

# Performance and usability evaluation of a VR virtual museum application

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## Abstract

This study presents the applications of virtual reality (VR) technology in various fields, with a particular focus on education and museology. The use of the Unity engine for creating VR applications is discussed. The study focuses on the case of the Chirchiq Virtual Museum, which was developed in both a desktop and a VR version. The conducted research demonstrated that VR technology can significantly enhance user engagement and interactivity, which is crucial for the future of education and the presentation of museum content. Based on the research findings, conclusions were drawn regarding the performance and usability of the virtual museum.

**Keywords:** virtual museum; virtual reality; Unity; education; museology

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## 1. Introduction

In recent years, there has been a growing interest in the virtual reality (VR) technology market, which has opened new opportunities in both entertainment and education. VR technology has been gaining popularity thanks to its unique features that enable the creation of immersive and interactive experiences. Various approaches to the development and application of this technology exist on the market, leading to innovative solutions in both gaming and educational applications.

VR-based virtual museums provide an excellent example of the innovative use of this technology. Through interaction and full immersion in a virtual world, users can experience unique sensations that not only enhance engagement but also improve the process of retaining information. Such solutions deliver distinctive educational effects by combining modern technology with an appealing way of presenting cultural and historical content.

### 1.1. Literature review

The results of the study “*Experiencing Immersive Virtual Reality in Museums*” [1] indicate that immersive VR environments can significantly enhance the authenticity and quality of the visiting experience, as well as influence the decision to visit a museum in reality. The authors emphasize that VR is not merely a substitute for tourism, but also a tool supporting new museology and education by combining absorptive and immersive elements.

The article “*A Case Study of Museum Exhibition*” [2] introduces the concept of the “*Tour Metaphor*”, which aims to complement traditional museum exhibitions without diminishing their educational impact. The authors present the architecture of *Scalable VR*, enabling the integration of different VR systems that enrich real-world museum exhibitions with interactivity and communication features. Applying this concept allows for the creation of a more effective and engaging educational experience compared to traditional exhibitions. According to the authors, in the future, museums could personalize exhibitions, tailoring them to the goals, interests, and

motivations of visitors, by combining real and virtual exhibits.

The article “*Construction of Ideological and Political Virtual Museum Based on VR Unity3D from the Perspective of Digital Humanities*” [3] describes the use of virtual museums for ideological and political education, highlighting their role as a medium of political communication and as a tool supporting educational objectives. Such virtual museums include exhibition galleries based on digital knowledge bases and interactive material libraries, which foster emotional education, practical learning, and the integration of history with theory. Using China as a case study, the authors demonstrate how these technologies help overcome the temporal and spatial limitations of traditional museums, telling “Chinese stories” and preserving cultural heritage a point also emphasized in “*Towards a More Effective Way of Presenting Virtual Reality Museums Exhibits*” [4].

The sudden rise in interest and demand for VR technology originates from the development of headsets and environmental changes such as the COVID-19 pandemic. For example, the article “*Heritage Museum Evolution: Virtual Realizing Heritage Museums in Taiwan with An Exploratory Virtual Reality Museum Project*” [5] analyzes the pandemic’s impact on local heritage museums, revealing their vulnerability to financial difficulties and the limitations of traditional marketing strategies. The author proposes using virtual reality as an innovative and relatively low-cost tool for museum promotion and marketing. Research indicates that VR tourism allows visitors to appreciate cultural, historical, sports, and artistic achievements, fostering local pride and inspiring the sharing of experiences. According to “*Cultural Heritage in Fully Immersive Virtual Reality*” [6], the COVID-19 pandemic acted as a catalyst, increasing the demand for VR applications dedicated to cultural heritage for a wide audience. Additionally, affordable VR headsets have changed the way people, including students and researchers, can visit heritage sites through immersive virtual reality. The variety of hardware has created a significant gap between applications and user expectations. The

authors also highlight the difficulty of evaluating VR applications due to the continuous updating of content.

