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VIRTUAL REALITY EFFICIENCY IN MOTOR AND COGNITIVE REHABILITATION IN PATIENTS AFTER CEREBRAL STROKE: A REVIEW

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Abstract

Introduction. Currently, stroke is considered to be one of the main causes of death and disability, highly contributing to mortality in the world. The critical issue is the rehabilitation process and the subsequent return of the patient to his daily life. Therefore, finding new approaches to recovery of lost functions is a pressing issue. Thanks to three key elements necessary for motor functions training (stimulation repetition, sensory feedback, patient motivation) VR provides an opportunity to train motor skills more effectively and in the same particular context in which they will be executed in real life. Another aspect of VR training sessions is the recovery of cognitive functions such as perception, memory, attention, speech and thinking.

Aim. To review publications devoted to virtual reality technology and evaluation of the effectiveness of its application using neuroimaging methods in stroke rehabilitation.

Search strategy. The search was performed in the following scientific databases: Scopus, Web of Science, PubMed, Cochrane Library, Google Scholar. The search depth was 20 years. Three sources of literature, dated by 1979, 1981 and 1992 year, were used, because they contain important conceptual information.

Criteria for considerations were: reviews, original papers, meta-analyses; full-text open-access publications both in Russian and English languages. *Exclusion criteria* included low methodological quality and conference proceedings. 56 papers were included in the present review.

Results. The use of modern methods of neuroimaging and EEG to assess the effectiveness of classes in virtual reality systems may allow us to build rehabilitation programs to recover the motor and cognitive spheres of patients after a cerebral stroke.

Conclusions. A combination of technologies with addition of VR-based intervention may affect results of motor-cognitive recovery and emotional sphere correction at all stages of rehabilitation process and influence further life of patient.

Keywords: *virtual reality, rehabilitation, stroke, EEG, MRI, cognitive functions, motor functions.*

Резюме

ОБЗОР ПОКАЗАТЕЛЕЙ ЭФФЕКТИВНОСТИ ВИРТУАЛЬНОЙ РЕАЛЬНОСТИ В ДВИГАТЕЛЬНОЙ И КОГНИТИВНОЙ РЕАБИЛИТАЦИИ БОЛЬНЫХ ПОСЛЕ ЦЕРЕБРАЛЬНОГО ИНСУЛЬТА

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Введение. В настоящее время инсульт является одной из основных причин смерти и инвалидности и был описан как одна из ведущих причин смертности во всем мире. Острым вопросом является процесс реабилитации и последующее возвращение пациента к прежней жизни. В связи с этим, актуален поиск новых подходов к восстановлению утраченных двигательных и когнитивных функций. Благодаря трем ключевым элементам, необходимым для тренировки моторных функций (повторение стимуляции, сенсорная обратная связь, мотивация пациентов) ВР создает возможность более эффективно оттачивать двигательные навыки именно в том контексте, в котором они должны применяться в жизни. Еще одним аспектом тренировочных сессий в ВР является восстановление таких когнитивных функций, как восприятие, память, внимание, речь и мышление.

Цель исследования: анализ публикаций, посвященных технологии виртуальной реальности и оценки эффективности ее применения с помощью методов нейровизуализации в реабилитации инсульта.

Стратегия поиска. Поиск источников был проведен в таких базах данных, как PubMed, Cochrane Library. Глубина поиска составила 20 лет. Были использованы три источника литературы, датированные 1979, 1981 и 1992 годом, поскольку они содержат важную концептуальную информацию. *Критерии включения:* обзоры литературы, оригинальные статьи, мета-анализы; публикации в открытом доступе и с полным текстом на английском и русском языках. *Критерии исключения:* публикации низкого методологического качества, материалы конференций. В данный обзор были включены 56 публикаций.

Результаты. Использование современных методов нейровизуализации и ЭЭГ для оценки эффективности занятий в системах виртуальной реальности может позволить выстроить реабилитационные программы для восстановления двигательной и когнитивной сфер больных после церебрального инсульта.

Выводы. Сочетание технологий, опосредованных вмешательствами на основе виртуальной реальности, может влиять на результаты моторно-когнитивной реабилитации и коррекции эмоциональной сферы на всех этапах восстановления и иметь последующее отражение в обычной жизни пациента.

