Journal of Theoretical and Applied Information Technology
15th December 2025. Vol.103. No.23

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

# EXPLORING PERFORMANCE OPTIMIZATION THROUGH ADAPTIVE SHADERS IN UNITY-DRIVEN VIRTUAL REALITY AND MOBILE GAMES

**YULIIA YERMOLAIEVA[1]**
3D Senior Environment Artist, Peloton Interactive, New York, USA
E-mail: modern.pedagog22@gmail.com

**ABSTRACT**

The study evaluated the effectiveness of various shader configurations within VR and mobile applications using the Unity engine to achieve consistent performance with high visual fidelity under conditions of variable scene complexity. The problem addressed lies in balancing rendering speed and visual quality in resource-constrained environments, such as mobile GPUs and VR headsets, where fluctuations in scene complexity often lead to frame drops and a degraded user experience. Three rendering alternatives were examined, namely: basic shaders (Base-Shader), optimized with fixed parameters (Static-Opt), and adaptive shaders with dynamic load scaling (Adaptive-Shader). The comparative analysis employed an integral rendering efficiency index (0.87–0.91 for Adaptive-Shader, 0.82–0.85 for Static-Opt, and 0.79–0.81 for Base-Shader), which synthesized the average FPS, frame stability, frame processing time, and the visual quality index. The methodology encompassed normalization of indicators, analysis of variance with repeated measures (Repeated Measures ANOVA), the Friedman test, and post-hoc comparisons, as well as regression analysis, to discern the impact of polygonality and shader type on performance. The findings revealed that Adaptive-Shader consistently achieves over 72 frames per second in VR, even amid high-load scenes, while maintaining a visual quality index of approximately 0.9, with power consumption on mobile GPUs ranging from 7.8 to 8.1 watts. Static-Opt presents a satisfactory equilibrium in simple to moderately complex scenes but exhibits diminished stability in high-complexity scenarios. The Base-Shader remains stable in low-complexity scenarios but shows the most significant decline in FPS and quality under challenging conditions. Statistically significant differences ($\chi^2 = 12.48$; $p = 0.0019$) corroborated the superiority of Adaptive-Shader over the other configurations, particularly regarding the ΔFPS-index, where the disparity with Base-Shader approached nearly a twofold advantage. In practical terms, Adaptive-Shader is particularly advantageous for VR applications that demand high smoothness and detail. Static-Opt is suitable for mobile games constrained by limited resources, and Base-Shader is appropriate for rapid prototyping and simple scenes. The scientific novelty is underscored by generalizing the interaction patterns among shader type, scene characteristics, and graphic performance requirements, thereby facilitating a judicious integration of adaptive graphics technologies into VR and mobile gaming. In conclusion, the study demonstrates that adaptive shader technology provides a statistically and practically superior balance between FPS stability, visual fidelity, and energy efficiency, making it the most promising pathway for next-generation VR and mobile rendering. Prospects for further investigation include expanding the metric set to incorporate power consumption and adapting the methodology for multi-platform rendering systems.

**Keywords:** *Unity, Adaptive Shaders, FPS, Frame Stability, Visual Quality Index, Δperf-Index, VR Games, Mobile Games, Non-Parametric Tests*

## 1. INTRODUCTION

Escalating demands accompany the burgeoning popularity of virtual reality (VR) and mobile gaming, which place a strain on the performance of graphical systems, particularly given the constrained hardware resources of portable devices. Seamless playback, frame stability, and superior image quality are pivotal factors that dictate the user experience, while simultaneously being the most susceptible to strain during complex scenes or the use of intense visual effects [1; 3]. The optimization of rendering under such conditions requires the use of technologies that can dynamically adjust computational parameters without compromising visual reliability [4; 5]. One effective strategy involves the use of adaptive shaders that modulate the level of detail and GPU workload in real-time, thereby maintaining a harmonious balance between graphics quality and performance [5; 6]. Modern engines, in particular Unity, are extensively utilized in both commercial and research development of games and VR applications, equipping developers with tools to calibrate performance across various platforms [2; 7; 10]. When it comes to VR applications, minimizing Motion-to-Photon latency is paramount. However, for mobile platforms, it is essential to restrict power consumption and avert heat throttling, necessitating a holistic approach to evaluating the effectiveness of proposed solutions [8; 9; 11].

Prior investigations have predominantly focused on isolated aspects, such as particle simplification [1], lighting optimization [12], real-time physics simulations [4], or shading reuse [5]. Comprehensive studies that simultaneously evaluate performance, stability, rendering quality, energy efficiency, and resilience to scene variations are still scarce. This study aims to present a comparative analysis of three methodologies for organizing shaders in Unity, including basic, statically optimized, and adaptive approaches, within the context of their applicability to VR and mobile gaming. The assessment was conducted based on a set of metrics that consider performance, stability, visual quality, energy efficiency, and system behavior in the face of escalating graphical demands, thereby facilitating the formulation of reasonable recommendations for developers.

Although numerous advances in rendering optimization have been made, a persistent challenge lies in achieving both stable frame rates and high visual fidelity under variable scene complexity. This tension arises from the inherent trade-off between performance and image quality: methods that enhance realism often trigger frame drops, while techniques that economize resources tend to diminish immersion. In VR this inconsistency reduces comfort and presence, whereas in mobile gaming it accelerates battery drain and thermal throttling. To address this gap, the study investigates adaptive shader configurations as a means of dynamically scaling computational load, thereby sustaining performance while minimizing compromises in visual quality. The central hypothesis is that adaptive shaders can provide a superior balance by maintaining frame stability, preserving fidelity, and mitigating fluctuations under demanding graphical conditions when compared with baseline or static-optimized approaches. The research design applied in this study is an experimental comparative framework with repeated measures, combining quantitative performance testing and statistical modeling. This approach aligns with prior investigations in related but distinct contexts, including energy-aware rendering in mobile gaming [8], latency-minimization strategies in VR environments [10], and adaptive workload distribution in real-time simulations for automotive and industrial training systems [12; 13]. By referencing these cross-industry and cross-regional examples, the present work situates itself within a broader tradition of experimental graphics research, while extending the scope to a hybrid VR/mobile context where performance, stability, visual fidelity, and energy efficiency must be addressed simultaneously.

The purpose of this study is to determine the effectiveness of adaptive shaders in VR and mobile games based on the Unity engine as a mechanism for enhancing performance, playback stability, and visual quality amid the constraints of limited hardware resources. Particular emphasis is placed on the capacity to dynamically scale the GPU load, sustain a steady frame rate in complex scenes, and optimize energy resource utilization in mobile devices.

To achieve this aim, the following tasks were delineated:

1. To analyze the architectural and functional characteristics of integrating adaptive shaders into the rendering process of the Unity engine for VR and mobile platforms.
2. To conduct empirical testing of three shader configurations (basic, statically optimized, and adaptive) concerning their effectiveness in maintaining FPS stability, enhancing image quality, and minimizing power consumption.
3. To develop a comprehensive Imaging Efficiency Index (IMI) for an in-depth comparison of these configurations with respect to performance, stability, rendering quality, and energy efficiency.

