given to guide the player's reasoning. For instance, Exercise 3 introduced loops through the blocks *Repeat 4 times do:* and *Repeat 2 times do:*, requiring players to insert *Move Forward* blocks within each loop and a *Turn Right* block between them to reach the goal. Similarly, Figure 1 demonstrates the importance of repetition, presenting a solution that relies exclusively on the correct use of the *Repeat* block despite the availability of additional blocks. Notably, each exercise was designed to have a single correct solution, reinforcing accuracy and conceptual clarity.

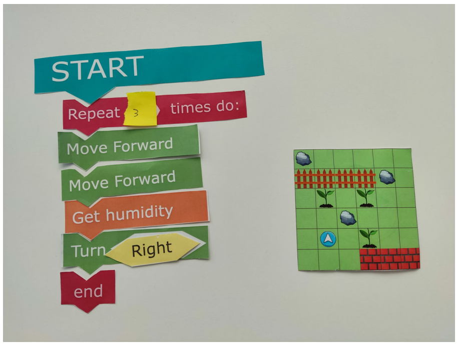


FIGURE 1. Block programming with paper cutouts.

2) DESIGN PROCESS: CO-DESIGN METHODOLOGY

Co-design, or collaborative design, is a participatory methodology that involves a wide range of stakeholders—not only end users—in both the design and sometimes the implementation of solutions. By integrating the experiences, expertise, and knowledge of all participants, co-design ensures that tools, such as applications or games, are developed in a way that addresses complex issues and meets the needs of both students and educators, thereby fostering mutual understanding and improving educational impact [32]. The process typically begins with user research to explore the needs and preferences of the target audience through interviews, surveys, and workshops [33], followed by an ideation phase where participants collaborate to define and refine key features and functionalities of the tools [34].

The BG prototype was conceived to enhance problem-solving skills and computational thinking through a traditional, tangible game format. Developed through a

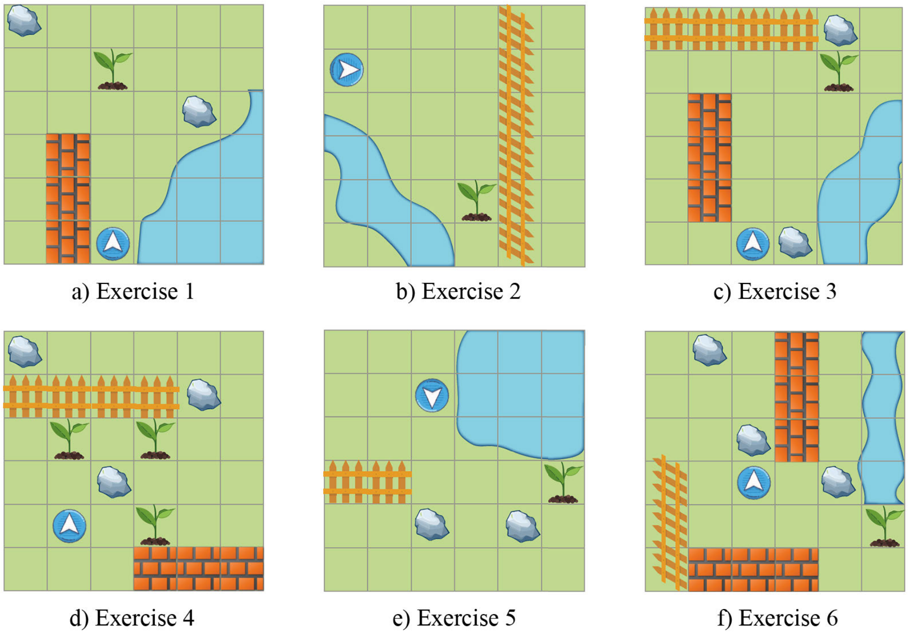


FIGURE 2. Initial scenarios for all programming exercises (1–6) showing the starting configuration for each task.

participatory design approach, it addressed real challenges in programming education while fostering innovation and learner engagement. The co-design process unfolded over two iterative cycles, each incorporating feedback from a variety of user profiles —including educators, learners, and professionals from multiple disciplines— to refine the content, functionality, and usability of both educational tools. Insights gathered during these sessions not only shaped the mechanics and structure of the BG but also informed the key requirements for the development of the VR application, ensuring that both prototypes align with the needs and expectations of modern learners.

The first iteration of the process involved eight adult participants (four males and four females) with prior experience in programming and backgrounds in teaching or software development. Each participant completed six programming exercises using paper cutouts, with completion times recorded and any observed challenges noted manually. On average, the exercises took approximately 15 minutes to complete, providing a baseline for evaluating task complexity and participant performance. After completing the tasks, participants took part in open-ended interviews to provide qualitative feedback on their experience, responding to questions such as "How would you describe your experience completing these exercises?" and "What difficulties did you encounter?". This initial phase aimed to identify usability issues and potential areas for improvement, thereby informing the refinement of the instructional approach and guiding the transition from paper-based activities to an immersive VR environment.

