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APPLICATION OF VR-TECHNOLOGIES FOR NEUROREHABILITATION OF PATIENTS WITH MOTOR AND COGNITIVE FUNCTION DISORDERS

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Abstract. The article explores the use of developed interactive 3D application with VR technology support, designed for the rehabilitation of patients after neurological disorders that cause motor and cognitive impairments. The neurorehabilitation hardware and software system is implemented on the Unity platform and includes an interactive 3D application and a Quest 3 VR headset. The VR headset consists of a virtual reality helmet and two controllers for the right and left hands, respectively, and supports highly accurate controller tracking using built-in cameras equipped with LiDAR technology. The causes of unilateral spatial neglect syndrome, or hemispatial neglect, and the possibility of its rehabilitation are considered. The hardware and software system developed by the authors enhances patient motivation through gamification and adaptive scenarios, allowing them to select and visualize various 3D scenes. When immersed in a realistic virtual environment, the patient acts instinctively. This helps develop hand motor skills, a sense of balance and spatial navigation abilities. Furthermore, the hardware and software system allows for the convenient storage of statistical data on the progress of prescribed procedures and can be used for further analysis during rehabilitation process.

Keywords: cognitive functions, motor functions, hemispatial neglect , rehabilitation, virtual reality, interactive 3D graphics, game engine

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ПРИМЕНЕНИЕ VR-ТЕХНОЛОГИЙ ДЛЯ НЕЙРОРЕАБИЛИТАЦИИ ПАЦИЕНТОВ С НАРУШЕНИЕМ ДВИГАТЕЛЬНЫХ И КОГНИТИВНЫХ ФУНКЦИЙ

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Аннотация. В статье рассматривается применение разработанного интерактивного 3D-приложения с поддержкой VR-технологий, направленного на реабилитацию пациентов после неврологических заболеваний, вызывающих нарушения двигательных и когнитивных функций. Программно-аппаратная система нейрореабилитации реализована на платформе Unity и включает в себя интерактивное 3D-приложение и VR-гарнитуру – Quest 3. VR-гарнитура состоит из шлема виртуальной реальности и двух контроллеров для правой и левой руки соответственно, поддерживается достаточно точный трекинг контроллеров с помощью встроенных камер, оснащенных технологией LiDAR. Рассмотрены причины развития одностороннего пространственного игнорирования, или синдрома неглекта, и возможность его реабилитации. Разработанный авторами программно-аппаратный комплекс повышает мотивацию пациентов за счет геймификации и адаптивных сценариев, позволяя выбирать и визуализировать различные 3D-сцены. При погружении в виртуальную среду, приближенную к реальности, пациент действует инстинктивно. Таким образом развивается моторика рук, чувство равновесия, навыки перемещения в пространстве. Кроме того, программно-аппаратный комплекс позволяет сохранять в удобном цифровом виде статистические данные о ходе выполнения назначенных процедур и может использоваться для дальнейшего анализа при прохождении реабилитации.

Ключевые слова: когнитивные функции, двигательные функции, синдром неглекта, реабилитация, виртуальная реальность, интерактивная 3D-графика, игровой движок

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Introduction

Today, in rehabilitation medicine for neurologists, instructors in adaptive physical education, addressing motor and cognitive impairments in patients who have suffered a stroke is of particular importance. In recent years, rehabilitation of patients after a stroke, has evolved significantly, reaching a fundamentally new level. Traditional methods (manual therapy, exercise equipment, physiotherapy, medications) have been supplemented by advanced developments based on digital technologies [1].

The article examines in detail the approach to the design and implementation of a hardware and software neurorehabilitation system based on the Unity game engine, including an interactive 3D application and a Quest 3 VR headset. The VR headset consists of a VR helmet and two controllers, for the right and left hands, respectively, with fairly accurate controller tracking enabled by built-in cameras equipped with LiDAR technology.

In particular, the article provides a detailed description and analysis of the causes of the unilateral spatial neglect syndrome, or hemispatial neglect, and proposes a method for its diagnosis and rehabilitation using VR technologies. The hardware and software complex developed by the authors increases patient motivation through gamification and adaptive scenarios, enabling users to select and visualize various 3D scenes. When immersed in a realistic virtual environment, patients act instinctively. This promotes the development of hand motor skills, a sense of balance and spatial navigation abilities. In addition, the hardware and software complex allows for highly accurate collection of statistical data on the progress of prescribed procedures, storing them in a convenient digital form and using them for further analysis during rehabilitation.