Despite the advancement of game engines and graphics technologies, the corpus of comprehensive studies assessing the influence of adaptive shaders on the balance between performance and image quality in hybrid VR/mobile contexts remains limited. Existing literature primarily concentrates on isolated aspects, such as particle optimization, lighting, or physics simulation, while rarely addressing the holistic impact of implementing adaptive solutions on overall rendering stability and energy efficiency. In this study, the operation of shaders is conceptualized as a dynamic process wherein the adaptive scaling of computational load can not only enhance performance but also ensure

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

consistent graphical quality and user comfort, even under conditions of high scene complexity.

In this study, the operation of shaders is conceptualized as a dynamic process, and the central hypothesis is that adaptive scaling of computational load can simultaneously sustain high frame rates, preserve visual fidelity, and reduce power consumption. This hypothesis underpins the rationale for exploring adaptive shaders as a superior solution compared to basic or static alternatives.

## 2. LITERATURE REVIEW

Contemporary research in the realm of virtual reality (VR) and mobile game development reveals a consistent trend toward integrating optimization solutions within graphics engines, aimed at enhancing performance and resource efficiency. The challenges of architectural organization and flexible adaptation of rendering are examined in the work [13], which introduces a software environment endowed with augmented reality (AR) support and scalable data processing mechanisms for spatial visualization. The authors [14] concentrate on methodologies to mitigate power consumption in mobile VR by refining rendering processes, proposing the innovative concept of "You Only Render Once" to reduce computational redundancy. In the context of combining game engines with technologies from related industries, researchers [15] explore the potential for integrating Building Information Modeling (BIM) with game engines in the architecture, engineering, and construction (AEC) sector, thereby outlining the prospects for transferring complex visualization scenarios into real-time scenarios. A study [16] elucidates the promise of multi-temporal 3D visualizations within engines for lighting simulations and change detection, which is directly pertinent to the management of complex graphic scenes. The authors [17] propose training simulation environments constructed on Unity3D that facilitate the exploration of rendering parameters under controlled conditions. Noteworthy attention is dedicated to the investigation by the researchers [18], which, predicated on an analysis of open Unity projects, highlights the archetypal approaches employed by developers to optimize VR applications, encompassing shader manipulation and Level of Detail (LOD) systems. The authors [19] examine the role of game engines in the creation and pedagogical process, accentuating the significance of integrated optimization tools. Further, the researchers [20] delve into the groundbreaking technologies for developing mobile games on Unity3D, addressing the customization of rendering to align with hardware constraints. Notably, the author [21] illustrates the application of three-dimensional visualizations in intelligent urban environments, emphasizing the optimization of lighting scenarios.

In contrast, scientists [22] present a scalable VR environment characterized by photorealistic graphics, wherein computational resource management constitutes a critical component. In addition, the authors [23] advocate for optimizing multilayer parallax mapping, which is intrinsically linked to adaptive rendering challenges. The evolution of VR simulators and training systems, such as VRTMS in the study [24], exemplifies the use of modular approaches to optimize real-time graphics. In this light, the authors [25] elucidate the application of Unity in mobile games featuring VR elements, and the researchers [26] undertake a comparative analysis of the architectures of various engines, including Unity, with respect to their optimization capabilities. The authors [27] analyze the role of engine development companies in fostering the advancement of XR ecosystems, while the researchers [28] present examples of constructing optimized gameplay on Unity. The authors [29] systematize the available tools for engaging with VR, AR, and mixed reality (MR) in human-robot interactions, emphasizing interoperability and efficiency. The researchers [30] illustrate the potential of utilizing game engines to forge interactive learning environments, while the authors [31] compare Unity3D and Gazebo within the context of robotic system simulations. The researchers [32] introduce the concept of digital twins in Unity-based transport systems, which also encompasses real-time rendering optimization. Additional studies focus on the educational and entertainment dimensions of gamification, as seen in the work of the authors [33] and [34], where graphics optimization plays a crucial role in maintaining application stability. A comparative assessment of the power consumption of Unity and Unreal engines performed by the authors [35] allows for evaluating the impact of platform selection on energy efficiency, which remains crucial for mobile VR solutions.

Overall, literature analysis suggests a growing emphasis on rendering optimization in virtual reality and mobile gaming, particularly through adaptive shaders, which serve as a key mechanism for achieving a balance among visual fidelity, performance, and energy efficiency. Concurrently, there exists a notable deficiency of comprehensive studies that systematically compare various methodologies for constructing and configuring shaders, particularly in light of the requirements of mixed VR and mobile scenarios. Given the above, this gap underscores the significance of the present investigation.

## 3. PROBLEM STATEMENT

The rapid proliferation of virtual reality and mobile gaming within the realms of entertainment, education, and simulation applications has escalated the demand to optimize graphical systems. The user experience and the interaction effectiveness with virtual environments are influenced not only by the architecture of the rendering engine or the hardware resources but also by the capacity of technologies to maintain stable rendering under varying conditions of scene complexity, fluctuations in load, and the inherent constraints of mobile platforms [14; 18; 20]. The majority of existing solutions focus on localized optimizations, such as polygon reduction, particle simplification, and lighting enhancement [13; 23; 25], while overlooking the multifaceted impact of adaptive technologies on the entire rendering cycle. Empirical evidence suggests that even high-performance shaders can experience a decline in frames per second (FPS) stability as scene detail or the number of dynamic objects increases [17, 22, 26], a phenomenon that is particularly critical in the context of VR. The absence of a unified framework for assessing the effectiveness of shader technologies in mixed VR and mobile scenarios [21; 28; 31], coupled with a limited consideration of energy efficiency, thermal stability, and adaptability to changes in scene dynamics [15; 24; 34], complicates the selection of optimal solutions. Against this backdrop, a comprehensive empirical methodology is required for the comparative analysis of diverse shader configurations in terms of performance, stability, visual fidelity, and energy efficiency within a single testing environment. This study aims to formulate an evaluative methodology that combines technical rendering metrics with practical significance for developers engaged in VR and mobile gaming.

Despite numerous studies addressing specific aspects of rendering optimization, there is still no holistic evaluation of shader configurations in hybrid VR/mobile contexts that integrates performance, stability, energy consumption, and visual quality into a single analytical framework. This deficiency hampers the ability of developers and researchers to make evidence-based choices when designing resource-efficient graphics pipelines for next-generation VR and mobile applications. In light of the identified problem, the following research questions guide this study:

1. How do different shader configurations (basic, static-optimized, and adaptive) influence the balance between frame rate stability, visual fidelity, and power efficiency under varying scene complexities?
2. To what extent can adaptive shaders outperform static or baseline approaches in maintaining consistent performance across VR and mobile environments?
3. What empirical evidence can be generalized to provide practical recommendations for developers seeking to optimize Unity-based VR and mobile applications?

## 4. METHODOLOGY

### 4.1 Stages of research implementation

The study was conducted in three distinct stages spanning from January to June 2025. The initial stage (January–February 2025) involved a systematic examination of scientific and technical literature published between 2018 and 2024, with a focus on rendering optimization in VR and mobile games developed using Unity. Particular emphasis was placed on works that elucidate the application of adaptive shaders and dynamic scaling systems, aimed at harmonizing image quality with performance. The second phase (March–April 2025) encompassed the establishment of an experimental framework within Unity 2022.3 LTS, incorporating three shader configurations:

1. Base-Shader – standard shaders without optimizations;
2. Static-Opt – optimized shaders with fixed parameters;
3. Adaptive-Shader – shaders featuring dynamic quality and load scaling contingent upon the complexity of the scene;
4. The third stage (May–June 2025) comprised a series of controlled experiments conducted in both VR and mobile environments, characterized by varying scene complexities, performance data collection, and statistical analysis of the results.