Findings from the individual interviews revealed that participants found the experience to be challenging, motivating, and enjoyable, while also effective in facilitating the learning of programming concepts such as sequencing, loops, and conditionals. However, the increasing difficulty of the exercises was evident, as participants required more time and support to complete the later tasks. The discussion highlighted the need to provide hints to assist with problem-solving and to further limit the number of blocks available in each exercise. This adjustment was intended to encourage the application of newly introduced concepts rather than relying on preconfigured solutions, thereby supporting a more gradual and pedagogically sound progression in both complexity and learning. Consequently, several modifications were implemented: Exercise 3 was removed and replaced by a simplified version of Exercise 1, solvable with a single block *Repeat N times do:* and the available elements; additionally, the order of Exercises 4 and 5 was swapped, as Exercise 4 was deemed more difficult than Exercise 5.

In the second iteration, six participants without prior programming knowledge (3 men and 3 women) took part in the same process. However, in this case, they tested the modified exercises that were redefined based on the results from the first iteration. The results of this second iteration reinforced the previous findings, as participants reported that they found the exercises to be engaging, entertaining, challenging and at the same time, accessible. They also indicated that they had learned fundamental programming concepts (such as sequence and instruction precision) enjoyably and straightforwardly while developing computational thinking skills.

All participants successfully completed the six exercises, with an average completion time of 26 minutes. From the third exercise onward, hints were required to guide them toward the correct solution. During the focus group, participants suggested the inclusion of feedback on the outcomes of the actions they defined with the blocks, as well as a guide that would assist in solving the exercises without directly providing the solution.

3) FINAL GAME STRUCTURE AND FEATURES

The game design evolved from an initial phase using paper cutouts to a more robust version made with foam board (Figure 3). This transition allowed for better durability and functionality of the prototype, facilitating user interaction with the game's blocks and elements. Similar to VR games, where a guide is often included to assist players with the mechanics and rules, this game also incorporates a facilitator who provides guidance to the players throughout the exercises. This guide, either in the form of a character or human instructors, offers support, answers questions, and ensures that players correctly understand the game mechanics and programming concepts, thereby fostering a more effective learning experience.

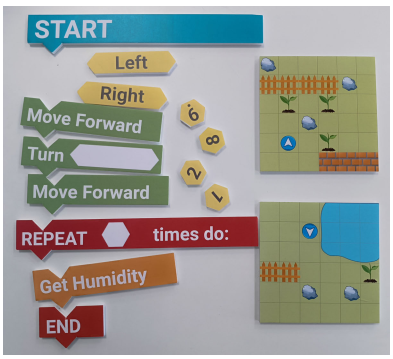


FIGURE 3. Some of the pieces of the final version of the BG.

B. BLOCK DRIVE RESCUE VR: BLOCKCODING IN VIRTUAL REALITY

Block Drive Rescue VR is an immersive Virtual Reality experience developed to teach foundational programming concepts through block-based learning. Designed to foster problem-solving and computational thinking skills, the application engages users in interactive challenges that require real-time decision-making. By translating the educational principles of the board game into a dynamic virtual setting, Block Drive Rescue VR offers an innovative and motivating approach to programming education. Its design process, interaction mechanics, and technical features collectively shape an experiential learning environment, detailed in the subsections that follow.

1) PRELIMINARY GAME DESIGN

The development process began with the creation of a virtual reality application, which involved adapting the mechanics and concepts of a board game into a virtual environment. This approach aimed to replicate the block programming tasks of the original physical game while enhancing the experience through the immersive capabilities of virtual reality. The application preserved the sequential logic of the board game, using VR technology to offer a more interactive and engaging educational experience. Built with the Unity 3D game engine and integrated with "Open XR" virtual reality libraries, the application ensures compatibility across multiple VR platforms. Scene models were designed using Blender, a powerful 3D design software. The application is compatible with both the HP Omnicept virtual reality headset (connected to a computer) and the Oculus Quest, allowing for flexibility in device use.

The virtual environment was structured with two walls containing blocks, positioned to the left and right, with the main game level placed directly ahead. A menu system, accessible through the VR controllers, was implemented to allow users to access essential functionalities such as restarting the game, returning to the main menu and receiving hints. Additionally, a retractable screen displayed the objective instructions, along with relevant details about the controls and available functionalities.

Participant engagement with the virtual reality environment was mediated via the VR headset controllers, which permitted the manipulation, displacement, and rotation of blocks within the three-dimensional setting. Additionally, the orientation of the camera could be modified through the use of the joystick on the VR controller, thereby permitting users to alter their viewpoint and obtain a more thorough understanding of the scenario. Participants were also endowed with the capability to traverse the virtual space by teleporting to various locations within the environment, thereby fostering spatial exploration and affording a more adaptable approach to resolving programming tasks.

