Research Article

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L-NeRVEn virtual environment for neurorehabilitation: architecture, functionality, and evaluation

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Abstract: This article presents L-NeRVEn, a software solution for after-stroke upper limb neurorehabilitation utilizing collaborative virtual reality (VR). L-NeRVEn offers a shared virtual environment, experienced via a VR headset, with animated full-body avatars representing both the therapist and the patient. The patient's task is to imagine a particular movement with his or her disabled limb and the success of this imagination is determined by the processing and classification of the patient's electroencephalography (EEG) signal. The EEG processing component is loosely coupled with the rest of the solution and can be easily modified or replaced. The article focuses on the architecture and appearance of L-NeRVEn, explains the role of its users, and the interaction of its components. It also presents the results of L-NeRVEn evaluation with $n = 18$ participants, utilizing subjective (SUS, IPQ and NASA-TLX questionnaires) and objective (video recordings and observer's notes) methods.

Keywords: neurorehabilitation; virtual reality; motor imagery; software architecture; collaboration; evaluation

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1 Introduction

Recent surveys and literature reviews indicate a significant interest in employing virtual reality (VR) in the neurorehabilitation of patients after a stroke [1], [2], a spinal cord injury [3], [4] or those suffering from conditions such as cerebral palsy [2]; with noticeably positive outcomes.

The L-NeRVEn (LIRKIS NEuroRehabilitation in Virtual Environment) software, presented here, contributes to the utilization of VR as an experimental solution for post-stroke neurorehabilitation of patients who have lost control of their upper limb. L-NeRVEn combines a collaborative VR, based on the Unity game engine (https://unity.com), with a brain-computer interface, utilizing electroencephalography (EEG). It offers a virtual environment (VE), where a patient, supervised by a therapist, may undergo training (therapy) sessions. The patient and the therapist share the same virtual room, which they see from a first-person perspective. They are represented by full-body animated avatars. L-NeRVEn utilizes active motor imagery (MI), where the patient's task is to imagine a particular movement with his or her disabled limb. The success of the MI task is determined by the processing and classification of the patient's EEG signal, using the procedure described in [5], [6]. The successful imagination is rewarded by playing an animation with the disabled arm in the VE. The animation is configurable and represents the movement imagined. L-NeRVEn is a development of a web-based prototype [5], [7], implemented in the A-Frame framework (https://aframe.io). The decision to move to the Unity engine was based on its superior performance, extensive asset availability, and streamlined development process.

This article provides an overall description of L-NeRVEn, focusing on its architecture, functionality and component interaction. A special emphasis is placed on the so-called basic training procedure, which contains one MI task and represents an atomic element of a training session. The current state of L-NeRVEn, described here, is a development of its previous versions [8], [9]. The article also presents an experimental evaluation of the system using 18 participants, employing both subjective and objective methods. The subjective methods are questionnaires focusing on usability (SUS), immersion (IPQ), and load (NASA-TLX), the objective ones rely on observations and video recordings.

The rest of the article is organized as follows. Section 2 provides an overview of works dealing with neurorehabilitation in VR and evaluation methods. The L-NeRVEn software, including the basic training procedure, is described in Sections 3–5. Section 6 deals with the experimental evaluation, and the article concludes with the future development and evaluation plans in Section 7.

2 Related work

2.1 Neurorehabilitation in VR

Several studies consider a neurorehabilitation scenario similar to L-NeRVEn (i.e., a patient placed in a VE, an MI task to imagine a limb movement, the MI task success determined from the EEG signal, and the reward manifested in the VE via a limb animation or other audiovisual means).

Karácsony et al. [10] present novel classification algorithms with deep learning and a convolutional neural network to determine the MI task success. As in our case, the VE used in [10] has been developed in Unity and is perceived through a VR headset from the first-person perspective. On the other hand, the patient's avatar in [10] lacks arms, only hands are presented, and there is no therapist presence in the VE. The VE in [10] has a form of game, where the task is to catch or kick objects, while the task in L-NeRVEn is to imagine various types of arm movements with different objects.

McDermott et al. [11] introduce a pre-configured EEG decoding pipeline, calibrated on EEG data from healthy participants. The VE used was implemented in Unity and is minimalistic: yellow squares that the participants have to reach with their hands. The position of real hands is recorded by a motion tracking system while their virtual representation is shown in the VE. In the study [11], the VE was rendered on a curved widescreen monitor.

Lin and Sie [12] focus on lower limb rehabilitation and combine the movement visualization in VR with a real movement of the paralyzed limb utilizing an exoskeleton robot. The VE used in [12] plays an animation of a person walking with the exoskeleton robot.

Choy et al. [13] evaluate how visualizing a movement to be imagined in VR (via a VR headset) helps to activate stroke patients' motor cortex; with positive results. The VE used is a basketball shooting game. As in the case of [11], [12], there is no support for therapy sessions, which is only natural considering the goals of these studies.