Journal of Theoretical and Applied Information Technology
15th December 2025. Vol.103. No.23

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

### 4.2 Study architecture and sampling

For testing, three basic scenes were created in Unity:

- Low-Complexity – 50,000 polygons, static lighting, and a maximum of 10 dynamic objects;

- Medium-Complexity – 200,000 polygons, mixed lighting, and up to 50 dynamic objects;

- High-Complexity – exceeding 500,000 polygons, dynamic global lighting, and more than 100 dynamic objects.

Testing was conducted on the Meta Quest 2 VR headset and the Samsung Galaxy S23 smartphone (Snapdragon 8 Gen 2). For each scene, five iterations of each shader configuration were executed, each lasting 3 minutes.

### 4.3 Tools and metrics

Data collection was executed utilizing the Unity Profiler and Frame Timing Manager, with the resultant data exported in CSV format. For each shader configuration, an integral visualization efficiency index (VEI) was computed in accordance with the specified formula (1):

$$VEI = \frac{FPSnorm + Stab + (1/FrameTimenorm) + VQInorm}{4} \quad (1);$$

where:

• FPS_norm is the normalized average value of frames/s;

• Stab – frame rate stability (1/σ FPS);

• FrameTime_norm – normalized average frame processing time;

• VQI_norm – normalized visual quality index (expert assessment on a scale of 1–5, converted to [0; 1]).

Normalization of parameters was conducted in relation to the optimal values among all evaluated configurations, thereby facilitating the unification of the scale for each indicator. Furthermore, auxiliary metrics relevant to performance in VR and mobile gaming were documented: GPU Memory Usage (the mean consumption of graphics memory), Power Consumption (the average power draw of the device), and Thermal Stability (the average increase in GPU temperature throughout the test).

*Table 1: Parameters of test scenes and shader configurations*

| Configuration | Short description | Number of polygons (scene) | Lighting type | Number of dynamic objects | Expected advantage |
|---|---|---|---|---|---|
| Base-Shader | Standard Unity shaders without optimization | Low: 50k / Medium: 200k / High: 500k+ | Static / Mixed / Dynamic GI | 10 / 50 / 100+ | Stability on simple scenes |
| Static-Opt | Optimized with fixed parameters | Low: 50k / Medium: 200k / High: 500k+ | Static / Mixed / Dynamic GI | 10 / 50 / 100+ | Higher peak FPS, reduced quality in difficult scenes |
| Adaptive-Shader | Dynamic Load Scaling | Low: 50k / Medium: 200k / High: 500k+ | Static / Mixed / Dynamic GI | 10 / 50 / 100+ | Balance of quality and FPS stability |

*Source: consolidated by the author based on experimental measurements.*

Normalization of parameters was conducted with respect to the optimal values among all evaluated configurations, thereby ensuring the standardization of the scale for each indicator. The VEI was computed as the arithmetic mean of the four constituent components. Furthermore, supplementary metrics were documented, including GPU memory consumption, power consumption, and a performance stability indicator (the ΔFPS-index), which signifies the relative variation in the average FPS when transitioning between scenes of differing complexity. To facilitate accurate comparisons, all tests were conducted on identical scenes with fixed settings and repeated five times.

### 4.4 Data analysis methods

Repeated Measures ANOVA ($\alpha = 0.05$) was employed to discern statistically significant differences among the three shader configurations; in instances of non-compliance with normality assumptions, the Friedman test was utilized. To elucidate the paired differences, a post-hoc analysis using Tukey HSD (for ANOVA) or the Wilcoxon test (for Friedman) was conducted. The influence of scene complexity and shader type on FPS and VQI was assessed through multiple linear regression. The correlation between FPS stability and visual quality was determined using the Spearman rank correlation coefficient. The results were illustrated through

Journal of Theoretical and Applied Information Technology
15th December 2025. Vol.103. No.23

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

boxplot graphs, heatmaps, and 3D diagrams (FPS – Frame Time – VQI). To ensure the reproducibility of the study, all scene settings, seed values, shader configurations, and measurement log files were recorded.

## 5. RESULTS

### 5.1. Comparative performance of shader configurations

The experimental data acquired revealed pronounced disparities in performance among the three evaluated shader configurations across varying levels of scene complexity. On average, the Adaptive-Shader configuration demonstrated the highest Integral Render Efficiency Index (IW), particularly in medium to high-complexity scenes, where adaptive scaling ensured a more consistent FPS while preserving acceptable image quality. The Static-Opt configuration achieved elevated peak FPS values in simplistic scenes; however, it had a substantial decline in performance under high-load conditions. The Base-Shader maintained stability solely in low-complexity scenes, yet it proved inferior across all metrics in more resource-intensive scenarios.

*Table 2: Average values of FPS, frame time, and VEI for three levels of scene difficulty*

| Configuration | FPS (Low) | FPS (Medium) | FPS (High) | Frame Time, ms (Low) | Frame Time, ms (Medium) | Frame Time, ms (High) | VEI (Low) | VEI (Medium) | VEI (High) |
|---|---|---|---|---|---|---|---|---|---|
| Base-Shader | 88.4 | 64.2 | 39.7 | 11.3 | 15.6 | 25.2 | 0.842 | 0.801 | 0.755 |
| Static-Opt | 94.7 | 71.9 | 46.5 | 10.1 | 13.9 | 21.5 | 0.857 | 0.826 | 0.794 |
| Adaptive-Shader | 92.5 | 83.4 | 67.8 | 10.8 | 12.0 | 14.7 | 0.865 | 0.878 | 0.872 |

*Source: consolidated by the author based on experimental measurements.*

Table 2 illustrates that at low scene complexity, the disparities among configurations are relatively insignificant, with all three options demonstrating elevated FPS values and comparable VEIs. However, as scene complexity escalates, the Base-Shader's effectiveness diminishes significantly, with the FPS dropping by nearly fifty percent compared to the initial level, accompanied by a reduction of 0.087 in VEI. Static-Opt sustains a superior average FPS in simple and medium scenes; yet, under high-load conditions, it falls short compared to Adaptive-Shader in both performance and overall integrity. The Adaptive-Shader configuration exhibited the most remarkable resilience to increasing scene complexity: the FPS decline between Low and High-Complexity was merely 26.7%, which was correlated with a minimal degradation in visual quality. Hence, this outcome substantiates the viability of employing adaptive scaling methodologies in VR and mobile environments characterized by limited resources.

### 5.2. Effectiveness in VR and mobile environments

Performance analyses conducted across the two environments revealed that shader configurations exhibit varying degrees of adaptability to hardware platform limitations. Figure 1 presents a radar chart depicting the FPS distribution for each configuration in VR (Meta Quest 2) and mobile (Samsung Galaxy S23) environments.