2) DESIGN PROCESS: CO-DESIGN METHODOLOGY

Co-design plays a crucial role in developing a VR application that effectively translates the principles of an interactive BG into an immersive learning experience. By collaborating with educators, students, and stakeholders, we adapt key educational concepts such as block-based programming and problem-solving into the VR environment, ensuring the VR tool retains the engaging, hands-on nature of the original game while leveraging VR's immersive potential. This transition from a physical game to VR requires careful attention to user experience, accessibility, and interaction design. Through continuous collaboration with users throughout the process, we ensure that the VR application remains intuitive, effective, and seamlessly integrates immersive techniques to teach programming.

The co-design process was carried out in two distinct iterations, each aimed at refining the application based on feedback from different user groups. The first iteration involved internal testing and trials with experienced VR users. Both iterations contributed to refining the application, with the feedback from each phase guiding the adjustments made to optimize the user experience.

The first iteration involved internal testing conducted by a group of individuals with prior experience in VR. The primary goal during this phase was to identify and resolve technical issues, ensuring the application functioned as intended. Testing focused on evaluating key features, including user interaction with the blocks, camera movement and spatial navigation within the virtual environment. While the initial prototype was functional, feedback from this group revealed several technical concerns, particularly about block alignment and user navigation, which necessitated targeted adjustments. Key modifications made during this phase included improvements to block interaction mechanisms and optimization of the VR environment to ensure smoother navigation. While valuable insights were gathered from this iteration, the focus remained largely on technical performance and thus, issues related to usability and accessibility were not fully addressed.

The second iteration of the co-design process involved a user testing phase with individuals with limited experience in VR. A primary concern raised by participants was the difficulty in interacting with the VR controls, particularly in manipulating and aligning the programming blocks. Users reported confusion regarding the rotation function, which created uncertainty about the correct orientation of the blocks and made task completion more difficult. This ambiguity introduced cognitive friction, as users struggled to position the blocks accurately to build the intended sequence. To address this issue, the block rotation system was redesigned so that the orientation of each block would depend on the direction of the user's view. This change ensured that blocks were always displayed in a way that felt intuitive, thereby facilitating smoother interaction and reducing cognitive load.

A key challenge encountered during the second iteration involved user interaction with the virtual environment, particularly regarding the camera control and teleportation features. Participants reported that the joystick-based camera rotation felt unintuitive and disorienting, preferring instead to adjust their view by physically moving their heads, which reduced cognitive load and enabled smoother navigation. Likewise, the teleportation feature—originally designed to facilitate movement—was often triggered unintentionally, leading to disorientation and discomfort, including dizziness. These issues disrupted task focus and diminished user engagement. To address these concerns, the virtual environment was comprehensively redesigned, removing both the joystick-based camera rotation and teleportation. All necessary elements were repositioned within the user's static field of view and reach, allowing interaction without physical movement. This adjustment improved usability and immersion, enabling users to concentrate fully on the programming tasks.

A significant challenge pertained to the user interface, specifically the retractable screen designed to display objectives and supplementary instructions. Many participants struggled to comprehend its intended use, and its placement often obscured the view of the game level. Despite the addition of a blinking animation to the retract button to signify its functionality, numerous users neither noticed it nor comprehended that the screen could be concealed. Additionally, the functional buttons —such as those for accessing hints or restarting the level— were inadequately sized and challenging to locate, thereby causing user frustration and diminishing interaction efficiency. Users also expressed confusion regarding the game objectives, which were displayed on the same peripheral screen that failed to capture attention. In response to these issues, the interface underwent restructuring by eliminating all nonessential on-screen elements, retaining only the control panel. In instances where users did not manually conceal the panel, it would automatically retract after one minute of gameplay during the initial level and remain hidden by default in subsequent levels. Core functionalities were repositioned to one of the primary walls within the virtual environment, and the level objectives were communicated in large, clear text above each level area. This redesign significantly enhanced clarity, minimized visual clutter, and allowed users to concentrate more effectively on the programming tasks.