Hemispatial neglect

Strokes lead to various disorders of motor and cognitive functions in the human body, as well as changes in emotional regulation. One consequence of brain damage is the development of hemispatial neglect [2, 3]. The term "neglect" derives from Latin *neglēctus*, perfect passive participle of *neglegō*, which means "disregard". It is a neuropsychological condition in which a deficit in attention and awareness towards the side of space opposite brain damageis observed. Fig. 1 shows manifestations of hemispatial neglect when the right or left hemisphere of the brain is damaged.

According to statistics, the overall prevalence of hemispatial neglect is up to 82% in post-stroke patients, while an average of 50% of patients still have manifestations of neglect. Visual neglect manifests as the patient's inability to detect objects located in the contralateral space. The patient acts as if unable to perceive anything on the left or right side, although in fact, vision is intact. Auditory neglect manifests as the patient's inability to perceive sounds in one ear, even when the information is important. Tactile neglect manifests as the patient's inability to respond to touch and other stimuli on one side of the body.

It should be noted that the wide variation in reported statistics is explained by the differences in approaches to understanding neglect and its underlying brain mechanisms, as well as the complex structure of the syndrome itself and the lack of specialized psychodiagnostic tools.

As a polymodal syndrome with a complex structure, hemispatial neglect presents itself with highly diverse manifestations. A patient may exhibit one, several or all signs of neglect. Among the clinical features of neglect, the following can be distinguished:

- hemineglect (failure to respond appropriately to surrounding stimuli such as approaching people or various sounds);

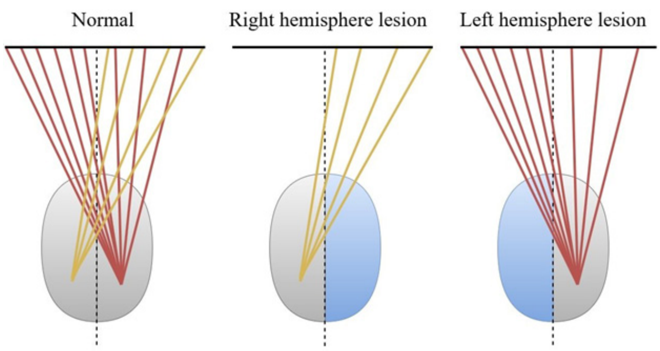

Fig. 1. Manifestations of hemispatial for the right or left hemisphere of the brain

- tactile neglect (failure to respond appropriately to tactile stimuli when both sides of the body are touched simultaneously);
- visual neglect (failure to respond appropriately to visual stimuli when both visual fields are stimulated simultaneously);
- alloesthesia (a condition in which a patient responds to stimuli presented to one side of their body as if they were presented at the opposite side);
- anosognosia (a condition in which a patient with a disability is cognitively unaware of having it);
- asomatognosia (failure to recognize or be aware of one's part of the body).

European Handbook of Neurological Management provides an overview of the methods and techniques for hemispatial neglect rehabilitation. There is evidence for the effectiveness of multiple approaches in reducing hemispatial neglect manifestations:

- combined training of visual scanning, reading, copying and figure description;
- spatiomotor or visuo-spatiomotor cueing;
- visual cueing with kinetic stimuli;
- video and visuomotor feedback;
- training of sustained attention, increasing of alertness or cueing of spatial attention;
- influencing multisensory representations;
- prism goggles;
- forced use of the left visual hemifield or left eye;
- computer training [4–6].

In addition, the use of biofeedback, such as eye-tracking [7] or motion capture [8], enables real-time adaptation of the rehabilitation program based on the patient's individual performance.

Recently, computer-based cognitive training has gained considerable popularity. To date, a substantial body of evidence has been accumulated, leading specialists to conclude that computer-based cognitive training is effective for patients with focal brain lesions[1].

Upon closer examination, it is evident that computer games actively engage higher mental functions such as attention, executive control, task maintenance, differentiation and memory. Therefore, the gamification of rehabilitation procedures, that allows for simulating everyday or extreme situations, can enhance patient motivation [9].

Two internationally standardized techniques widely accepted for correcting hemispatial neglect are combined training of visual scanning, reading, copying and figure description and spatiomotor or visuo-spatiomotor cueing. These methods aim to improving spatial perception, orientation and ultimately the functional independence of patients with hemispatial neglect[2].

The literature to date describes various methods of restorative neuropsychological intervention for patients with hemispatial neglect. In addition to developing specialized computer-based cognitive trainings for patients with cognitive impairments, existing computer games can also be used. Most of these techniques focus on rehabilitating sensory and motor functions [10].