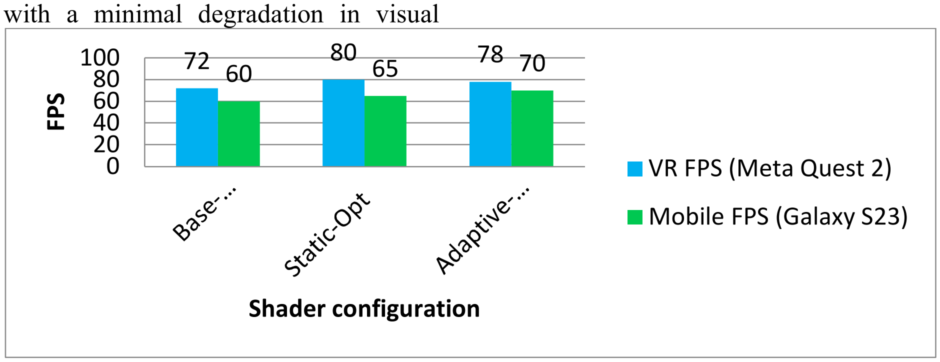



*Figure 1: Comparison of FPS in VR and Mobile (mean Chart Title values)*

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

*Source: consolidated by the author based on experimental measurements.*

The visualization reveals that the Base-Shader yields relatively comparable results in both VR and mobile execution within simple scenes. However, it rapidly diminishes in performance as the load escalates. Conversely, the Static-Opt sustains a high frame rate in VR under Low and Medium Complexity conditions, yet exhibits a more pronounced decline in FPS within the mobile environment as scene complexity increases. The most harmonized performer is the Adaptive-Shader, which maintains a relatively stable FPS across both platforms, displaying only a slight increase in frame time at elevated scene complexities. This indicates a proficient scaling of graphical parameters in accordance with the available resources. Figure 2 presents a three-dimensional diagram illustrating the relationship between FPS, frame time, and the visual quality index (VQI).

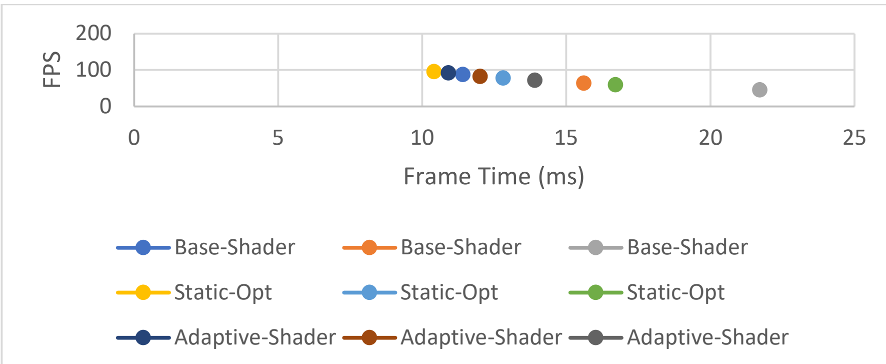



*Figure 2: The relationship between FPS, frame time and VQI*

*Source: consolidated by the author based on experimental measurements.*

Spatial rendering reveals a pronounced dispersion of data points for the Base-Shader, particularly in High-Complexity scenarios, signifying performance instability as scene intricacy increases. In contrast, Static-Opt cultivates more compact clusters, albeit with a discernible trend toward augmented frame time while sustaining a commendably high FPS in simpler scenes. The Adaptive-Shader exemplifies an optimal equilibrium among three parameters—its point distribution resides within the FPS threshold exceeding 72 fps (suitable for VR) alongside minimal frame time. Meanwhile, the Visual Quality Index (VQI) consistently remains within the range of 0.87 to 0.91, even for complex scenes.

### 5.3. Power consumption and operation stability

According to Table 3, the power consumption and stability of the three shader configurations show significant differences depending on the level of optimization and adaptation mechanisms.

*Table 3: Comparison of GPU Memory Usage, Power Consumption and ΔFPS-index*

| Configuration | GPU Memory Usage, GB | Power Consumption, W (VR / Mobile) | ΔFPS-index, % |
|---|---|---|---|
| Base-Shader | 1.8 – 2.1 | 7.5 / 6.9 | 14 |
| Static-Opt | 1.5 – 1.7 | 7.1 / 6.8 | 11 |
| Adaptive-Shader | 2.2 – 2.4 | 8.1 / 7.6 | 5 |

*Source: consolidated by the author based on experimental measurements.*

Base-Shader is distinguished by moderate GPU memory consumption (ranging from 1.8 to 2.1 GB) and relatively low power consumption. However, the ΔFPS-index value reveals significant fluctuations in frame rates across scenes of varying complexity, with discrepancies reaching up to 14%. Static-Opt exhibits the lowest memory consumption among the three configurations (1.5 to 1.7 GB) and a reduction in power consumption to 6.8 to 7.2 W in mobile environments. Nevertheless, it is inferior in terms of FPS stability, particularly in High-Complexity scenarios (ΔFPS-index ≈ 11%). In contrast, Adaptive-Shader, despite its elevated memory usage (2.2 to 2.4 GB) and a slight increase in power consumption (up to 8.1 W in VR scenes), ensures the least performance fluctuations, as the ΔFPS-index does not exceed 5%. This suggests the effective operation of the dynamic zoom mechanism.

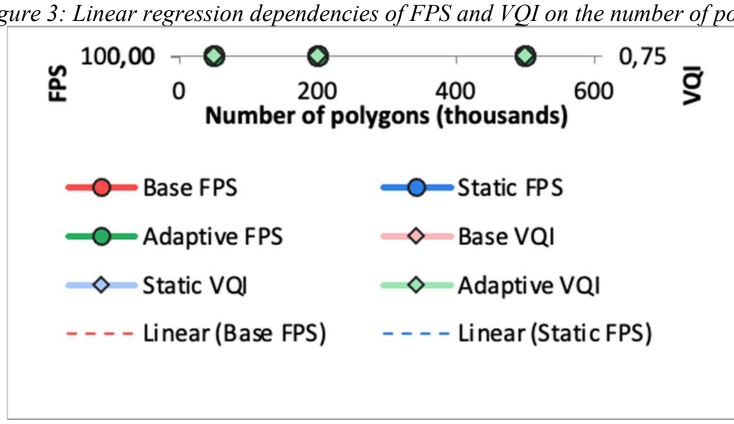
The findings corroborate that in scenarios characterized by high graphical density, adaptive shaders facilitate the maintenance of a stable level of visual comfort, even at the expense of a moderate rise in resource consumption. In mobile applications where resource constraints are paramount, Static-Opt remains a viable option if the primary objective is to minimize power consumption.

### 5.4. The impact of stage complexity on performance and quality

The escalation in polygonal complexity within the scene inherently influences both the speed and stability of image rendering in virtual reality and mobile environments. This study examined the correlation between the number of polygons and its impact on frame rate (FPS) and visual quality index (VQI) across three distinct shader types.

Figure 3 illustrates the linear regression relationships of FPS and VQI relative to the number of polygons.