## 1.2. Review of available VR museums

Currently, there are numerous VR museums on the market offering a wide range of experiences and exhibits. Among them are:

- Google Arts & Culture - a platform providing access to virtual museums and art galleries from around the world, allowing users to explore exhibitions and interact with artworks. It is based on 360° technology and can be experienced using VR headsets (<https://artsandculture.google.com>).
- The Louvre Museum - offers the possibility to view the Mona Lisa up close and observe the process of its creation (<https://www.louvre.fr/en/explore/life-at-the-museum/the-mona-lisa-in-virtual-reality-in-your-own-home>).
- The Vatican Museums - provide virtual tours of famous chapels and galleries, including the Sistine Chapel. The experience is based on 360° technology and can be accessed with VR headsets (<https://www.museivaticani.va/content/museivaticani/en/collezioni/musei/tour-virtuali-elenco.html>).
- VR All Art - a platform that allows anyone to visit and create exhibitions in virtual reality ([https://vrallart.com/vrexhibitions/ea/loudly\\_quiet/](https://vrallart.com/vrexhibitions/ea/loudly_quiet/)).

## 1.3. Research aim and hypotheses

The aim of this work was to compare and evaluate the performance and usability of a VR application of a virtual museum. The study utilized a custom virtual museum on both the PC platform and the VR platform. Both virtual museums ran on the same Unity engine version 6 and used the same exhibits obtained from 3D scanning, adapted to the needs of the virtual museum. Based on the preliminary analysis of the research problem and the objectives of the study, the following research hypotheses were formulated:

- **H1:** Configuration and Optimization within Unity Have a Significant Impact on Application Performance.
- **H2:** VR applications require higher performance compared to desktop applications.
- **H3:** VR applications are more engaging for users and increase interest in museums.

## 2. Research method selection

This chapter employs two research methods: comparative method and survey research. The comparative method allowed for a comparison of the performance of the desktop application with its VR version. Survey research enabled the assessment of usability based on users' subjective experiences within the VR application

### 2.1. Planning of the experiment

To obtain data for the comparative method, similar testing conditions were established for both application versions. The desktop application and the VR application contained the same exhibits, and the user followed the

same route through the virtual museum. During the experiment, performance data were collected. CapFrameX was used to monitor performance for the PC version, while OVR Metrics Tool was employed for the VR version. Tables 1 and 2, containing weights for the PC and VR platforms, were used in the comparative analysis.

Table 1: Criteria and weights for the desktop application

No.	Criterion	Weight
1	Avg. FPS	0.5
2	RAM Usage	0.3
3	1% Low FPS	0.2

Table 2: Criteria and weights for the VR application

No.	Criterion	Weight
1	Avg. FPS	0.5
2	GPU Usage	0.2
3	RAM Usage	0.15
4	CPU Usage	0.1
5	Battery Usage	0.05

The weights were assigned based on a subjective evaluation, considering prior experience with VR technology, the hardware capabilities of the headsets, and an analysis of the scientific literature.

Survey research was used to assess the usability of the VR application compared to the PC application. During the experiment, users evaluated the application in terms of comfort, smoothness, attractiveness, and overall satisfaction with the experience. Data was collected using a questionnaire based on a Likert scale. The questionnaire results were subjected to statistical analysis to obtain the mean rating and standard deviation.

### 2.2. Test environment

The study was conducted using two PC devices and one VR device. The specifications of these devices are presented in Table 3 (components not listed were considered identical or insignificant). Additional elements of the PC setup included a keyboard, mouse, and monitor, while the VR setup included the appropriate VR headset controllers and a space allowing free movement (approximately 2 m × 2 m). VR testing was conducted using the Meta Quest 3S headset. Other headsets, such as the Meta Quest 3 and Meta Quest Pro, were also considered due to their identical or nearly identical hardware and technical specifications.

Table 3: Applied devices and testing platforms

Device	CPU	GPU	RAM
Laptop	Ryzen 5 5600H	RTX 3050 Laptop	16.0 GB
PC	Ryzen 5 2600	RX 570 8GB	32.0 GB
Meta Quest 3/3S	Snapdragon XR2 Gen 2	Adreno 740	8.0 GB
Meta Quest Pro	Snapdragon XR2+	Adreno 650	12 GB

### 2.3. Research group

The research group consisted of 12 participants aged between 18 and 65. Participants tested both applications and were able to ask questions and provide feedback during the sessions. After using the applications, they were

asked to complete a questionnaire. Additionally, information such as the time spent in the virtual museum and the degree of completion of the experience was recorded. Basic demographic data, including age and gender, were also collected, as these factors could potentially influence the study results.

#### 2.4. Virtual museum

The application used as the basis for comparative analysis is the *Chirchiqstroy Museum*, which was developed as part of an engineering thesis [7]. This museum is a virtual environment that allows users to explore the museum space and interact with the exhibits. Using only publicly available images of the Chirchiqstroy building, it was recreated as a 3D model (Figure 1). This model was created in Blender and subsequently imported into the Unity engine.