For patients with hemispatial neglect, the rehabilitation involves modifying the physical environment and engaging the patient in virtual environments through alternating hand use. The key requirement is the active involvement of the affected side of the body in purposeful activities.

Rehabilitation 3D-system with VR-technology support

Considering that the purpose of the application is the rehabilitation of patients with complete or partial impairment of cognitive and motor functions, the rehabilitation process must be carried out under

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[1] Home – Хабилект, Available: https://habilect.com/en/home_en/ (Accessed 15.01.2026); NIRVANA | Sensory and interactive room | BTS Bioengineering, Available: https://www.btsbioengineering.com/products/nirvana/ (Accessed 15.01.2026); VRRS Evo – Khymeia, Available: https://khymeia.com/en/products/vrrs-evo/ (Accessed 15.01.2026); Rehabilitation, Available: https://www.who.int/news-room/fact-sheets/detail/rehabilitation (Accessed 15.01.2026)

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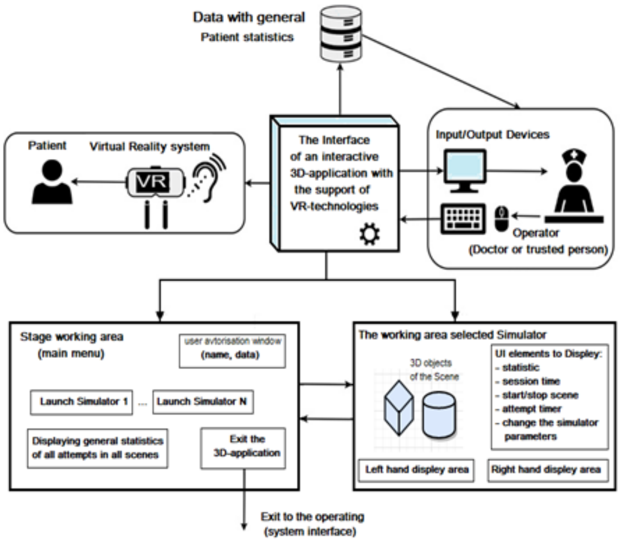

Fig. 2. General diagram of the diagnostic and rehabilitation system

the supervision of an operator. The operator monitors the progress of the procedure and adjust the parameters in accordance with the patient’s limitations.

The operator can be the attending physician or another trained person who can oversee the session and adhere to all necessary rehabilitation guidelines. The operator is responsible for user authorization, selecting the type of simulator, adjusting 3D scene parameters, saving statistics and exporting the results to a separate file for further analysis if necessary.

The operator controls the procedure from a desktop computer or laptop, using a mouse and keyboard(or a touchpad in case of a laptop).

The procedure is displayed on the operator’s monitor in full synchronization with the virtual environment seen by the patient. It also provides an interface for interacting with the application.

The VR helmet displays only the 3D image of the environment, with which the patient interacts using hand-held controllers (in one or both hands). The helmet also includes built-in speakers for audio playback.

A general diagram of the diagnostic and rehabilitation system is shown in Fig. 2.

The main functions required in the application are:

- authorization of the patient by indicating their full name;
- simulator selection, including one of the 3D scenes from the list, with the scenario appropriate for rehabilitation;
- ability to start/stop the simulator session, restricted to the operator;
- tracking of time spent in the VR system, as well as calculation of statistics for each session;
- ability to export statistics from the 3D scene for deeper analysis;
- ability to restart the simulator, resetting the timer and attempt statistics;
- ability for the operator to adjust exercise parameters for specific simulators.

The Quest 3 modern VR system was chosen as the hardware component of the project. The system includes a VR headset and two controllers (for the right and left hand, respectively) (Fig. 3).

The patient benefits from high device quality, comfortable ergonomics, a stable connection to a desktop computer or laptop, high image clarity with adjustable focal length, and fairly accurate controller tracking using built-in cameras equipped with LiDAR technology (for digitizing the surrounding space).

The main characteristics of the VR headset are presented in Table 1.

Fig. 3. Quest 3 VR System

Table 1

Main characteristics of the VR system

Characteristic	Value
Per-eye resolution	2064×2208 pixels
Memory	8 GB
Storage	128 GB
Display refresh rate	90–120 Hz
Field of view	104°H/96°V
Connectivity	Bluetooth 5.2, Wi-Fi 6E

The minimum system requirements are presented in Table 2.

Table 2

Minimum system requirements

OS	Windows 10, Windows 11
CPU	AMD Ryzen 5 1500, Intel Core i5-4590
Video card	AMD R9 290, NVIDIA GTX 970
RAM	8 GB

To facilitate further testing, the headset is additionally equipped with a special accessory that ensures secure fixation on the patient's head when put on.