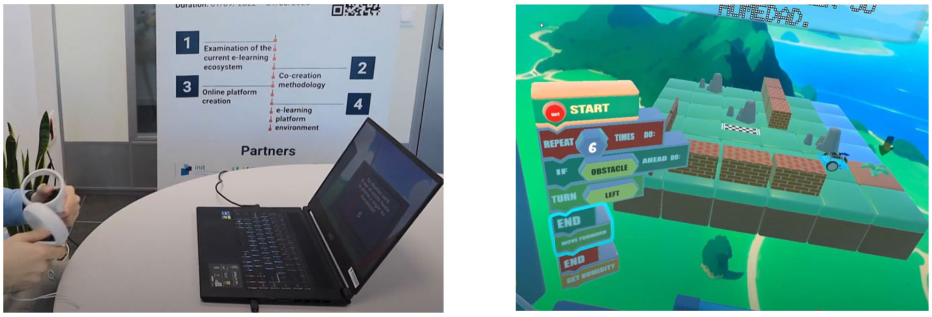
3) INITIAL GAME STRUCTURE AND FEATURES

Building on the valuable insights gathered during the co-design phase -and in addition to the previously mentioned adjustments— several key refinements were made to optimize the usability and functionality of the VR application. To enhance the onboarding experience and user engagement, two instructional tutorials were integrated: one that provides guidance on general VR controls, and another that explains the game dynamics. These tutorials were carefully designed to help users familiarize themselves with the interface and game mechanics, ensuring a smoother introduction to the immersive experience.

Moreover, the hint system was refined to better support learners and encourage progress while maintaining user autonomy. Based on feedback and data from the co-design phase, when the application detects that a user is spending an unusually long time on a particular task —indicated by the average completion times from the co-design trials— a visual icon appears, signaling the availability of a hint. This feature allows users to make informed decisions about whether they want to continue independently or receive additional guidance to move forward. In terms of visual enhancements, the interface was also restructured to improve clarity and accessibility. The updated virtual environment is depicted in Figure 4, with external and internal views shown in Subfigures 4.a and 4.b, respectively. These changes ensure that users can focus on the task at hand without unnecessary distractions, while also providing clear and intuitive access to game elements.

IV. METHODOLOGY

The research framework systematically evaluates learning outcomes, knowledge retention, and engagement metrics across three distinct delivery methods: an immersive VR



a) External Visualization of the VR game. b) Internal Visualization of the VR game.

FIGURE 4. Side-by-side view of the external and internal Visualization of the VR game.

environment, a physically interactive BG incorporating research-based educational mechanics, and a conventional digital PDF manual. Special attention is given to identifying educational contexts where well-designed physical games achieve results comparable to those of immersive technologies, and where technological mediation provides unique advantages. The PDF manual, which presents the same concepts in a traditional theoretical format, serves as a counterpart to both the immersive VR environment and the interactive BG, providing an essential baseline for comparison. This allows for differentiation between the effects of basic digital delivery, physical interaction and social dynamics, and the specific benefits of immersive simulation. Ultimately, this study aims to explore how carefully designed analog games can replicate certain advantages of VR systems while preserving the accessibility and collaborative benefits inherent to physical formats.

A. PARTICIPANTS

A total of twenty-seven adults participated in this three-condition study, with nine participants randomly assigned to each experimental group: (1) the virtual reality condition, (2) the BG condition, and (3) the PDF manual condition. All participants had completed at least secondary education, with the sample predominantly comprising individuals aged 18-26 years (89%), while the remaining 11% were aged 27-40 years. The selection criteria ensured participants possessed comparable baseline characteristics across groups. First, the educational requirement guaranteed sufficient cognitive capacity to engage with the programming concepts. Second, we controlled for prior programming experience, excluding individuals with more than introductory-level knowledge. Third, all participants demonstrated normal or corrected-to-normal vision to ensure equivalent access to visual materials across conditions.

The experimental VR group excluded individuals possessing significant prior experience with VR applications, as well as those affected by health conditions that might impede VR usage, including motion sickness, visual impairments, or recent occurrences of epileptic episodes, dizziness, or vertigo. These exclusion criteria were implemented for the group designated to engage with the VR application to ensure that participants represented typical users of VR-based educational tools, devoid of physical limitations or specialized expertise that might confound the results. All participants satisfied the inclusion criteria and provided informed consent prior to their involvement in the study.

B. STUDY DESIGN

The experimental protocol comprised three sequential stages: pre-activity assessment, intervention, and post-activity evaluation. Initially, all participants completed uniform demographic surveys and pre-test questionnaires assessing their pre-existing knowledge of block-based programming concepts. During the intervention stage, participants engaged with their designated learning modalities under standardized conditions. Participants in the VR condition interacted with the Block Drive Rescue VR environment to tackle six programming exercises, whereas those in the BG condition utilized physical game components and received immediate feedback from the experimenter. Concurrently, the PDF group examined equivalent instructional content presented in a digital manual format. To ensure parity across conditions, the exposure for the PDF group was synchronized with the average completion time derived from pilot test outcomes of the interactive modalities (27±3 minutes). Notably, participants in the PDF group did not maintain access to the manual in subsequent evaluation phases.

Following the intervention, all participants completed an identical post-test measuring knowledge acquisition. Additionally, participants in the VR and BG conditions completed the standardized Game Engagement Questionnaire (GEQ) and took part in structured group discussions exploring their subjective learning experiences. The PDF group, however, did not participate in these engagement assessments, as the nature of their learning modality did not involve interactive or experiential components. This design allowed for the comparison of cognitive and affective learning outcomes across formats, while controlling for confounding factors such as exposure time and material accessibility.