Figure 1: Chirchiqstroy in Unity.

The Chirchiqstroy Museum is surrounded by a forest and placed on a floating island, which serves as the sole element of the environment. This design also allows for potential expansion of the application by adding additional floating islands to host other museums.

Users navigate the museum using a keyboard and mouse, while interaction with exhibits is achieved by looking at an exhibit and pressing a key to enter the “examination” mode. In this mode, users can rotate and scale the exhibit to examine it more closely (Figure 2).



Figure 2: Exhibit in Chirchiqstroy (Unity).

The VR application uses a user interface (UI) in the form of a Canvas (Figure 3), which is responsible for displaying information about the exhibits. The implementation of the Canvas differs from the desktop version, as in the VR application the Canvas is placed within the 3D space rather than on the screen. This allows users to view exhibit information directly within the VR environment.

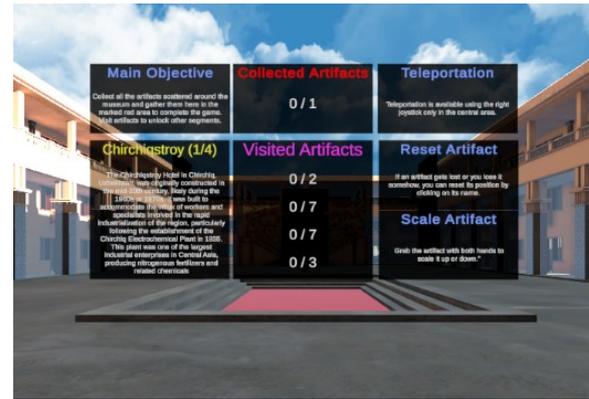


Figure 3: User interface in the VR application.

Due to the way VR headsets operate, placing the interface on the screen is not an ideal solution, as users would need to strain their eyes to look at the corners of the display, potentially causing eye fatigue and discomfort over extended periods. Navigation and interaction with exhibits also differ from the desktop application. The VR application has been adapted for controller use and the characteristic interaction with objects using virtual hands.

### 3. Results

This chapter presents the results of the comparative and survey-based studies conducted on the research group. These studies aimed to compare the desktop and VR versions of the Chirchiqstroy Museum and to examine users' preferences regarding both application versions.

#### 3.1. Comparative study - PC workstation

For the PC research setup, the application achieved a high average frame rate of 339.6 FPS. The values in the bottom 1% of the frame rate distribution reached 130.4 FPS, indicating smooth performance of the application without noticeable performance drops (Figure 4).

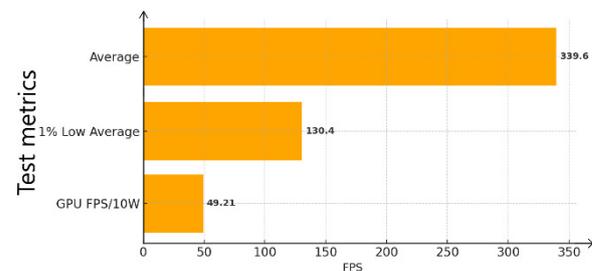


Figure 4: PC setup - bar chart.

The average RAM usage was 346.5 MB, with a clock frequency of 2933 MHz. Additionally, the chart also includes data on GPU power consumption. Although this metric is not directly considered in the comparative analysis, it was included due to current socio-industrial trends related to energy efficiency and the effort to reduce power consumption.

Figure 5 presents the results obtained during the first 300 seconds of the application's operation. A clear relationship can be observed between the direction in which the player moves and the engine's performance. When the user faces the outer areas of the Chirchiqstroy

museum, turning their back to most scene objects, the game engine does not need to render them. As a result, the frame rate locally increases, reaching values of up to 500 FPS. Conversely, when the player moves toward the central parts of the map, the GPU must process more visible objects, causing a decrease in performance. Nevertheless, thanks to the applied optimization techniques, the FPS in the most demanding areas does not drop below approximately 130 frames per second.

The chart also shows a gradual widening of the recorded value range, which is related to the extended runtime of the application. As the player moves through the museum, more 3D models are loaded and retained in VRAM, allowing subsequent references to the same objects to occur more quickly.