Ключевые слова: *виртуальная реальность, реабилитация, инсульт, ЭЭГ, МРТ, когнитивные функции, двигательные функции.*

Түйіндеме

ЦЕРЕБРАЛЬДЫ ИНСУЛЬТТАН КЕЙІНГІ НАУҚАСТАРДЫҢ МОТОРЛЫ - КОГНИТИВТІ ОҢАЛТУЫНДАҒЫ ВИРТУАЛДЫ ШЫНДЫҚТЫҢ ТИІМДІЛІК КӨРСЕТКІШТЕРІНЕ ШОЛУ

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Кіріспе. Қазіргі уақытта инсульт өлім мен мүгедектіктің негізгі себептерінің бірі болып табылады және бүкіл әлемде өлім-жітімнің жетекші себептерінің бірі ретінде сипатталған. Оңалту процесі және пациенттің кейінгі өміріне оралуы жедел мәселе болып табылады. Осыған байланысты жоғалған моторлық және когнитивті функцияларды қалпына келтірудің жаңа тәсілдерін іздеу өзекті мәселе болып табылады. Мотор функцияларын жаттықтыруға қажетті үш негізгі элементтің арқасында (ынталандыруды қайталау, сенсорлық кері байланыс, пациенттердің мотивациясы) ВШ моториканы өмірде қолдануға болатын контекстте тиімдірек шыңдауға мүмкіндік береді. ВШ-дағы жаттығу сеанстарының тағы бір аспектісі - қабылдау, есте сақтау, зейін, сөйлеу және ойлау сияқты когнитивті функцияларды қалпына келтіру.

Зерттеудің мақсаты. виртуалды шындық технологиясына арналған басылымдарды талдау және инсультті оңалтуда нейробейнелеу әдістерін қолдану арқылы оны қолдану тиімділігін бағалау.

Іздеу стратегиясы. Дереккөздерді іздеу PubMed, Cochrane Library сияқты мәліметтер базасында жүргізілді. Іздеу тереңдігі 20 жылды құрады. 1979, 1981 және 1992 жылдардағы үш әдебиет көзі пайдаланылды, себебі бұл әдебиеттер маңызды тұжырымдамалық ақпаратты қамтыды. Қосу критерийлері: әдебиеттерге шолулар, түпнұсқа мақалалар, мета-талдаулар; ашық қол жетімді және ағылшын және орыс тілдеріндегі толық мәтіні бар басылымдар. Шығару критерийлері: төмен әдістемелік сападағы жарияланымдар, конференция материалдары. Бұл шолуға 54 басылым енгізілді.

Нәтижелер. Виртуалды шындық жүйелеріндегі сабақтардың тиімділігін бағалау үшін заманауи нейробейнелеу және ЭЭГ әдістерін қолдану церебральды инсульттан кейін науқастардың моторлық және когнитивті салаларын қалпына келтіру үшін оңалту бағдарламаларын құруға мүмкіндік береді.

Қорытындылар.Виртуалды шындыққа негізделген араласулар арқылы жүзеге асырылатын технологиялардың үйлесімі қалпына келтірудің барлық кезеңдерінде моторлы-когнитивті оңалту мен эмоционалды сфераны түзету нәтижелеріне әсер етуі мүмкін және пациенттің қалыпты өмірінде кейінгі көрініске ие болуы мүмкін.

Түйін сөздер: виртуалды шындық, оңалту, инсульт, ЭЭГ, МРТ, когнитивті функциялар, мотор функциялары.

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Introduction

Currently, stroke is considered to be one of the main causes of death and disability, highly contributing to mortality in the world [12]. Clinical outcomes of stroke consist in development of persistent motor impairments, incoordination, and decrease in motor execution speed [27] as well as in development of sensory systems functioning, impairments in perception, analysis and programming of activity - restriction visual fields, ignoring part of the space, reduced visual acuity, cognitive function deficits, especially in information processing and executive function [19].

Analysis of the literature data shows that the use of virtual environments solves not only the problems of correcting motor disorders, but also modifies cognitive, motivational and social deficits [29, 52, 14].

Rehabilitation activities carried out in virtual environments, unlike classical methods of cognitive rehabilitation, can create complex conditions of varying degrees of complexity, linking together such diverse processes as motivation, motor control, cognitive processes and learning mechanisms, anxiety and depression based on sensory feedback. In recent years, high-tech methods have been increasingly used in neurorehabilitation to restore the motor functions of paretic limbs. Training using the brain-computer interface (BCI) is often combined with the use of virtual reality (VR) technology, which provides visual biofeedback, which contributes to better assimilation of instructions and more efficient performance of motor imagination tasks [7].