Participants accessed informed consent forms and pre-and post-experiment questionnaires via a Moodle platform, where login was facilitated through anonymous user credentials. The outcomes of the knowledge assessment were recorded on Moodle. Data pertaining to sociodemographic variables and the GEQ were collected using the Qualtrics platform. Additionally, experimenters documented remarks made during open-ended question sessions.

V. EVALUATION AND RESULTS

This section describes how the evaluation of the developed prototypes was conducted. By outlining the evaluation procedure, it provides context for understanding the results that follow and the basis for comparing the different learning modalities.

A. QUANTITATIVE DATA

To assess the impact of the activities on participants' programming knowledge, an identical test was administered both prior to the activity (pre-test) to evaluate initial knowledge and subsequent to the activity (post-test) to quantify knowledge acquisition. The test comprises seven questions that address key concepts practised during the activity. All questions pertain to a 3×3 grid scenario, wherein participants are required to program a moving entity to traverse the grid and arrive at a designated goal square. Questions 1 to 4 evaluate understanding of directional instructions, as delineated in *Move Forward* and *Turn*. Questions 5 and 6 assess comprehension of the loop concept. Finally, Question 7 integrates the application of conditionals, amalgamating this concept with the previously introduced instructions.

Table 1 delineates the descriptive statistics regarding pre-test and post-test scores across the three experimental conditions: VR, BG, and PDF. All cohorts demonstrated a measurable enhancement in scores from pre-test to post-test, although the magnitude of improvement varied. The VR condition recorded the highest mean learning gain of 1.59 points, subsequently followed by the BG condition at 1.27 points, whereas the PDF condition exhibited the lowest gain of 0.71 points. To ensure comparability between groups at baseline, a Kruskal-Wallis H test was conducted to examine differences in pre-test scores across the three groups. The analysis revealed no statistically significant differences in median pre-test scores among the groups, $H(2) = 2.27, p = 0.322$, indicating that the groups were comparable before the intervention. This strengthens the validity of subsequent comparisons regarding learning gains.

The boxplot depicted in Figure 5 offers a visual depiction of the score distributions across three experimental conditions: VR, BG, and PDF. It facilitates a comparison between pre-test and post-test outcomes for each condition, illustrating the shifts in score distributions resulting from the intervention.

The Game Engagement Questionnaire (GEQ) [35] was utilized to assess participants' engagement levels during the activity. This instrument consists of 19 items, each rated on a scale of "No", "Maybe", or "Yes", with corresponding numerical values of 1, 2, and 3, respectively. The items are designed to evaluate constructs such as absorption, flow, presence, and immersion. Table 2 presents a comprehensive summary of the response distribution to questions that examine various aspects of the immersive experience for participants in both the VR and BG groups. The responses are categorized, with percentages reflecting the proportion of participants selecting each option. These items evaluated dimensions such as temporal awareness loss, the automaticity of actions, and the emotional responses elicited during gameplay.

TABLE 1. Descriptive statistics for the Pre-test, Post-test, and learning gains across the three study groups.

Statistic	VR	BG	PDF
Pre-test Mean	6.19	6.51	7.62
Post-test Mean	7.78	7.78	8.33
Learning Gain (Mean)	1.59	1.27	0.71
Pre-test Median	7.14	5.71	7.14
Post-test Median	7.14	7.14	8.33
Pre-test SD	2.76	1.45	1.24
Post-test SD	1.26	1.26	1.44
Pre-test Min	1.43	4.29	5.71
Post-test Min	5.71	5.71	5
Pre-test Max	10	8.57	10
Post-test Max	10	10	10

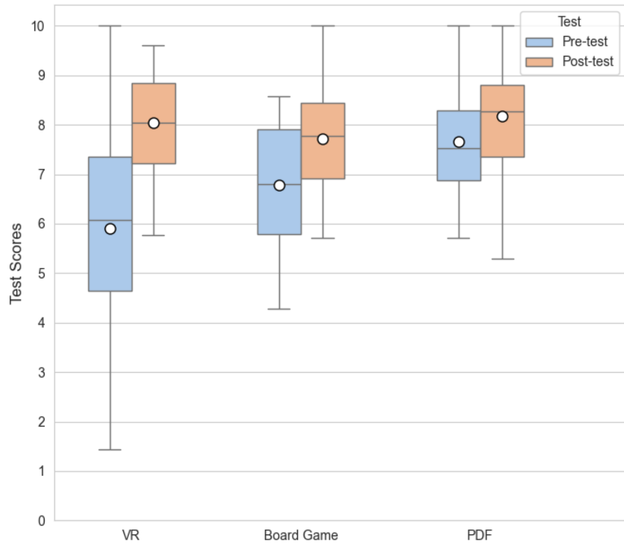


FIGURE 5. Boxplot of Pre- and Post-Knowledge Scores.