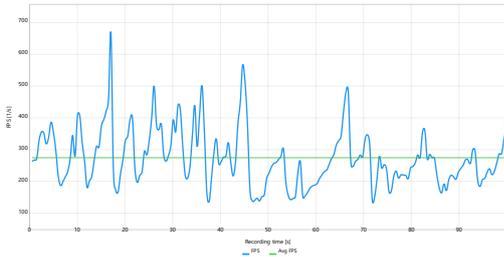


Figure 5: PC setup - line chart of performance.

It is also worth noting the pie chart (Figure 6) available in the CapFrameX tool, which further confirms the high performance of the application. The application ran smoothly for 99.9% of the time, while stuttering was recorded in only 0.1% of the total runtime. This result indicates high stability and good responsiveness of the application.

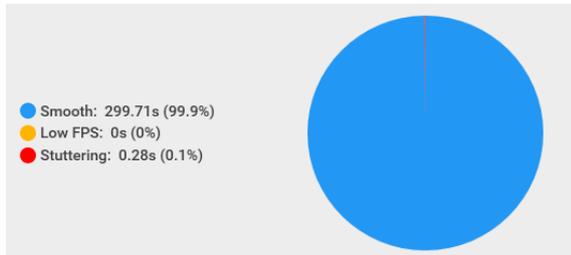


Figure 6: Pie chart of application performance.

Next, in order to calculate performance with respect to the weighting system, the data were first normalized. Normalization was carried out based on reference values, which were established using the maximum values for each indicator. These values were determined based on the analysis of the results and available performance data for the application. The reference values for data normalization are presented in Table 4, along with the calculated results based on formula (1).

$$v_{norm} = \begin{cases} \frac{v_{actual}}{v_{max}} & \text{if higher is better} \\ 1 - \frac{v_{actual}}{v_{max}} & \text{if lower is better} \end{cases} \quad (1)$$

Table 4: Reference values for data normalization

Criterion	Measurement	Reference Value	Result
Avg. FPS	339.6 FPS	144 FPS	2.3583
1% Low FPS	130.4 FPS	60 FPS	2.1733
RAM Usage	346 MB	8096 MB	1-0.0427

The reference value for each indicator was defined as the point at which the application's performance is considered baseline (100%). First, for each indicator, the normalized value was calculated by dividing the measured result by the reference value. Next, the normalized values were multiplied by the assigned weight of the indicator and summed up, in accordance with equation (2):

$$(2.3583 \times 0.5) + (2.1733 \times 0.2) + (0.9582 \times 0.3) = 1.9009 \quad (2)$$

This result was converted into a percentage value by multiplying it by 100. Ultimately, for the desktop version of the Chirchqstroy Museum, a result of 190.09% relative to the reference value was obtained. This value indicates high application performance.

### 3.2. Comparative study - laptop workstation

For the test setup using a laptop, the application also achieved a high average frame rate of 265 FPS. The values in the lower 1% of the frame rate distribution reached 120.2 FPS, which confirms the smooth operation of the application without noticeable performance drops (Figure 7).

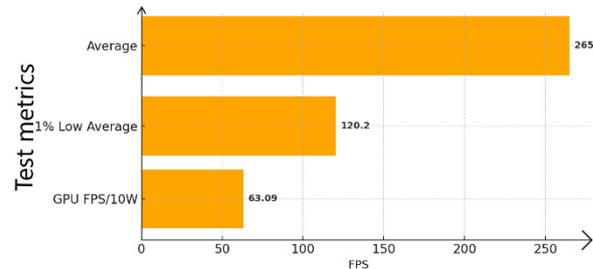


Figure 7: Bar chart for the laptop workstation.

The average RAM usage was 286.6 MB at a clock frequency of 3200 MHz. This value was lower than in the case of the PC workstation, most likely due to the use of faster memory modules that enable more efficient management of the application's resources. Despite the use of newer hardware, the obtained values were lower than those for the desktop PC. This may result from cooling system limitations as well as the maximum power consumption limits of the graphics processor. This is indicated by the higher frame rate per 10 W of GPU power consumption, which suggests greater energy efficiency at the cost of maximum performance.

In the chart (Figure 8), one can observe the same trends as in the case of the PC workstation. The only noticeable difference is a smaller gap between the minimum and maximum values. This is most likely due to stricter power consumption limits imposed on the graphics

processor (GPU), which in turn resulted in higher energy efficiency expressed as the number of frames per second per 10 W of power consumption.