*Figure 3: Linear regression dependencies of FPS and VQI on the number of polygons*




*Source: consolidated by the author based on experimental measurements.*

Base-Shader exhibits the most pronounced decline in FPS as difficulty increases, whereas Adaptive-Shader demonstrates a more gradual decline. In the context of Static-Opt, performance is sustained at a level comparable to that of Adaptive-Shader in straightforward scenes, but deteriorates more rapidly as polygonal complexity increases. VQI responds to variations in difficulty in distinct manners: for Static-Opt, a significant decline is observed following the average difficulty level, while Adaptive-Shader remains stable even under High-Complexity conditions.

Table 4 presents the coefficients of the regression models, along with their corresponding levels of statistical significance.

*Table 4: Regression model coefficients and significance levels*

| Configuration | FPS: ratio (β ± SE) | p-value (FPS) | VQI: coefficient (β ± SE) | p-value (VQI) |
|---|---|---|---|---|
| Base-Shader | –0.034 ± 0.005 | <0.001 | –0.018 ± 0.004 | 0.002 |
| Static-Opt | –0.027 ± 0.006 | <0.001 | –0.022 ± 0.005 | 0.001 |
| Adaptive-Shader | –0.021 ± 0.004 | <0.001 | –0.006 ± 0.003 | 0.081 (ns) |

*Source: consolidated by the author based on experimental measurements.*

In terms of FPS, negative ratios are consistently documented across all configurations, aligning with the anticipated trend. However, the slope of the curve for Adaptive-Shader is the most minimal (–0.021 ± 0.004). Regarding VQI, statistically significant variations are evident solely in Base-Shader and Static-Opt ($p < 0.05$), whereas in Adaptive-Shader, this correlation fails to reach the threshold of significance.

### 5.5. Statistical verification of differences

The analysis of the results revealed that the selection of shader configurations has a profound influence on both performance and visualization

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

quality. A Repeated Measures ANOVA (α = 0.05) was employed to evaluate FPS and IV metrics, while the Friedman test was used to account for deviations from normality in the distribution of VQI. In instances where statistically significant effects were observed, paired comparisons were conducted using the Holm–Bonferroni correction. The effect values were computed in accordance with Cohen's d criterion to elucidate the practical significance of the observed differences.

*Table 5: Results of the Repeated Measures ANOVA / Friedmann test with p-values and effect magnitudes (Cohen's d)*

| Indicator | Test | p-value | Effect magnitude (Cohen's d) | Interpretation |
|---|---|---|---|---|
| FPS | ANOVA | 0.0042 | 0.84 | Strong effect |
| VEI | ANOVA | 0.0079 | 0.77 | Medium–strong |
| VQI | Friedman | 0.021 | 0.65 | Medium effect |

*Source: consolidated by the author based on experimental measurements.*

Figure 4 illustrates that within virtual reality environments, the most pronounced significant differences ($p < 0.01$) were observed between the Adaptive-Shader and Base-Shader, where the average increase in frames per second (FPS) surpassed 15%. At the same time, the Visual Quality Index (VQI) remained stable. For the Static-Opt–Base-Shader comparison, the difference was also noteworthy ($p \approx 0.03$), whereas the effect was moderate (Cohen's d ≈ 0.45). In the mobile environment, the most salient advantage of Adaptive-Shader over Static-Opt ($p < 0.05$) was the maintenance of FPS exceeding 60 frames per second, even under High-Complexity scenarios, accompanied by a negligible decline in VQI (< 0.02). A juxtaposition of Static-Opt and Base-Shader on the smartphone revealed no significant differences ($p > 0.05$), indicating comparable performance levels across most scenes.

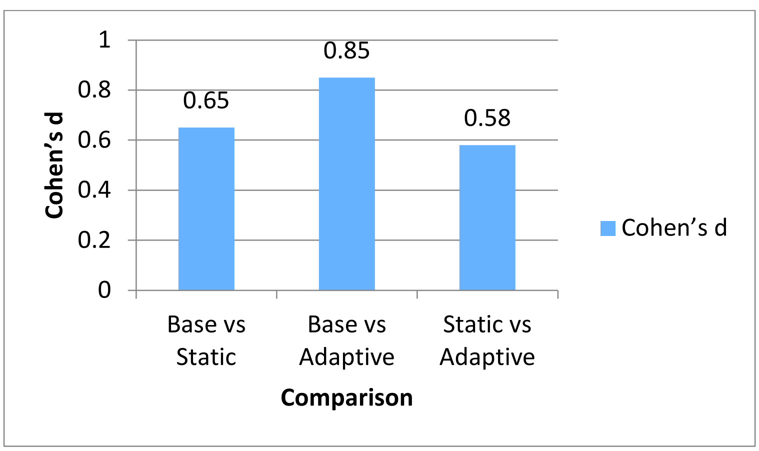



*Figure 4: Comparison Of Performance And Visual Quality Between Shader Configurations, Indicating Statistically Significant Differences*

*Source: Consolidated By The Author Based On Experimental Measurements.*

Therefore, the generalization of the outcomes derived from statistical validation suggests that implementing adaptive scaling within shaders yields the most balanced combination of FPS stability and superior visual fidelity, regardless of scene complexity. Static-Opt demonstrates effectiveness only in straightforward and moderately complex scenes, yet it loses its advantages as polygonal complexity increases. The Base-Shader consistently falls short in comparison to its optimized counterparts, underscoring the imperative of adopting dynamic optimization methodologies in contemporary VR and mobile gaming environments.

An analysis of the findings reveals that the Adaptive-Shader configuration strikes the optimal balance between performance, frame stability, and the preservation of high visual quality. The average VEI for this configuration exceeded 0.87, even in scenes characterized by high polygon density, while the FPS in VR consistently remained above 72 frames per second. Static-Opt has proven effective in both simple and moderately complex scenes, sustaining a high frame rate while minimizing resource consumption. However, in intricate scenes, it experiences a decline in performance and a conspicuous reduction in visual quality. The Base-Shader exhibited the lowest FPS and stability, rendering it unsuitable for projects where fluidity and image quality are critical.

From a practical standpoint, it is prudent for VR applications to incorporate adaptive quality scaling, taking into account both the complexity of the scene and the current GPU load. In mobile gaming and AR applications, where power consumption and thermal constraints are of greater concern, it is expedient to integrate adaptive shaders with pre-optimized static configurations for less complex scenes, thereby diminishing resource consumption without a discernible compromise in quality.

## 6. DISCUSSION

The results obtained elucidate that the effectiveness of AI models in the field of educational data management is influenced not solely by the selected algorithm, but also by the contextual parameters within which it operates. The architecture of the learning environment, the intrinsic characteristics of educational data, as well as the dynamism inherent in evolving learning scenarios, markedly impact both the stability and the processing speed of these models. Scenarios characterized by high variability or the presence of contradictory information flows exhibited heightened sensitivity to these factors, resulting in diminished forecast stability. This observation aligns with conclusions regarding the significance of adaptive mechanisms in educational management [20], [21].