The combination of VR and BCI can arouse interest in patients and increase their motivation, which contributes to improved patient compliance [8, 28].

Active rehabilitation phase is known to take several weeks though patients were shown to be able to improve their functioning month after the onset of the disease as well [51]. At the same time, many stroke patients report persistent disablement and quality of life decrease due to motor and cognitive impairments [35]. Therefore, finding new approaches to recovery of lost functions is a pressing issue.

The aim of the study: to analyze published data on the virtual reality technologies and assessment of its efficiency using neuroimaging methods in stroke rehabilitation.

Search strategy

The search was performed in the following scientific databases: PubMed, Cochrane Library (Fig. 1). A search was made in English keywords: "virtual reality", "motor rehabilitation", "cognitive rehabilitation", "cerebral stroke", "MRI", "EEG". The search depth was 20 years. Three sources of literature, dated by 1979, 1981 and 1992 year, were used, because they contain important conceptual information. 1115 records were found. Articles were not limited by publication date. The inclusion criteria were as following: literature reviews, original articles, meta-analyses, full-text open-access publications; various causes of cerebral stroke, absence of psychotropic pharmacology, presence of visual-spatial societies (neglect syndrome and hemianopia), diagnostic methods of neuroimaging MRI and EEG. The exclusion criteria were as following: case reports; conference proceedings; small sample sizes of patients; availability of a complete description of the intervention protocol. In accordance with the recommendations above criteria, 1059 records were excluded and 56 full-text articles were searched.

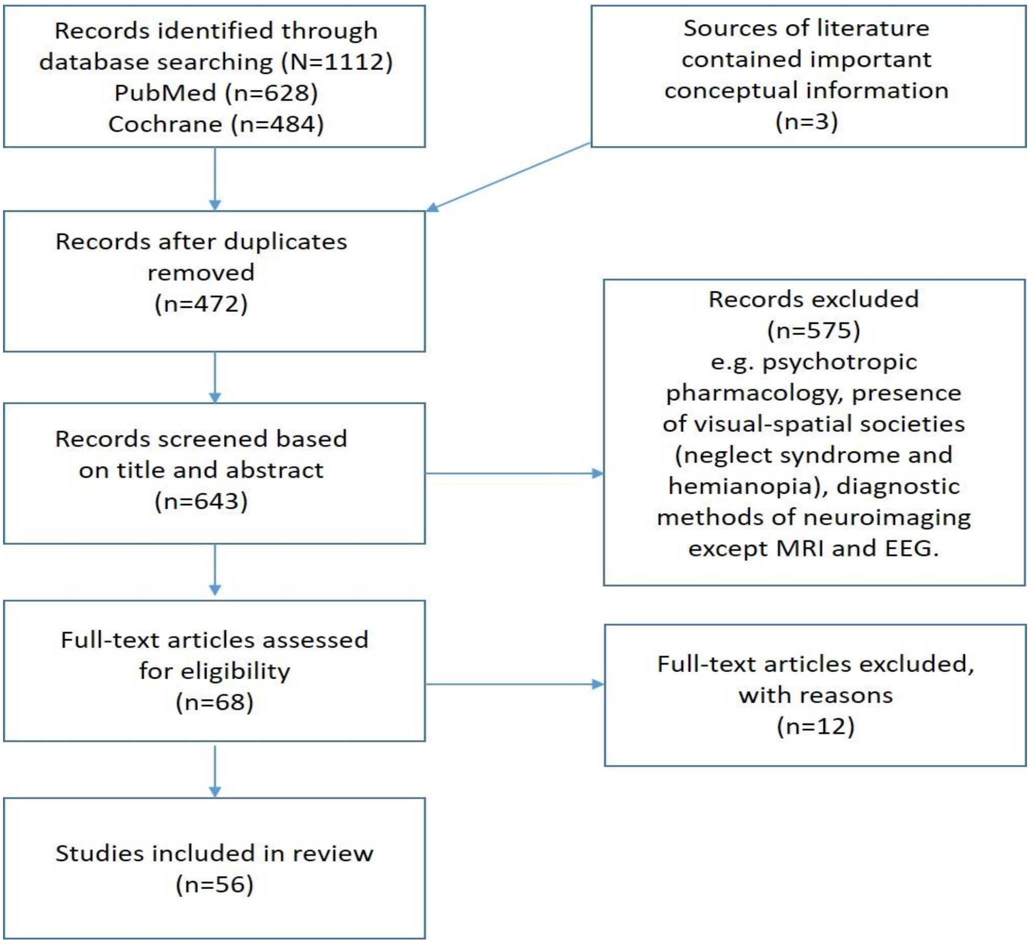

Fig. 1. Algorithm of the study selection.