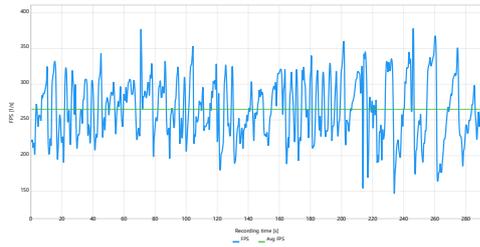


Figure 8: Line chart for the laptop workstation.

In the case of the pie chart (Figure 9), a slightly higher percentage of “stutters” can be observed, reaching 0.5%. It is difficult to clearly determine the cause of this phenomenon; however, it is most likely related to the hardware’s power limitations.

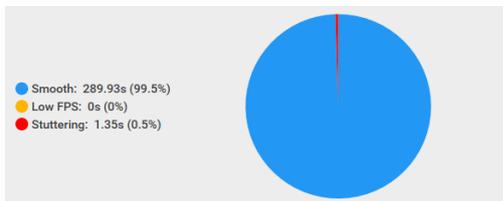


Figure 9: Pie chart of application performance.

Next, based on the reference values determined from the maximum values for each indicator, the data were normalized. The reference values for data normalization are presented in Table 5, along with the calculation result based on the formula from the previous subsection.

Table 5: Reference values for data normalization

Criterion	Measurement	Reference Value	Result
Avg. FPS	265 FPS	144 FPS	1.8403
1% Low FPS	120.2 FPS	60 FPS	2.0033
RAM Usage	286.6 MB	8096 MB	1 - 0.0349

Ultimately, the result for the desktop version of the Chirchiqstroy Museum on the laptop platform is 161.03% relative to the reference value.

### 3.3. Comparative study - VR workstation

The results obtained during the performance tests of the VR Chirchiqstroy Museum application are shown in the chart (Figure 10). The average frame rate was 58 FPS, which is below expectations.

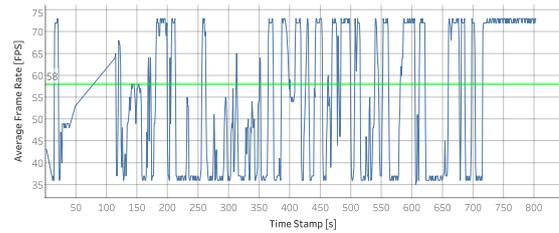


Figure 10: Performance chart for the VR version of the Chirchiqstroy museum.

Next, GPU usage averaged 80%, indicating a high load on the graphics processor during the application’s operation. This value is close to the maximum load, suggesting that the application is approaching its performance limits (Figure 11).

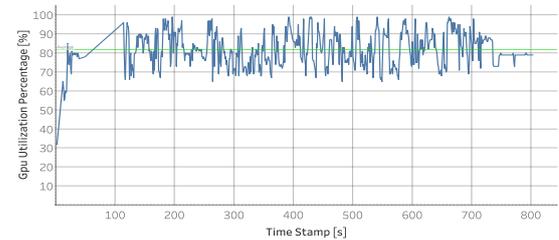


Figure 11: GPU usage chart for the VR version of the Chirchiqstroy Museum.

Regarding RAM usage, the OVR Metrics Tool software only allows measuring the remaining available memory, which averaged 2 GB. This value is satisfactory and does not negatively affect the application’s performance. In the case of the Chirchiqstroy Museum, the available RAM is sufficient for smooth operation of the application (Figure 12).

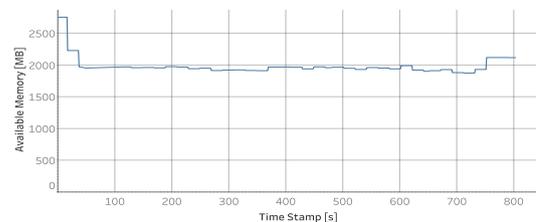


Figure 12: Available RAM chart for the VR version of the Chirchiqstroy museum.

CPU usage in the VR application averaged 38%, which is very good value. This indicates the characteristics of a VR application, which is more demanding on the graphics processor than on the CPU. Due to the use of a small number of scripts responsible for game logic, the VR application does not significantly load the CPU (Figure 13).

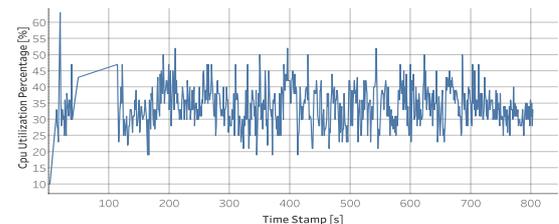


Figure 13: CPU usage chart for the VR version of the Chirchiqstroy museum.