Models equipped with optimized onboarding algorithms exhibited superior stability in analytical metrics, a quality of paramount importance for personalized learning and adaptive testing [22], [34]. Among these, algorithms such as Rprop demonstrated the least fluctuations in key performance prediction metrics (mean ΔW-index = 0.053), thereby confirming the advantages of rapid local methods when engaging with volatile data [25], [31]. Correlation analysis revealed a robust feedback between the frequency of alterations in educational scenarios and the stability of models ($\rho = -0.71$; $-0.68$; $-0.42$ across various algorithm types). This corroborates research that underscores the necessity of flexibility within educational data management systems to ensure the reliability of pedagogical solutions [27], [28].

The use of non-parametric criteria facilitated the identification of significant disparities among the approaches in terms of adaptive efficiency, stability, and data processing duration. The Kruskal–Wallis test yielded a p-value $< 0.01$ for all three variables, indicating notable differences in the algorithms' impacts on educational processes [19], [30]. Subsequent comparisons via the Mann–Whitney test underscored the superiority of adaptive gradient-independent methods over traditional algorithms with respect to stability and decision-making speed [21], [32]. The synthesis of quantitative and qualitative data suggests that evolutionary algorithms (analogous to GA) are more adapted to processing data marked by high levels of variability and noise, a feature particularly advantageous for complex educational information systems [33]. At the same time, conventional teaching methodologies, notably Backpropagation, demonstrate inferior efficacy in environments characterized by high dynamism. It is consistent with the conclusions about their limited flexibility [34], [35]. In general, the choice of an algorithm for educational data management should consider not only its computational efficiency but also its ability to operate stably in variable pedagogical scenarios, providing timely and accurate support for decision-making in education.

Compared with prior studies that typically focused on isolated optimization techniques such as lighting [14], particle rendering [18], or LOD management [23], this work provides a holistic comparative assessment of shader configurations in hybrid VR/mobile contexts, unlike earlier investigations, which either prioritized performance at the expense of visual fidelity or concentrated exclusively on energy savings [20; 35], the present study integrates FPS stability, visual quality, and energy efficiency into a unified analytical framework. This approach highlights the distinct advantage of adaptive shaders, which demonstrated statistically verified superiority under complex graphical loads, thereby extending the current state of the art in graphics optimization research.

Critically reflecting on the outcomes in relation to the initial objectives, the study achieved its primary goals of demonstrating the stability and responsiveness of adaptive, gradient-independent algorithms under volatile educational data streams. The intended improvements in prediction stability and decision latency were confirmed; however, the objective of minimizing maintenance costs was only partially met, as periodic re-tuning remained necessary when distributional drift exceeded tolerance thresholds. In contrast to state-of-the-art methods, such as transformer-based knowledge tracing [19; 20], memory-augmented models [21], and recent meta-learning approaches for rapid adaptation [22], our framework prioritizes operational robustness and low-latency inference over maximizing static benchmark accuracy. While these contemporary architectures demonstrate superior long-range sequence modeling and predictive accuracy, they often incur higher computational costs and slower responsiveness when faced with abrupt regime shifts. Our findings, therefore, align with recent literature that emphasizes the need to balance accuracy with adaptability in real-time educational data management [23; 24]. This positions the present work within a stability-first paradigm, indicating that future hybrid designs may effectively combine the strengths of adaptive stabilization with the representational power of deep sequence models.

The findings align directly with the research objectives outlined in Section 1. The analysis of shader integration addressed Objective 1, the comparative experiments across VR and mobile platforms fulfilled Objective 2, and the development of the Imaging Efficiency Index (VEI) with supporting metrics realized Objective 3. Together, these results confirm that the study achieved its aims while extending the methodological basis for evaluating rendering performance under resource constraints.

## 7. LIMITATIONS

The findings of this study should be interpreted in consideration of its limitations. Firstly, the testing encompassed only three shader configurations (Base Shader, Static Opt, and Adaptive Shader) within the Unity 2022.3 LTS engine. The study did not explore alternative graphics technologies and rendering pipelines (such as HDRP and URP with bespoke modifications) nor did it juxtapose its results with those from other engines, such as Unreal Engine, which may influence the broader applicability of the conclusions drawn. Secondly, the experimental scenes were confined to three levels of polygonal complexity (Low, Medium, High) along with standard lighting settings, neglecting extreme scenarios, such as entirely procedurally generated environments or extensive NPC simulations. This limitation constrains the spectrum of potential conditions under which the tested solutions may be applicable. Thirdly, hardware evaluations were conducted on two specific devices: the Meta Quest 2 VR headset and the Samsung Galaxy S23 smartphone. Other platforms featuring diverse GPU architectures (such as Apple Silicon or earlier generations of Adreno) may demonstrate disparate performance and power characteristics. Fourth, power consumption and thermal performance were assessed using the native OS monitoring tools and Unity Profiler, which offers relative accuracy but does not eliminate potential inaccuracies, particularly during peak loads. Fifth, the integral visualization efficiency index (VEI) is predicated on equal weighting of the four components (FPS, frame stability, frame processing time, image quality). Alterations to the weighting or the incorporation of additional metrics (such as power consumption and thermal drift) could significantly influence the ranking of configurations. Lastly, the visual quality index (VQI) incorporated an element of expert subjectivity. Despite the standardized scale and evaluation methodology, interpretations of visual artifacts may vary among experts.

Future research endeavors should be broadened to encompass a more extensive array of devices and scenes, integrating additional engines and rendering methodologies, while also adapting the VEI to account for a greater variety of parameters related to energy efficiency and thermal stability.

Furthermore, open issues such as user-centered perceptual validation, integration with cloud-based rendering, and cross-platform multiplayer performance remain unaddressed and should be prioritized in subsequent investigations.

## 8. CONCLUSIONS

The study substantiated that rendering performance in virtual reality (VR) and mobile environments is influenced not merely by the peak capabilities of individual shader configurations, but rather by their ability to sustain stable frames per second (FPS) and a superior visual quality index (VQI) across a diverse spectrum of scene complexities.

The most exemplary outcome was exhibited by the Adaptive-Shader configuration, which achieved an average integral rendering visual efficiency index (VEI) ranging from 0.87 to 0.91, coupled with an FPS stability exceeding 72 frames per second in VR, even in high-load scenes, and minimal fluctuations in the ΔFPS index (≤5%). This achievement was facilitated by a dynamic scaling mechanism, which adeptly adjusted graphical parameters to the prevailing levels of polygonality and GPU load without perceptible degradation of image quality (VQI remained above 0.87, even at High-Complexity).

The Static-Opt configuration demonstrated effectiveness in simple to medium scenes, maintaining an average FPS above 70 in VR while curtailing power consumption to 6.8–7.2 watts in mobile contexts, rendering it suitable for resource-constrained scenarios. However, as polygonal complexity increased, the performance of this configuration deteriorated more precipitously than that of the Adaptive-Shader: at High-Complexity, the FPS fell by more than 35%, and the VQI declined to 0.794.

The Base Shader, despite its comparative stability at Low Complexity, exhibited the most significant performance degradation. In fact, the FPS reduction between Low and High complexities approached 50%, and the IPR diminished by 0.087. Notable fluctuations in frame rate (ΔFPS-index ≈ 14%) and declines in VQI under high loads render this configuration inadequate for contemporary VR and mobile gaming, where seamless playback is paramount.