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Search results and discussion

Virtual reality (VR) is a computer simulation of real environment reproducing certain situation through sensory output (visual, auditory, olfactory, tactile etc.) in order to generate response [39].

Currently, the following technical variants of virtual reality are most often used:

1. Computer monitor, plasma panel or 3D playback panel.
2. A virtual reality room where the image is projected onto several screens that are placed around the user, a sound system and polarizing glasses that provide stereoscopic perception can be used.
3. Virtual Reality helmet (HMD – head mounted display), connected to a computer and a device that tracks the position of the head. In this option, the user is completely immersed in the virtual environment.

All three variants in foreign literature are considered, namely, as variants of VR. For the patient's perception, all three options have different values and the result of perception. A computer monitor with its two-dimensional or pseudo-three-dimensional image is the most familiar and simple tool of reproducing VR. Moreover, modern monitors always contain the appropriate sound-reproducing equipment, and the realism of the image is close to natural.

The virtual reality room is a composite complex that affects several modalities at once. The patient is located in the center of the room on the treadmill, projection screens are located around him, covering about 270 degrees of the field of view. It can be three or more plane screens connected
in one system or one representing a semi-cylindrical screen. A synchronized image of a task or a game is presented on the screens by several projectors.

The patient controls the system using the movements of his body or external devices. The latter can be dynamic platforms, treadmills or motion capture system sensors. However, systems of this type are not yet massive due to their high cost and the need to allocate a large area of space. There are also more compact devices for specialized tasks that can be installed in a room of the usual size for a hospital. The advantages of such devices are that contraindications for central nervous system and vision, in this case, is minimal. After a short time of training, what is happening on the screen begins to be perceived as real. Motion-recording video cameras and the corresponding software allow for a detailed analysis of the patient's movement features.

A head-mounted display (HMD) is a display device worn on the head or as part of a helmet that has a small optical display in front of one (monocular HMD) or each eye (binocular HMD). The HMD creates a three—dimensional image, showing two images - one for each eye. The speaker system adds the effect of full presence. HMD are often divided into two classes according to the ability to combine an artificial image with a real one. Most HMD can only display an artificial (virtual) image. Some HMD allow user to combine real and virtual images, realizing augmented reality or mixed reality. The combination can occur due to translucent mirrors (Optical See-Through) or with the help of video cameras that capture reality, and the use of this video stream when generating an image (Video See-Through).

The most contemporary models use eye tracking technology, which allows user to register the orientation and fixation of the user's gaze. Applications for virtual environments can be simple linear games, as well as complex story versions with several levels of complexity.

It is difficult to reveal the most effective option for VR reproduction, since they differ in cost, complexity and duration of implementation, training of patients and staff education.

VR and interactive games are used as therapeutic methods for rehabilitation. This use consists in implementing computer programs for modeling real-life objects and situations. VR and interactive games may have certain advantages in comparison to tradition rehabilitation approaches as they can provide patients with greater sense of involvement in the imitation of functional task execution as opposite to usual hospital practices [23]. VR therapy is used mainly on the later stages of rehabilitation after stroke [5,40]. Simple VR systems can be used at home at the post-rehabilitation stage [47].

Videogames, in particular, exergames, namely, games concentrated on correction of physical impairments such as visuomotor coordination and response latency, improve attention and spatial cognition [4]. Exergames were shown to affect positively cognitive abilities, namely, executive functions, attention and visuospatial skills in clinical as well as non-clinical groups [48].