The final parameter is battery consumption, which averaged 1% per 100 seconds of gameplay. This value is very good because VR headsets are mobile devices that must be powered by a battery. Thanks to the use of appropriate optimization techniques, the VR Chirchqstroy Museum application can operate on VR headsets for a long time without the need for recharging. The obtained result corresponds to a nominal time of 166 minutes, or 2.77 hours of operation, which is an excellent outcome. This value is sufficient for comfortable use of the VR Chirchqstroy Museum application.

After presenting the results of the comparative tests, the data were normalized to obtain percentage values. The reference values for data normalization are presented in Table 6, along with the calculation result based on formula (1).

Table 6: Reference values for data normalization

Criterion	Measurement	Reference Value	Result
Avg. FPS	58 FPS	72 FPS	0.8056
Avg. GPU Usage	80%	100%	1 - 0.8000
Available RAM	2GB	4GB	1 - 0.5000
Avg. CPU Usage	38%	100%	1 - 0.3800
Battery Usage	1%/100s	5%/100s	1 - 0.2000

Ultimately, the result for the VR version of the Chirchqstroy Museum is 61.98% relative to the reference value. This indicates high performance of the VR application, even though the frame rate is lower than the expected value. The application does not use enough interactive elements for the lower frame rate to negatively affect the user experience

### 3.4. Survey study - questionnaire

The study was conducted in a group of 12 people who had the opportunity to test both versions of the application. The participants were mainly individuals without prior experience using VR applications. The questionnaire for the desktop application consisted of 11 neutral questions, meaning questions that applied to both the desktop and VR versions. The questionnaire for the VR application included the same 11 questions plus 5 additional questions specifically related to VR aspects.

A 5-point Likert scale was used for the questions, where -2 indicated a very negative opinion, 0 a neutral opinion, and 2 a very positive opinion. For each question, the arithmetic mean, and standard deviation (SD) were calculated.

### 3.5. Survey study - desktop application

The next stage of the study involved surveys conducted among users. Table 7 presents the neutral questions and their results. These questions were asked to users after testing the desktop version of the Chirchqstroy Museum application.

Table 7: Results of the desktop version questionnaire

Question	Result	SD
How would you rate the visual aspects of the application (graphics, aesthetics, details)?	1.17	0.72
Was the application easy for you to use?	1.17	0.72
Was the user interface clear and understandable?	1.17	0.83
Did you notice any performance drops while using the application?	1.08	1.51
Did this experience encourage you to visit a real museum?	1.00	0.95
How would you rate your overall experience of the visit?	0.92	0.67
Did this experience encourage you to visit another virtual museum in the future?	0.83	1.03
Would you recommend the virtual museum to your friends?	0.67	1.07
How would you rate your level of engagement while using the application?	0.42	0.90
How would you rate the level of immersion in the application?	0.33	0.98
Did you learn anything new from this experience?	0.25	1.14

Based on the obtained data, it can be observed that users mostly rated the desktop version of the Chirchqstroy Museum application positively. The highest-rated aspects were the application's visual elements, ease of use, and clarity of the user interface. Users were also satisfied with the smoothness of the application's performance. The lowest-rated aspects were related to the level of immersion and the degree of engagement. The standard deviation for all questions is relatively low, suggesting that users were consistent in their opinions about the application. However, differences appeared in responses to the question regarding performance drops. This indicates that some users experienced performance drops or were more sensitive to them, while others did not notice any issues with application smoothness. Users were most consistent in their overall impressions of the visit, which suggests that the desktop version of the Chirchqstroy Museum application is well received and generates similar feelings among all participants.

### 3.6. Survey study - VR application

The next stage of the study involved surveys for the VR application. Table 8 presents the neutral questions and their results. These questions were asked to users again after testing the VR application. It can be observed that the results differ slightly from those obtained for the desktop version. Some aspects of the applications were exactly the same, and users often rated them similarly.