Since hand movements of patients undergoing post-illness rehabilitation are not always predictable, the use of special controller straps is essential.

Scenarios

Developing scenarios for patient interaction with the virtual environment is one of the most important stages of designing an interactive 3D application with VR technology support aimed at rehabilitation and restoration of lost cognitive and motor skills. At this stage, it is necessary to define the logic of how the patient will interact with the events in each specific scene, what actions they will perform, and how the system should respond.

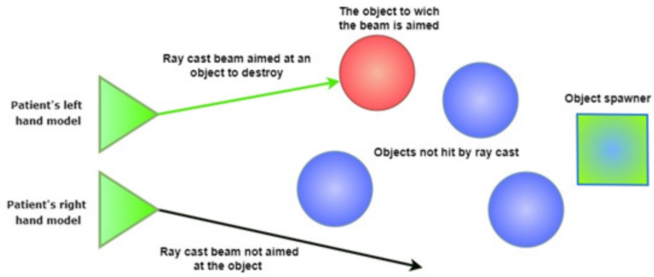

Fig. 4. Simplified diagram of patient's interaction with the virtual environment

Consider a rehabilitation scenario using a specific example of one of the simulators implemented in the diagnostic and rehabilitation system.

After the operator (the attending physician) selects a simulator's 3D scene from the main menu, the image in the VR helmet changes and the patient enters the simulated virtual space. The patient surveys the environment, verifies the representation of their right- and left-hand models in space, and then confirms readiness to begin interaction with the simulator. Once readiness is confirmed, the operator starts the simulator mechanics using the available interface.

A timer built into the scene starts counting down, and within a defined area of the environment, objects begin to appear at a given interval, moving toward the patient.

In turn, the patient, using beams emitted from their hand models, must aim at the approaching objects. Accurate targeting changes the object's texture. By pressing a certain trigger on the controller, the patient can destroy the approaching object. Each successful destruction adds one point to the statistics counter. Upon reaching a certain result or a time limit, the patient ends the session, and the operator stops the simulator.

The operator logs the session statistics and, if necessary, resets the indicators.

A simplified diagram of the patient's interaction with the surrounding virtual environment is shown in Fig. 4.

Implemented system on Unity platform

The diagnostic and rehabilitation system is implemented as an interactive 3D application with VR technology support on the Unity platform[3].

The following software tools were used:

- Unity 6.0 (6000.0.37f1) – a modern game engine designed for developing interactive applications, games and visualizations, used as the main tool for developing mechanics, scene environments and interfaces.
- SteamVR Plugin 2.8.0 (SDK 2.0.10) – a key tool for VR development in Unity, used as an integrated tool in the project.
- Visual Studio 2022 – a modern integrated development environment for creating software solutions in a variety of languages, including C# for scripting.
- Excel 2021 – a spreadsheet application designed for collecting, analyzing and processing data in various formats, used to collect and analyze the resulting statistical data.

The final appearance of the operator interface for the simulator, implemented in the Unity project, the scenario for which is given above, is shown in Fig. 5.

[3] Платформа Unity для разработки в реальном времени | Движок для 3D, 2D, VR и AR, Available: https://unity.com/ru (Accessed 15.01.2026); GitHub – gkngkc/UnityStandaloneFileBrowser: A native file browser for unity standalone platforms, Available: https://github.com/gkngkc/UnityStandaloneFileBrowser (Accessed 15.01.2026)

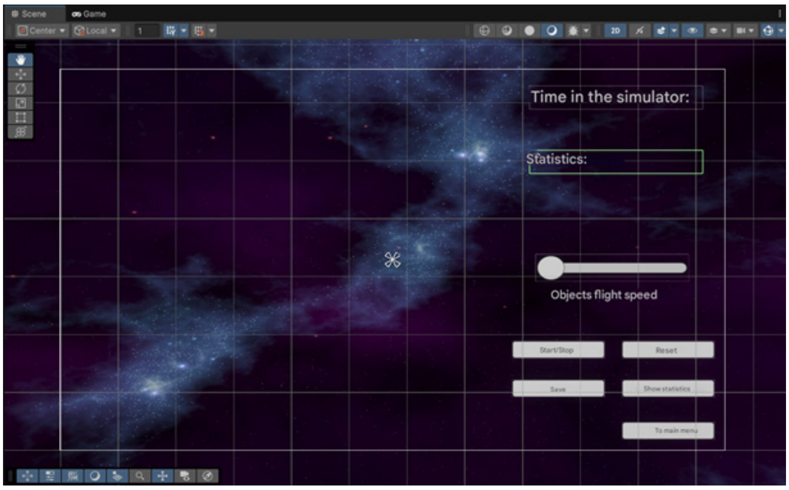

Fig. 5. Operator interface for the simulator

The following interface elements have been added and configured:
- Time spent in the session.
- Statistics of destroyed objects.
- Slider for changing the speed of the objects' movement.
- "Start/Stop" button to start or pause the movement of objects, timer or statistics.
- "Reset" button to reset the timer and statistics.
- "Save" button to save the results.
- "Show Statistics" button to show general statistics.
- "To Main Menu" button to get the main menu.