Compared to the aforementioned VEs, the distinctive features of L-NeRVEn are the shared presence of the therapist and the patient in the VE, where both are represented by animated full-body avatars, and the distributed nature, allowing the participants to join a therapy session from different locations. In addition, the EEG processing and MI task recognition component is separated from the VE and can be easily replaced.

2.2 Virtual reality application evaluation

There are several subjective questionnaires that can be used to evaluate VR applications with respect to usability, immersion, and load.

The System Usability Scale (SUS) questionnaire [14]–[16] is a widely used tool for assessing usability across various technologies, including hardware, software, and also VR systems. It provides a quick and straightforward method for comparing the usability of the system, but does not analyze the underlying causes of its poor usability. SUS is regularly used in the VR context, for example, to compare the usability of VR headsets, such as Oculus Rift DK2 and Samsung Gear VR [17], to evaluate different interaction methods, such as controllers versus hand tracking for typing [18], and to assess VR architectural simulations [19].

Igroup Presence Questionnaire (IPQ) [20] has been designed to measure the presence or the perception of presence in VR systems. It provides a comprehensive assessment of how real users feel within the virtual environment. It does so by evaluating three key dimensions [21]: spatial presence, involvement, and experienced realism. There are several IPQ utilization cases focusing on healthcare, such as the presence evaluation in emergency medical VR training [22] and in e-mental health rehabilitation programs aimed at enhancing empathy and health literacy regarding schizophrenia among future health professionals [23]. In [22], Knudsen et al. used IPQ and NASA-TLX questionnaires to evaluate a virtual reality-based emergency medicine skill training.

The NASA Task Load Index (NASA-TLX) [24], [25], is a widely used questionnaire designed to measure perceived workload during task performance. It was originally intended for assessing the workload of pilots in aviation and space programs [24]. Over time, it has become a standard tool for evaluating workload across various fields, including VR systems [25]. In the VR field, NASA-TLX has been used to assess the mental workload of surgeons during laparoscopic procedures [26], in cognitive fatigue studies in immersive

VR, focusing on virtual grocery shopping [27], in the already mentioned work [22], and many others. In [28], NASA-TLX has been used in a setting similar to ours, namely to evaluate a collaborative virtual environment perceived through VR headsets.

According to numerous works, for example [29]–[31], a combination of subjective questionnaires and objective methods is essential for accurately assessing user experience, as self-reported data may be biased. The evaluation of L-NeRVEn, presented in Section 6, combines the aforementioned three questionnaires (subjective) with a video – and observation – based analysis (objective).

3 Architecture and communication

The L-NeRVEn software had been designed to support multiple neurorehabilitation training sessions with one patient and one therapist in each of them. As they interact over a network in the VE, they do not need to share the same physical space. Any EEG processing and MI recognition component can be used, provided it has the appropriate interface to communicate with the VE. The patient wears an EEG cap and a VR headset, while the therapist can use a VR headset or a PC.

3.1 Software architecture

A component-level architecture of the L-NeRVEn system can be seen in Figure 1. There are four main components:

VE-PA. A client application to provide the VE for the patient. It has been designed to run primarily within a VR headset. But for development purposes, it can also be used on a PC with emulated headset controls. Inside the VE, the patient can observe the therapist's avatar, the movement to be imagined, and the therapist's commands. The patient can also perform the MI task and watch the rewarding animation if successful. VE-PA has been developed primarily for the Oculus/Meta Quest family of VR headsets. However, thanks to the utilization of the OpenXR plugin, it can be easily adjusted for other headset types.

VE-TH. A client application to provide the VE for the therapist. The visual appearance of VE-TH is the same as VE-PA, but its possibilities are much greater: the therapist can adjust the position of the patient and of the table they sit at, configure a training session, and start and manage a training session in a manual or automatic mode. These capabilities are described in more detail in Sections 4 and 5.

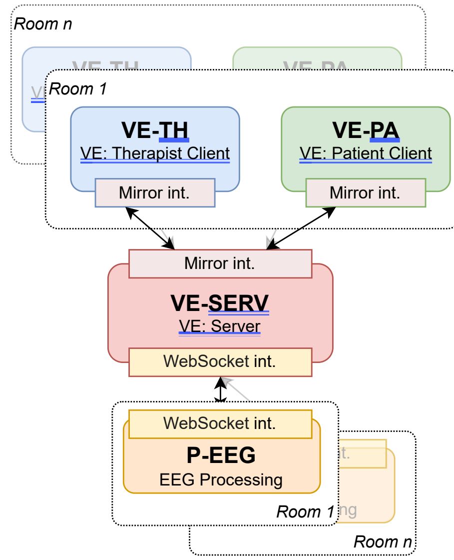


Figure 1: Software architecture of L-NeRVEn with its components, their interfaces, and communication channels.

P-EEG. An EEG processing and MI recognition component. It continuously monitors the patient's EEG signal and notifies the VE when the patient completes the MI task successfully. To recognize the success of the MI task, a resting period is required before the patient begins to imagine the movement. The operation of the P-EEG currently used in L-NeRVEn is described in more detail in [5], [6].

VE-SERV. The server application. It is responsible for the synchronization and communication between the VE of the patient and the therapist (VE-PA and VE-TH) and communication with the P-EEG.