Table 8: Results of the VR version questionnaire

Question	Result	SD
How would you rate the visual aspects of the application (graphics, aesthetics, details)?	1.50	0.52
Was the application easy for you to use?	1.17	0.72

Was the user interface clear and understandable?	1.17	0.72
Did you notice any performance drops while using the application?	1.17	0.83
Did this experience encourage you to visit a real museum?	1.08	0.79
How would you rate your overall experience of the visit?	1.00	0.85
Did this experience encourage you to visit another virtual museum in the future?	0.92	1.00
Would you recommend the virtual museum to your friends?	0.92	1.00
How would you rate your level of engagement while using the application?	0.92	0.79
How would you rate the level of immersion in the application?	0.58	0.90
Did you learn anything new from this experience?	0.25	1.14

Based on the obtained data, it can be observed that users of the VR version rated the application higher than the desktop version in almost every aspect. The highest-rated aspects were related to the clarity and comprehensibility of the user interface. Users were also satisfied with the visual aspects of the application, ease of use, and the level of immersion. The lowest-rated aspects were related to the degree of engagement and learning something new. The level of user engagement was also low, as users often noted the “game-like” nature of the application. The application uses gamification techniques, but it is not a full-fledged game, there are no narrative elements that could increase engagement. The standard deviation (SD) for all questions is relatively low, suggesting that users were consistent in their opinions about the application. The lowest-rated aspect was learning something new, which also had the highest standard deviation along with the lowest mean score. This indicates that some users rated the educational aspect negatively.

In addition to the neutral questions, the VR version questionnaire included 5 additional questions regarding VR-specific aspects (Table 9). These questions aimed to examine users’ opinions on the use of VR technology in education, preferences regarding VR museums, and any potential discomfort experienced while using the application.

Table 9: VR-related results for the VR version questionnaire

Question	Result	SD
Was using the VR application intuitive?	1.58	0.51
Would you like VR to play a greater role in the field of education?	1.00	1.13
Did the VR application seem more engaging to you than other forms of virtual visits (e.g., websites, videos)?	0.42	0.51
Would you prefer to visit a real museum instead of a VR museum?	0.08	1.31
Did you experience any symptoms of discomfort (e.g., nausea, dizziness) while using the application?	-0.25	1.36

The mean results for the questions related to VR aspects indicate that users had varying opinions about the use of

VR technology. The highest-rated question concerned the intuitiveness of using the VR application. This leads to an interesting conclusion: all kinds of interaction systems with objects in the desktop version perform worse than those on the VR platform. In VR, users intuitively approach an object, grasp it with virtual hands, and can examine it from every angle without needing an explanation of how the interaction system works. The standard deviation for this question was also low, suggesting that users were consistent in their opinions about the intuitiveness of using the VR application.

The next question concerned the role of VR technology in education, which received a mean score of 1.00. Users were divided on this issue, suggesting that VR technology has potential in education, but not everyone is convinced about its use.

The question regarding the level of engagement received a moderate rating, which aligns with earlier conclusions about users’ engagement with the application. On average, users were neutral regarding their desire to visit a real museum instead of a VR museum. This question had a high standard deviation, indicating that some users would prefer a real museum, while others were satisfied with the VR museum experience. Similarly, the question regarding symptoms of discomfort received a negative mean score of -0.25, indicating that many users experienced some discomfort. This can be attributed to users’ lack of experience with VR applications, motion sickness, or insufficient VR application performance, which could exacerbate discomfort symptoms. The standard deviation for this question was the highest; users prone to motion sickness rated it negatively, while other users did not experience any discomfort.

## 4. Conclusions

This chapter presents a summary of the conducted research. The obtained results are compared with the initially formulated research hypotheses.

### 4.1. Research hypotheses

The first hypothesis concerns the impact of Unity configuration and optimization on application performance. The results of both comparative and survey studies showed that the Unity engine, when properly configured, can deliver high performance for the desktop application and acceptable performance for the VR application. Comparative results indicated performance levels of 190.09% for the desktop version and 61.98% for the VR version, corresponding to an average frame rate of approximately 58 FPS in VR. Although this frame rate falls slightly below the optimal comfort threshold for VR, the application remained usable, with occasional signs of discomfort likely linked to frame-time instability and the activation of reprojection or asynchronous space warp (ASW). This observation aligns with survey responses, in which users generally rated the visual and performance aspects positively despite minor issues with smoothness.

The second hypothesis concerns the higher hardware demands of the VR application compared to the desktop application. The study results confirmed that the VR

version requires significantly greater computational resources particularly GPU and CPU power to maintain acceptable performance. However, direct cost to performance comparisons between VR and desktop systems are inherently limited, as the two platforms differ in rendering complexity and performance perception. While the desktop and VR test setups were priced at approximately 4000 PLN and 1500 PLN respectively, the VR application achieved an average frame rate up to five times lower. This discrepancy should not be interpreted linearly, since VR performance also depends on factors such as frame-time stability, reprojection percentage, and overall user comfort. Therefore, a more reliable evaluation would combine both technical metrics (e.g., FPS at target refresh rate, reprojection ratio) and subjective usability indicators (e.g., SUS or UEQ scores) to express a compound cost performance ratio. Therefore, this hypothesis remains unresolved.