For general statistics, the following interface elements have been added and configured:
- Statistics of each simulator scene.
- "Clear Statistics" button to clear the general statistics.
- "Download to Excel" button to export statistics to a CSV file.
- "To Main Menu" button to get the main menu.

After the interactive 3D application was created, tests were run to verify its functionality. Testing was conducted in accordance with the intended application logic and defined objectives:
- Capturing the view from the VR headset camera and transmitting the image to the operator's display.
- Correct patient interaction with the environment using controllers.
- Performance of the operator interface.
- Interaction between scenes.
- Exporting statistics data to a CSV file.

After the simulator scene loads, the operator's screen displays the image from the patient's headset camera, along with control elements.

Pressing the "Start/Stop" button launches the simulator. Objects appear, which the patient must destroy with a specially directed green beam. A countdown timer starts, and statistics on the number of objects destroyed are recorded.

The result of the functionality described above is shown in Fig. 6.

Clicking the "Save" button saves the obtained data. Adjusting the 3D scene parameters increases the object speed using the corresponding slider.

If a new session is launched and its result is saved, the "Show Statistics" button can be slicked to show the general statistics.

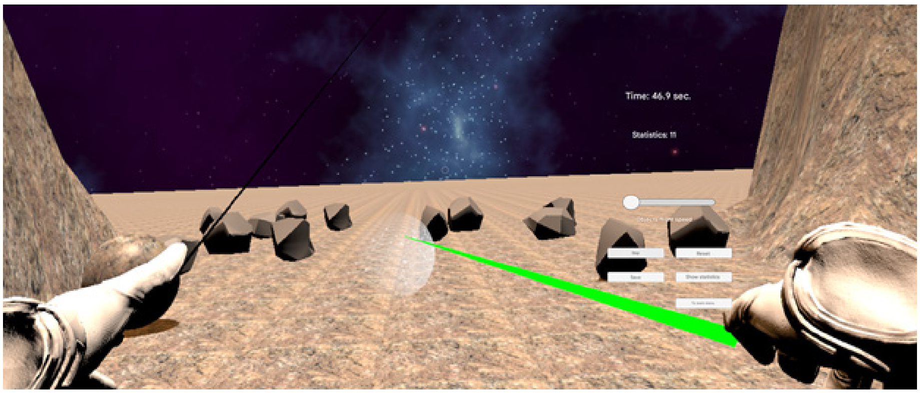

Fig. 6. Mirroring patient's display (Quest 3) to the operator's monitor

To export data from the general statistics to a separate CSV file the "Export to Excel" button should be clicked.

All functions implemented in the application were verified during testing.

The final build of the application takes up 271 MB of disk space.

Frame rate of up to 144 FPS at a resolution of 2064x2208.

Response time to patient actions is 0.1 ms.

Application optimization ensures moderate load on the hardware of a PC or laptop.

Conclusion

In conclusion, the following points should be noted:

1. Experimental testing of an interactive 3D application with VR support for the rehabilitation of patients with motor impairments demonstrates that VR technologies not only enhance patient immersion in the rehabilitation process, but also enable an individualized approach to correcting motor and cognitive functions based on medical indicators.

2. Impaired visual perception affects body function and structure, which in turn limits activity and participation in daily life. Visual impairment has significant physical, social, emotional, behavioral and economic consequences. It can have a pronounced impact on patients' disability one year after a stroke, making the timely use of VR technologies in neurorehabilitation a relevant direction of work.

3. The core objective of neurorehabilitation is the restoration of cognitive and sensorimotor functions essential for daily living and their impairment significantly affects overall quality of life. Therefore, advanced technologies such as VR and augmented reality open up new possibilities for creating immersive environments where patients can perform exercises as simple and understandable tasks in a safe and controlled environment, fostering a sense of "presence" in the virtual space.

4. Equally important is to record patient's progress and, based on the data obtained, to understand whether the chosen rehabilitation scenario is appropriate or whether adjustments to the sequence of procedures are required.

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