VR technologies allow training to be conducted in the environment perceived as closely resembling real life which results in improved movement restoration and increased physical activity as well as higher motivation and active involvement of patients in rehabilitation process [2]. Thanks to three key elements necessary for motor functions training (stimulation repetition, sensory feedback, patient motivation) VR provides an opportunity to train motor skills more effectively and in the same particular context in which they will be executed in real life [24]. From the neurobiological point of view VR provides multisensory stimulation capable of causing mirror neurons system activation and may involve movement observation thus complementing other therapeutic methods considered effective for motor skills recovery [49].

Virtual reality in motor and cognitive function recovery

In Russia VR therapy rehabilitation of patients with motor impairments develops along with robotized and mechano-therapies [7]. VR approach is based on the fundamental mechanisms of movement physiology established by the classics of Russian physiology – N. A. Bernstein and P. K. Anokhin. Evidence-based approach to study of the VR technologies allowed to determine that it demonstrated the greatest efficiency in recovery of walking [44]. Generalized data showing relatively high efficiency of VR technologies implementation in motor function rehabilitation after cerebral stroke is provided in a series of Russian papers [7, 45].

VR influence on cognitive abilities was not considered in the previous studies [29] although a demand for VR approaches to non-motor deficits correction is reflected in a series of studies analyzing memory and attention function in relation to VR use [15]. Despite evidence for strong interconnection between cognitive and motor functions [17], neurological rehabilitation traditionally focuses on the motor system, ignoring perceptive-cognitive aspects [33].

Activities of daily living (ADLs) are known to require simultaneity of several cognitive and physical processes. Execution of so-called dual-task (dual-tasking) was found to disturb walking causing falling especially in patients with cognitive function deficits [46].

One of the first attempts to combine physical and cognitive training was made by Carlo Perfetti from Italy [37] who proposed a theory of learning based on the theory of self-regulation of conditioned reflex of P. K. Anokhin. Motor function regulation is seen as cognitive training as it involves perception-cognition-activity integration [33]. The main training process engages such cognitive functions as perception, memory, attention, speech and thinking [37].

In comparison with traditional therapies, training using cognitive strategies showed a relatively high efficiency in upper limb movement rehabilitation [20]. A series of investigations demonstrated cognitive rehabilitation, dual tasking, computer games and cognitive and motor-cognitive interventions such as VR to improve physical activity [30, 16, 38, 45]. To name one, Liao et al. showed a program of physical and cognitive training using VR to result in a substantial improvement in dual-tasking in senior citizens with moderate cognitive deficits, probably due to increased demand for executive function activation [25].

In a study of an ability to move one's limb while performing a cognitive task it was found that activity increased in premotor cortex as well as in dorsolateral prefrontal cortex involved in memory function. This result contributes to our understanding of motor activity and movement correction as well as in learning and task technique memorization [41]. Therefore, cognitive training in spatial task may be more effective for impaired motor function recovery.

Bang et al. found that learning elements in upper limb motor function rehabilitation improved everyday activity in stroke patients [3].

VR efficiency evaluation using MRI

Currently functional MRI and electroencephalography (EEG) are employed for VR capabilities assessment.

In a series of studies using fMRI BOLD signals dependent on oxygen level in blood were analyzed as an indicator of functional connectivity between different areas of the brain in the resting state (rsFC) [6, 55]. During the acute phase after stroke functional connectivity within hemispheres and between them differ depending on the severity of injury, weakening in patients in a serious condition [9, 55]. Clinically, these results support use of functional connectivity to assess brain networks as a prognostic factor for after-stroke rehabilitation, and also can be viewed as an 'entry point' for VR [6].

A study by Chinese scientists focused on the effects of cognitive computerized training in stroke patients using resting state fMRI [26]. They found the patients from therapy group (n=16) to have greater connectivity between hippocampus and frontal lobe (right lower, middle, left lower, middle and higher frontal gyri) and left parietal lobe after 10 weeks of training in comparison to the control group. Improved neuropsychological scores were shown to correlate with increased functional activity of the hippocampus in connection with frontal and parietal lobes only in the therapy group.

Adamovich et al. evaluated VR training efficiency [1], demonstrating that:

1. Virtual avatar imitation with real-time feedback correlated with activation in fronto-parietal areas;
2. Transient increase of activation in left insula occurred during observation with purpose of mimicking movements executed by virtual avatar;
3. Virtual avatar imitation with feedback (in relation to control conditions) was associated with localized involvement of oblique gyrus, pre-cuneus and exstrastrial area being the structures involved in 'free will' execution.