The third hypothesis assumes that the VR application is more engaging and can increase engagement with museums. Survey results showed that users were slightly more engaged with the VR application than with the desktop version. Additionally, the level of immersion, which users rated significantly higher in the VR version, should be considered. Users were also more likely to recommend the VR museum to friends than the desktop version. Therefore, the third hypothesis was confirmed.

#### 4.2. Limitations and sources of error

The article identifies potential sources of errors as well as the limitations of the study. Sources of errors may have arisen from the selection of reference values used in the comparative analysis, as well as from the determination of parameters and their weights. However, these parameters were chosen not only based on subjective impressions but also on a literature review, which significantly reduces the risk of errors.

Standardized usability and presence questionnaires (e.g., SUS, IPQ, SSQ) were not employed in this study due to its primary focus on technical performance metrics rather than subjective user experience. Nevertheless, subjective comfort and engagement were partially assessed through custom survey questions inspired by the dimensions covered by these tools.

The limitations of the study, on the other hand, may have resulted from the small number of participants (12), the limited time allocated for the development of the VR application, and the skills of the programmer responsible for creating both applications. Finally, limitations can also be seen in the number of questions dedicated to the topic of VR.

#### 4.3. Key findings and original conclusions

Among the key findings, a theoretical, estimated value can be highlighted, representing the amount one would need to pay for a headset if it were to achieve performance results comparable to PC and laptop platforms.

A surprising finding was the VR application's advantage over the desktop application in specific aspects. The majority of users rated the intuitiveness of the VR

application more positively and were more likely to recommend it. Additionally, visual aspects such as graphics and the user interface performed better. It was also found that immersion alone is not a sufficient factor to increase user engagement with the application.

#### 4.4. Further research directions

Based on this article, the need for larger-scale studies on the potential use of VR in learning processes and interactions with cultural heritage elements can be considered. The article also observed interesting results regarding discomfort symptoms, which hindered the use of the application for a significant portion of users, particularly those with little prior experience. This raises the question of how motion-related issues associated with VR technology can be minimized or resolved.

#### References

- [1] H. Lee, T. H. Jung, M. C. Tom Dieck, N. Chung, Experiencing immersive virtual reality in museums, *Information & Management* 57(5) (2020) 103229, <https://doi.org/10.1016/j.im.2019.103229>.
- [2] T. Tanikawa, M. Ando, Y. Wang, K. Yoshida, J. Yamashita, H. Kuzuoka, A case study of museum exhibition - historical learning in Copan ruins of Mayan civilization, In *IEEE Virtual Reality* (2004) 257-258, <https://doi.org/10.1109/VR.2004.1310097>.
- [3] Y. Liu, S. Li, Construction of Ideological and Political Virtual Museum Based on VR Unity3D from the Perspective of Digital Humanities, In *International Conference on Computer, Big Data and Artificial Intelligence (ICCBDE)* (2022) 83-86, <https://doi.org/10.1109/ICCBDE56101.2022.9888161>.
- [4] C. Terlikkas, C. Poullis, Towards a More Effective Way of Presenting Virtual Reality Museums Exhibits, *Proceedings of the 9th International Conference on Computer Vision Theory and Applications - Volume 3: VISAPP* (2014) 237-241, <https://doi.org/10.5220/0004844702370241>.
- [5] H. Shih, Heritage Museum Evolution: Virtual Realizing Heritage Museums in Taiwan with An Exploratory Virtual Reality Museum Project, In *Pacific Neighborhood Consortium Annual Conference and Joint Meetings (PNC)* (2023) 38-43, <https://doi.org/10.23919/PNC58718.2023.10314973>.
- [6] H. Cecotti, Cultural Heritage in Fully Immersive Virtual Reality, *Virtual Worlds* 1(1) (2022) 82-102, <https://doi.org/10.3390/virtualworlds1010006>.
- [7] K. Gabrysiewicz, A. Kruczyński, K. Dziedzic, Project and creation of a virtual exhibition of 3D models of archaeological artifacts with elements of gamification, Bachelor thesis, Lublin University of Technology, Lublin, 2024.