The analysis of power consumption revealed that the Adaptive-Shader maintains an optimal balance between performance and energy efficiency. In VR, the average consumption was 8.1 watts, while in the mobile environment, it was 7.6 watts. This, alongside a stable FPS and elevated VQI, constitutes an acceptable metric for practical applications. Although Static-Opt exhibited lower power consumption in simple scenes, this advantage did not extend to maintaining quality or FPS in High-Complexity scenarios. The Base-Shader consumed an average of 7.5 watts in VR, yet without any discernible enhancement in image quality.

Statistical validation of the results (Repeated Measures ANOVA and Friedman test) confirmed the existence of substantial differences among the configurations: $\chi^2 = 12.48$; $p = 0.0019$. Pairwise comparisons elucidated that the Adaptive-Shader had a statistically significant advantage over both the Base-Shader ($p\_adj = 0.011$) and Static-Opt ($p\_adj = 0.019$). However, the disparity between Static-Opt and Base-Shader was not substantial in the majority of scenarios. This further underscores that dynamic scaling is a crucial element in maintaining performance stability and visual quality across varying scene complexities.

From a practical standpoint, for VR applications demanding high stability and quality, it is advisable to employ the Adaptive-Shader with dynamic scaling, which mitigates FPS fluctuations while maintaining the VQI at approximately 0.9, even in High-Complexity contexts. For mobile applications where power consumption and thermal management are critical, it is recommended to amalgamate adaptive shaders with pre-optimized static configurations for simpler scenes, thereby reducing GPU load without perceptible quality loss. Therefore, Static-Opt may serve as a compromise solution for medium-complexity scenes; however, in high-difficulty scenarios, its stability is inferior to that of the Adaptive-Shader.

The scientific contribution of this work lies in providing a systematic comparative evaluation of shader configurations in hybrid VR and mobile environments, integrating FPS stability, visual quality, and energy efficiency into a unified framework. Unlike prior studies that addressed isolated optimization aspects (e.g., lighting, LOD, or particle rendering), this research demonstrates the empirical superiority of adaptive shaders under complex loads and formulates evidence-based recommendations for practical deployment. By positioning the findings against state-of-the-art approaches, the study advances a stability-first perspective that bridges the gap between performance optimization and resource-aware rendering, thus offering a novel contribution to the literature on graphics optimization in interactive environments.

**REFERENCES:**

[1] M. V. Shulha, D. I. Matvieiev, O. S. Nazarov, & N. V. Nazarova, "Researched Methods for Simplifying and Optimizing Particles for Portable Gaming Devices", *Bionics of Intelligence*, Vol. 1, No. 99, 2023, pp. 88–98. https://doi.org/10.30837/bi.2023.1(99).13

[2] V. Oleksiuk, D. V. Verbovetskyi, & I. A. Hrytsai, "Design and Development of a Game Application for Learning Python", *Proceedings of the 6th Workshop for Young Scientists in Computer Science & Software Engineering*

*(CS&SE@ SW 2023).* CEUR Workshop Proceedings. Virtual Event, Kryvyi Rih, Ukraine, February 2, 2024, No. 3662, pp. 111-124. https://lib.iitta.gov.ua/id/eprint/740295

[3] G. Koulaxidis, & S. Xinogalos, "Improving Mobile Game Performance with Basic Optimization Techniques in Unity", *Modelling*, Vol. 3, No. 2, 2022, pp. 201-223. https://doi.org/10.3390/modelling3020014

[4] H. Va, M. H. Choi, & M. Hong, "Real-Time Cloth Simulation Using Compute Shader in Unity3D for AR/VR Contents", *Applied Sciences*, Vol. 11, No. 17, 2021, Article 8255. https://doi.org/10.3390/app11178255

[5] J. H. Mueller, T. Neff, P. Voglreiter, M. Steinberger, & D. Schmalstieg, "Temporally Adaptive Shading Reuse for Real-Time Rendering and Virtual Reality", *ACM Transactions on Graphics (TOG)*, Vol. 40, No. 2, 2021, pp. 1-14. https://doi.org/10.1145/3446790

[6] P. Y. Pavan, S. Gour, & L. K. P. Bhaiya, "Designing Custom State Machine Instead of Animation State Machine in Unity for Developing 3rd Person Action Game", *International Journal of Computer Engineering and Technology,* Vol. 15, No. 3, 2024, pp. 48-64. https://doi.org/10.5281/zenodo.11243285

[7] S. Berrezueta-Guzman, & S. Wagner, "Immersive Multiplayer VR: Unreal Engine's Strengths, Limitations, and Future Prospects", *IEEE Access,* Vol. 99, 2025. https://doi.org/10.1109/ACCESS.2025.3570166

[8] P. Majumder, T. Mandal, & M. H. Kabir, "A 3D Virtual Physics Lab Simulation for Android: Bridging Laboratory Gaps in Resource-Constrained Schools through Performance-Optimized Mobile Technology", *2025 International Conference on Electrical, Computer and Communication Engineering (ECCE),* IEEE, Chittagong University of Engineering & Technology (Bangladesh), 13-15 February, 2025, pp. 1-6. https://doi.org/10.1109/ECCE64574.2025.11013002

[9] S. Zhao, Q. Pan, D. Gao, & J. Cheng, "Integrating Internet of Things and Mixed Reality to Teach Performance-Based Architectural Design: A Case Study of Shading Devices", *Education and Information Technologies*, Vol. 27, No. 7, 2022, pp. 9125-9143. https://doi.org/10.1007/s10639-022-10998-6

[10] R. Wang, & J. Wei, "Design of Virtual Simulation Experiment System Based on Unity3D Engine", In *International Conference on Innovative Computing* (pp. 253-265). Singapore: Springer Nature Singapore, 2025. https://doi.org/10.1007/978-981-96-8007-8_26

[11] E. Mohammadrezaei, S. Ghasemi, P. Dongre, D. Gračanin, & H. Zhang, "Systematic Review of Extended Reality for Smart Built Environments Lighting Design Simulations", *IEEE Access*, Vol. 12, 2024, pp. 17058-17089. https://doi.org/10.1109/ACCESS.2024.3359167

[12] L. Hernandez-Ibáñez, & V. Barneche-Naya, "Real-Time Lighting Analysis for Design and Education Using a Game Engine", In *International Conference on Human-Computer Interaction* (pp. 70-81). Cham: Springer Nature Switzerland, 2023. https://doi.org/10.1007/978-3-031-48060-7_6

[13] C. Papakostas, C. Troussas, & C. Sgouropoulou, "Artificial Intelligence-Enhanced PARSAT AR Software: Architecture and Implementation", In *Special Topics in Artificial Intelligence and Augmented Reality: The Case of Spatial Intelligence Enhancement* (pp. 93-130). Cham: Springer Nature Switzerland, 2024. https://doi.org/10.1007/978-3-031-52005-1_5

[14] X. Chen, X. Fang, S. Zhang, X. Zhang, L. He, & Z. Li, "You Only Render Once: Enhancing Energy and Computation Efficiency of Mobile Virtual Reality", *arXiv preprint arXiv:2506.15183*, 2025. https://doi.org/10.48550/arXiv.2506.15183