In another study, efficiency of cognitive training in fully immersive VR for pre-dementia patients was evaluated using rs-fMRI [18]. After cognitive multidomain training experimental group demonstrated an improvement of visuospatial function and decrease of apathy in comparison with control group. Also, improved performance in spatial task was associated with increase in fronto-temporal FC in the experimental group.

VR efficiency evaluation using electroencephalography (EEG)

Changes in cerebral blood flow after stroke can be detected as they cause particular EEG patterns in the ischemic area consisting in decrease in faster (alpha and beta) and increase in slower (theta and delta) frequencies power [21]. Apart from its role as highly sensitive method for locating cerebral ischemia, EEG can be used as diagnostic and prognostic tool for therapy efficiency assessment after stroke [42].

Many studies showed certain cEEG indexes to be characteristic of such changes in cognitive functions as moderate cognitive impairments [21] and dementia [10]. In accordance with generally accepted view on cognitive functions and memory [22], in this studies alpha and theta rhythms may be of interest for screening for cognitive deficits after stroke. Unlike relative power of theta-rhythm or calculated from three electrodes as in Schleiger et al., EEG evaluation revealed global alpha-power [42], synchronous EEG alpha-rhythm, and lower peak alpha-frequency [43] for assessment of cognitive disturbances after stroke.

Current research of brain activity by means of EEG allowed to associate cognitive, emotional and social functions with influence of certain stimuli. While modern VR devices are portative and mobile, traditional EEG requires patient immobilization thus limiting their implications and opportunities for researcher, which lead to development of portative EEG devices which can be attached to VR glasses [53]. A substantial number of researches on VR describe changes in patient motor functions due to VR training. Changes in VR parameters such as screen inclination angle, exposure time, realism, and animated avatar use all increase presence effect. Avatar use promotes neural plasticity in sensomotoric areas associated with the mirror neurons system (MNS) [11]. Observation of movement, even modeled (on the screen, as is the case in VR), allows to engage present motor programs which, in turn, will contribute to the movement execution [36]. These processes are reflected in changes of amplitude of alpha and beta rhythms in EEG, in particular, decrease in alpha-rhythm and increase in beta-rhythm in brain areas associated with MNS, including lower frontal gyrus, lower part of precentral gyrus, rostral part of lower parietal lobe and temporal, occipital and parietal areas [28].

Suppression of μ –rhythm is considered to be the main indicator of MNS activity [34].

Combination of VR and movement rehabilitation promote increase in neurophysiological processes intensity due to a group of factors associated with motor control, psychological aspects, including inner motivation, goal, working memory, decision making and positive self-esteem. These aspects influence brain EEG-rhythms, associated with MNS activation, such as theta and gamma oscillations [56]. In particular, theta-rhythm is believed to be involved in extraction of motor memory traces while gamma-rhythm reflects conscious access to visual representation of the goal [8]. Such a broad frequency band is evident for engagement of multiple neural pathways of cerebrum, including both ascending (automatic selection of movement) and descending (task management) neural processes in MNS involved in movement decoding [31]. A recent work has shown that images of observed, executed and imagined movements can be decoded from suspected MNS areas such as area of Broca and ventral premotor cortex involved in complex interplay with traditional MNS areas generating μ-rhythm [13].

Apart from rehabilitation of motor functions, VR technology is used in therapy of emotional disorders, especially generalized anxiety disorder (GAD) [50]. GAD is characterized by alternated response stress evaluated quantitatively using various methods of physiological parameters measurement, including muscle tension, skin conductivity, nerve impulse conduction speed, heart activity and levels of hormone concentrations. Changes in EEG were studied in VR, demonstrating increase in alpha-rhythm amplitude while watching natural in comparison with urban landscapes [54], while watching plants with flowers in comparison with pots without plants, and while watching greenery in comparison with a wall made of concrete blocks [32].

Conclusion

Thus, virtual reality is probably one of the most perspective technologies for neurorehabilitation capable of combining scientifically proven methods of rehabilitation and principles of neurobiology into motivating approach to therapy, allowing patients to control their rehabilitation. Use of modern methods of neuroimaging and EEG may provide an opportunity to evaluate the efficiency of influence, to localize the necessary the area of interest and build a rehabilitation program for motor and cognitive recovery in patients after cerebral stroke.

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The authors report there are no competing interests to declare

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