B. QUALITATIVE DATA

To complement quantitative measures, semi-structured discussions were conducted to examine user experiences and engagement patterns across conditions. Participants in both the VR and BG groups responded to standardized open-ended questions. These discussions followed an unstructured interview format, allowing participants to provide spontaneous, naturalistic responses while ensuring coverage of key thematic areas.

- What aspects of the game made you feel attracted to it?
- How would you describe your level of concentration during the game, was there anything that helped or hindered you from staying focused?

TABLE 2. Summary of responses to GEQ, grouped by VR and BG participants.

Question	VR			BG		
	Yes (%)	Maybe (%)	No (%)	Yes (%)	Maybe (%)	No (%)
Q1: Losing track of time	30.00%	40.00%	30.00%	25.00%	35.00%	40.00%
Q2: Things happen automatically	25.00%	25.00%	50.00%	15.00%	25.00%	60.00%
Q3: Feeling different	33.33%	22.22%	44.44%	20.00%	30.00%	50.00%
Q4: Feeling scared	10.00%	0.00%	90.00%	5.00%	0.00%	95.00%
Q5: Game feels real	40.00%	20.00%	40.00%	35.00%	15.00%	50.00%
Q6: Ignoring external speech	30.00%	10.00%	60.00%	25.00%	15.00%	60.00%
Q7: Feeling disturbed	10.00%	10.00%	80.00%	0.00%	10.00%	90.00%
Q8: Time stopping	20.00%	20.00%	60.00%	10.00%	25.00%	65.00%
Q9: Feeling disconnected	25.00%	15.00%	60.00%	20.00%	25.00%	55.00%
Q10: Not responding to others	20.00%	0.00%	80.00%	10.00%	5.00%	85.00%
Q11: Not noticing fatigue	10.00%	10.00%	80.00%	15.00%	20.00%	65.00%
Q12: Playing feels automatic	30.00%	20.00%	50.00%	20.00%	20.00%	60.00%
Q13: Thoughts going fast	50.00%	25.00%	25.00%	40.00%	30.00%	30.00%
Q14: Losing sense of location	15.00%	20.00%	65.00%	10.00%	30.00%	60.00%
Q15: Playing without thinking	20.00%	30.00%	50.00%	25.00%	35.00%	40.00%
Q16: Playing feels calming	35.00%	30.00%	35.00%	30.00%	35.00%	35.00%
Q17: Playing longer than planned	25.00%	30.00%	45.00%	20.00%	30.00%	50.00%
Q18: Really immersed in the game	45.00%	30.00%	25.00%	35.00%	25.00%	40.00%
Q19: Cannot stop playing	10.00%	25.00%	65.00%	5.00%	20.00%	75.00%

- If you felt you were doing automatic actions, what were they?
- What emotions did you experience while playing?
- Which elements of the game (mechanics, graphics, gameplay) motivate you to keep playing and which would you improve?
- Anything else to add that has not already been said

The qualitative data, obtained through participant feedback, provided insights into various dimensions of their experiences, including attraction, concentration, emotional responses and motivations.

VI. DATA ANALISYS

This section presents the data analysis of the collected result from the evaluation phase. It focuses on examining the participant performance, feedback, and interaction with the prototypes. The analysis aims to provide a comprehensive understanding of the prototype effectiveness in facilitating learning.

A. QUANTITATIVE ANALISYS

To assess the differences between the three experimental conditions (VR, BG, and PDF), non-parametric permutation tests with 10,000 iterations were conducted, complemented by Holm correction to adjust for multiple comparisons. This approach was selected due to several key considerations.

First, the sample size was small, with only $n = 9$ participants per group, limiting the statistical power of traditional parametric tests such as ANOVA, which are more reliable with larger datasets. Second, the data for the PDF group did not meet the assumption of normality, as indicated by the Shapiro-Wilk test ($p < 0.05$), making parametric tests unsuitable. Non-parametric tests do not require the assumption of normality and are more robust to small sample sizes, thus providing a more appropriate alternative in this context. Additionally, given the exploratory nature of the study, a significance level of $\alpha = 0.1$ was chosen to balance the risk of Type I errors (false positives) with the need to detect potentially meaningful effects. This slightly higher threshold is commonly used in exploratory research, where the goal is often to identify trends or patterns that could inform future investigations. Table 3 provides both the raw and adjusted p-values for each comparison, as well as the effect sizes calculated using Cliff's δ, which help to interpret the magnitude of the differences observed between groups.

TABLE 3. Summary of results.