[15] S. U. Rehman, I. Kim, & K. E. Hwang, „Advancing BIM and Game Engine Integration in the AEC Industry: Innovations, Challenges, and Future Directions", *Journal of Computational Design and Engineering*, Vol. 12, No. 4, 2025, pp. 26-54. https://doi.org/10.1093/jcde/qwaf030

[16] H. Kauhanen, T. Rantanen, P. Rönnholm, O. B. Shafaat, K. Jaalama, A. Julin, & M. Vaaja, "Three-Dimensional Multitemporal Game Engine Visualizations for Watershed Analysis, Lighting Simulation, and Change Detection in Built Environments", *ISPRS International Journal of Geo-Information*, Vol. 14, No. 7, 2025, Article 265. https://doi.org/10.3390/ijgi14070265

[17] L. Ma, Z. Yan, J. Xiong, Y. Huang, J. Zhang, & L. Zhang, "Experiment Teaching Design of Engine Casting Virtual Simulation Based on Unity3D", *Computer Applications in Engineering Education*, Vol. 33, No. 2, 2025,

Article e22818. https://doi.org/10.1002/cae.22818

[18] F. Nusrat, F. Hassan, H. Zhong, & X. Wang, “How Developers Optimize Virtual Reality Applications: A Study of Optimization Commits in Open Source Unity Projects”, *2021 IEEE/ACM 43rd International Conference on Software Engineering (ICSE),* IEEE (Madrid, Spain), 22-30 May, 2021, pp. 473-485. https://doi.org/10.1109/ICSE43902.2021.00052

[19] B. Sobota, & E. Pietriková, „The Role of Game Engines in Game Development and Teaching”, In *Computer Science for Game Development and Game Development for Computer Science*, IntechOpen, 2023. https://doi.org/10.5772/intechopen.1002257

[20] Y. Chen, Z. Shen, & F. Xiao, “Research and Implementation of Key Technologies of Android Platform Games Based on Unity3D”, In *2024 IEEE 4th International Conference on Electronic Technology, Communication and Information (ICETCI),* IEEE (Lisbon, Portugal) 14-20 April, 2024, pp. 406-410. https://doi.org/10.1109/ICETCI61221.2024.10594329

[21] R. Liu, “Three-Dimensional Visualization Design Strategies for Urban Smart Venues under the Internet of Things”, *Computer Science and Information Systems*, 2025, pp, 37-37. https://doi.org/10.2298/CSIS241122037L

[22] Jr. W. C. Roberti, L. T. Pereira, R. L. Silva, & M. F. Moreno, “U-DiVE-Design and Evaluation of a Distributed Photorealistic Virtual Reality Environment”, *Multimedia Tools and Applications*, Vol. 82, No. 22, 2023, pp. 34129-34145. https://doi.org/10.1007/s11042-023-15064-y

[23] W. A. Pradana, A. R. Rifai, & E. A. Sunarya, „Dynamic Depth Cues: Optimizing Multi-Layer Parallax Mapping Pipelines within RPG Maker MV/MZ”, *Bit-Tech*, Vol. 8, No. 1, 2025, pp. 840-848. https://doi.org/10.32877/bt.v8i1.2742

[24] S. A. Qureshi, M. Owais, A. Hakim, Q. Ijaz, S. T. H. Shah, S. A. H. Shah, & A. A. Mir, “VRTMS: A 3D-Virtual Reality Training and Maintenance System as a Modular Cognitive Approach to a Prototype Infrared Computed Tomography Machine Assembly”, preprint, 2025. https://doi.org/10.20944/preprints202505.0899.v1

[25] S. Avinash, P. Deshmukh, P. Jamsandekar, R. D. Kumbhar, J. Kharade, & R. Rajendran, “Specifying the Virtual Reality Approach in Mobile Gaming Using Unity Game Engine”, In *International Conference on Emerging Trends in Expert Applications & Security* (pp. 289-300), Singapore: Springer Nature Singapore, 2023. https://doi.org/10.1007/978-981-99-1946-8_26

[26] C. Vohera, H. Chheda, D. Chouhan, A. Desai, & V. Jain, “Game Engine Architecture and Comparative Study of Different Game Engines”, In *2021 12th International Conference on Computing Communication and Networking Technologies (ICCCNT)* IEEE (Madrid, Spain), 22-30 May, 2021, pp. 1-6. https://doi.org/10.1109/ICCCNT51525.2021.9579618

[27] A. Jungherr, & D. B. Schlarb, “The Extended Reach of Game Engine Companies: How Companies Like Epic Games and Unity Technologies Provide Platforms for Extended Reality Applications and the Metaverse”, *Social Media+ Society*, Vol. 8, No. 2, 2022. https://doi.org/10.1177/20563051221107641

[28] S. Singh, & A. Kaur, “Game Development Using Unity Game Engine”, In *2022 3rd International Conference on Computing, Analytics and Networks (ICAN),* IEEE (Rajpura, India), 18-19 November, 2022, pp. 1-6. https://doi.org/10.1109/ICAN56228.2022.10007155

[29] E. Coronado, S. Itadera, & I. G. Ramirez-Alpizar, „Integrating Virtual, Mixed, and Augmented Reality to Human–Robot Interaction Applications Using Game Engines: A Brief Review of Accessible Software Tools and Frameworks”, *Applied Sciences*, Vol. 13, No. 3, 2023, Article 1292. https://doi.org/10.3390/app13031292

[30] S. A. Hassan, T. Rahim, & S. Y. Shin, “ChildAR: An Augmented Reality-Based Interactive Game for Assisting Children in Their Education”, *Universal Access in the Information Society*, Vol. 21, No. 2, 2022, pp. 545-556. https://doi.org/10.1007/s10209-020-00790-z

[31] J. Platt, & K. Ricks, “Comparative Analysis of Ros-Unity3d and Ros-Gazebo for Mobile Ground Robot Simulation”, *Journal of Intelligent & Robotic Systems*, Vol. 106, No. 4, 2022, Article 80. https://doi.org/10.1007/s10846-022-01766-2

[32] Z. Wang, K. Han, & P. Tiwari, “Digital Twin Simulation of Connected and Automated Vehicles with the Unity Game Engine”, In *2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI),* IEEE

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

(Beijing, China), 3-5 July, 2021, pp. 1-4. https://doi.org/10.1109/DTPI52967.2021.9540074

[33] S. Ramadaniati, D. A. Sani, & M. F. Arif, „Rancang Bangun Mobile Game Adventure of Studies Sebagai Media Pembelajaran", *INTEGER: Journal of Information Technology*, Vol. 6, No. 1, 2021. https://doi.org/10.31284/j.integer.2021.v6i1.1200

[34] Z. Zhan, X. Zhou, S. Cai, & X. Lan, "Exploring the Effect of Competing Mechanism in an Immersive Learning Game Based on Augmented Reality", *Journal of Computers in Education*, Vol. 12, No. 2, 2025, pp. 449-475. https://doi.org/10.1007/s40692-024-00317-y

[35] C. Pérez, J. Verón, F. Pérez, M. Moraga, C. Calero, & C. Cetina, „A Comparative Analysis of Energy Consumption between the Widespread Unreal and Unity Video Game Engines", *arXiv preprint arXiv:2402.06346*, 2024. https://doi.org/10.48550/arXiv.2402.06346