Comparison	VR > PDF	BG > PDF	VR = BG
Raw p-value	0.048	0.053	0.82
Adjusted p-value	0.096	0.106	0.82
Cliff's δ	0.56	0.52	0.08
Conclusion	Significant	Marginal	Not significant

The analysis of the data yielded several key findings. First, the VR group demonstrated a significant improvement in learning gains compared to the PDF group ($p = 0.096$, $\delta = 0.56$). This suggests that the immersive and interactive nature of VR provides a notable advantage over traditional, non-interactive learning formats like PDFs. The BG group also exhibited a marginally significant difference compared to the PDF group ($p = 0.106$, $\delta = 0.52$), indicating that physical interaction through a BG can enhance learning as well. However, the evidence for this effect is less robust than for VR. On the other hand, the comparison between the VR and BG groups ($p = 0.82$, $\delta = 0.08$) revealed no significant difference, suggesting that both interactive formats are statistically equivalent. These results imply that the key factor in learning outcomes is the interactivity of the experience, rather than the medium itself.

Regarding the GEQ, the dimensional analysis groups the 19 items into psychological dimensions (Table 4). This allows for a simplified analysis and a better interpretation of the data. By consolidating related items, the approach reduces the number of statistical comparisons, thereby minimizing the

TABLE 4. Dimensions, items, and definitions.

Dimension	Items	Definition
Immersion	Q1, Q5, Q6, Q8, Q9, Q11, Q14, Q18	Absorption in the experience
Flow	Q2, Q12, Q13, Q15, Q17	Optimal concentration and automation of actions
Negative Affect	Q4, Q7, Q10, Q19	Adverse emotions
Positive Affect	Q3, Q16	Pleasurable emotions

TABLE 5. Comparison of VR and BG data.

Dimension	VR (Mean ± SD)	BG (Mean ± SD)	U	p-value
Immersion	39.8% ± 5.9	32.1% ± 5.5	138.0	0.022
Flow	32.4% ± 5.3	26.7% ± 4.9	155.0	0.051
Negative Affect	15.0% ± 3.2	10.2% ± 2.8	168.3	0.092
Positive Affect	28.6% ± 4.7	25.3% ± 4.5	172.1	0.110

risk of Type I errors and increasing statistical power through more aggregated and robust data.

Table 5 compares data from two conditions, VR and BG, across four psychological dimensions: Immersion, Flow, Negative Affect, and Positive Affect. For each dimension, the table presents the mean percentage values along with the standard deviations (SD) for both VR and BG conditions. It also includes statistical values such as the U statistic from the Mann-Whitney U test and the associated p-values, which assess the significance of differences between the two groups. The results indicate that Immersion shows a statistically significant difference, with VR participants demonstrating higher levels of immersion compared to BG participants ($p = 0.022$). However, Flow, Negative Affect, and Positive Affect do not exhibit statistically significant differences between the two conditions, as their p-values exceed the 0.05 threshold, suggesting no significant differences in these dimensions.

B. QUALITATIVE ANALISYS

Participants in the board game condition consistently reported being drawn to the hands-on, problem-solving nature of the activity. The tactile engagement offered by the physical coding blocks was frequently mentioned as a source of motivation, with one participant stating, “The puzzle itself was motivating – I liked that it was practical, not just theory”. In contrast, VR participants emphasized the immersive virtual environment as their primary source of engagement, commenting on the beauty and richness of the surroundings. However, engagement in the VR condition was more variable, with some users reporting that technical issues—such as the laser-based selection system and repetitive sound effects—distracted from the experience and occasionally caused frustration.

Focus and cognitive flow developed progressively in the board game condition. Participants reported increased concentration as they advanced through the levels, with one noting, “By the end, I was completely absorbed”. Early-stage distractions were mentioned by two participants, who cited background noise as a factor, highlighting the relevance of environmental conditions for optimal engagement. In the VR condition, participants remained task-focused even in the presence of discomfort, such as dizziness or interface challenges. One user described a strong internal drive to complete the tasks, stating, “I kept trying until solving it, even when dizzy”. These qualitative findings align with the higher immersion scores observed quantitatively for VR, although breaks in presence were occasionally reported due to interface limitations.

Emotionally, the two conditions elicited distinct patterns. The board game group expressed uniformly positive affect, with feelings of enjoyment, competitiveness, and relaxation. Participants expressed a desire for more levels and increased difficulty, and no frustration was reported. Conversely, emotional responses in the VR group were more polarized: while many users enjoyed the challenge and felt motivated, others reported frustration with aspects of the interface (e.g., object collisions) and noted a sense of fatigue, particularly due to the repetitive audio cues.

VII. DISCUSSION

This study successfully met the three objectives outlined. First, two educational prototypes were designed and developed: an immersive VR environment for block-based programming and a tactile BG, both rigorously validated in terms of functionality and educational content. This achievement of the first objective (O1) allowed for meaningful comparisons between these prototypes and the traditional PDF format.

Regarding the second objective, which aimed to assess the effectiveness of these prototypes in terms of engagement, conceptual comprehension, and learner satisfaction (O2), the results indicated that both VR and BG outperformed the PDF format. In terms of conceptual understanding, both VR and BG demonstrated superior learning outcomes, with VR showing a slightly more pronounced improvement. This difference could be attributed to the higher level of immersion provided by VR, as indicated by the engagement analysis. Nevertheless, BG also performed positively, particularly in terms of user experience, suggesting that non-digital tactile tools can be equally effective in certain contexts, especially when access to advanced technology like VR is limited.

As for the third objective of the study (O3), which sought to compare how VR and BG address gaps in programming education with the PDF serving as a control, the results showed that both interactive methods (VR and BG) were significantly more effective than the static PDF format. The comparison between VR and BG revealed no significant differences, indicating that both interactive formats are equally effective in terms of learning outcomes, highlighting interactivity as the key factor in improving educational results.

Regarding the hypotheses formulated at the beginning of the study, H1 proposed that VR would yield higher levels of engagement and computational thinking gains, but BG would closely approximate VR’s effectiveness, while PDF would perform the worst. The results supported this hypothesis, as VR demonstrated an advantage in terms of immersion, which translated into higher engagement levels. However, BG exhibited similar results in terms of learning, and PDF performed significantly worse compared to both interactive methods, validating the effectiveness of interactive tools over traditional formats.

H2, which suggested that the BG, despite being a traditional tool, would have a positive impact on teaching programming principles and closely approximate the effectiveness of VR, was also supported. The results showed that both BG and VR were equally effective in terms of understanding programming concepts, significantly outperforming the PDF format. Despite the differences in technology, the effectiveness of BG was comparable to VR, emphasizing the value of well-designed traditional tools.

Finally, H3 proposed that BG, due to its accessible and user-centered design, would be particularly effective for learners without VR access, whereas PDF would reflect the limitations of non-interactive methods. The results confirmed this hypothesis clearly, showing that BG was not only more accessible than VR, but also provided a more positive emotional experience for users without the technical hurdles associated with VR. This demonstrates that BG can be a valid option, especially in resource-limited environments.

In summary, the results of this study reinforce the importance of interactivity in learning processes and highlight the effectiveness of both VR and BG. While VR showed a higher level of immersion, BG provided significant benefits in terms of accessibility and user experience. These findings have key implications for the design of educational tools in programming education, suggesting that interactive methods are superior to traditional text-based approaches, and BG can serve as an effective alternative when technological resources are limited.

VIII. LIMITATIONS AND FUTURE WORK

While this study provides valuable insights into the effectiveness of interactive educational tools, several limitations should be considered. First, the small sample size of the study ($n = 9$ per group) limits the generalizability of the results. Although non-parametric tests were employed to account for the small sample and non-normality of the data, larger sample sizes would provide more robust and reliable results.

Another limitation concerns the duration of the study. The assessment was conducted over a relatively short period, which may not fully capture the long-term effects of using VR, BG, or PDF tools on learner retention and deeper learning. Longitudinal studies would help in understanding how these tools affect the ability of learners to retain knowledge and apply concepts over time. Furthermore, future work could explore additional interactive formats, such as AR or hybrid learning tools, to assess their relative effectiveness. Investigating how various interactive formats work together or complement each other could provide further insight into optimal learning strategies.

In summary, while the findings of this study contribute to our understanding of the role of interactive educational tools in programming education, there are several avenues for future research. Expanding the sample size, exploring long-term effects, incorporating additional learning tools, and considering individual differences will help refine and further validate the effectiveness of interactive learning methods.

IX. CONCLUSION

Regarding effectiveness, both VR and BG significantly outperformed the PDF format in conceptual comprehension, with VR showing a slight edge in engagement, particularly due to its immersive nature. However, BG also proved to be highly effective, offering an accessible and user-friendly alternative to VR. These results support the notion that interactivity, rather than the medium itself, plays a key role in enhancing learning outcomes. Moreover, the accessibility and positive emotional impact associated with the BG render it an invaluable tool, particularly in settings where VR may present feasibility challenges.

The findings indicate that both VR and BG enhance learning outcomes more effectively than traditional PDF materials, thereby corroborating the assertion that interactive learning tools cultivate heightened engagement and comprehension. Moreover, these results highlight the critical importance of delivering educational experiences that are both accessible and captivating, thereby meeting the diverse needs of learners.

In conclusion, this study provides evidence that both VR and BG offer substantial benefits for programming education. The results suggest that the use of interactive tools, whether digital or physical, should be prioritized in educational contexts. Given their effectiveness in enhancing learning and engagement, these tools present promising alternatives to traditional teaching methods, with the BG offering a particularly valuable option for resource-constrained environments. Future research should explore the long-term impacts of such interactive tools and further investigate their applicability across different educational contexts.

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