The VE-PA, VE-TH, and VE-SERV applications have been implemented in Unity and use the Mirror networking library (https://mirror-networking.com, [32]), namely its synchronized variables and remote procedure calls, for their synchronization and communication between them. As can be seen in Figure 1, one instance of VE-SERV may serve multiple rehabilitation training sessions, while a separate instance of VE-PA, VE-TH, and P-EEG is required for each of them. Each session occurs in a dedicated virtual room and the room is selected from a predefined list in VE-PA and VE-TH before the session begins.

3.2 Communication between P-EEG and VE-SERV

The P-EEG component is interchangeable and therefore loosely coupled with the rest of L-NeRVEn. There is a two-way communication between P-EEG and VE-SERV, utilizing the WebSocket protocol. Each message sent between P-EEG and VE-SERV consists of two parts. The first one is a command the receiving part should carry out and the second one is the name of the virtual room where the corresponding training (therapy) session occurs. The commands allowed in messages from P-EEG to VE-SERV are

- *checkin*, which registers a P-EEG instance to the virtual room of the corresponding training session; and
- *move*, which is sent when the P-EEG instance confirms the successful completion of the MI task by the patient.

In the opposite direction, the commands sent from VE-SERV to P-EEG during normal operation are

- *startEegEvaluation*, indicating that the patient started the MI task, i.e., to imagine the movement with the disabled arm;
- *stopEegEvaluation*, indicating that the period dedicated to the MI task ended;
- *startRestPeriod*, to mark the start of the resting period, during which the patient should stay still and not imagine any movement; and
- *stopRestPeriod*, indicating that the resting period ended.

There are also two error-indicating commands (or, rather, notices) VE-SERV can send to P-EEG:

- *unknown*, if the last message sent from P-EEG has a wrong format, unknown command, or room name; and
- *failedCheckin*, if the last check-in operation failed (e.g., because the room is already taken or does not exist).

4 Appearance and user roles

The virtual environment in both VE-TH and VE-PA consists of two rooms, a *lobby* and a *training room*. As the state machine in Figure 2 shows, the *lobby* is the room where the user appears after starting L-NeRVEn.

In the lobby, the user chooses their appearance (avatar), adjusts audio and video settings and, most importantly, selects the server (VE-SERV) and virtual room they intend to connect to. All these options are available from a menu located on a wall in the lobby (Figure 3). The menu is also available in a head-up display form. The avatar is chosen from six predefined types and can be observed in an optional wall mirror. Provided that the user is wearing a headset and standing, the avatar size can be adjusted to their real height. The server can be chosen from a list and new servers can be added. In Figure 3, we can see a localhost (127.0.0.1) server, listening on port 7,778, chosen. Finally, the

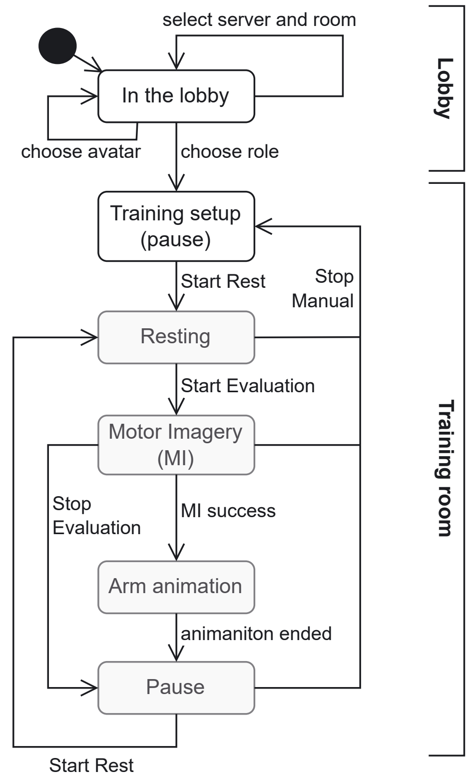


Figure 2: UML state machine depicting L-NeRVEn user activities, involving the manual training mode. The information on the right indicates which room the activities occur in. The states with the gray background are part of the basic training procedure.

user selects their role by hitting the “Therapist” or “Patient” button in the wall menu. This automatically teleports them to the training room.

The visual appearance of the *training room* (Figure 4(a)) is very similar to the lobby. The wall menu is still there, but with different options. The centerpiece of the room is a table, where the training is carried out. Contrary to the lobby, the training room is a collaborative space with which both the patient and the therapist interact via their avatars.

After the therapist and the patient enter the training room, their first task is to set up the training session. This means that, in the real world, the patient is seated comfortably at a table with their disabled arm resting on the table. In the virtual environment, the therapist uses a dedicated part of the wall menu to match the situation in the real one. The therapist can change the height of the table and the position of the patient’s avatar. In addition, the position of the virtual representation of the disabled arm can be adjusted independently from the rest of the avatar.

The remaining setup depends on the mode used for the training session. There are two modes, manual and automatic. In both of them, the session consists of several

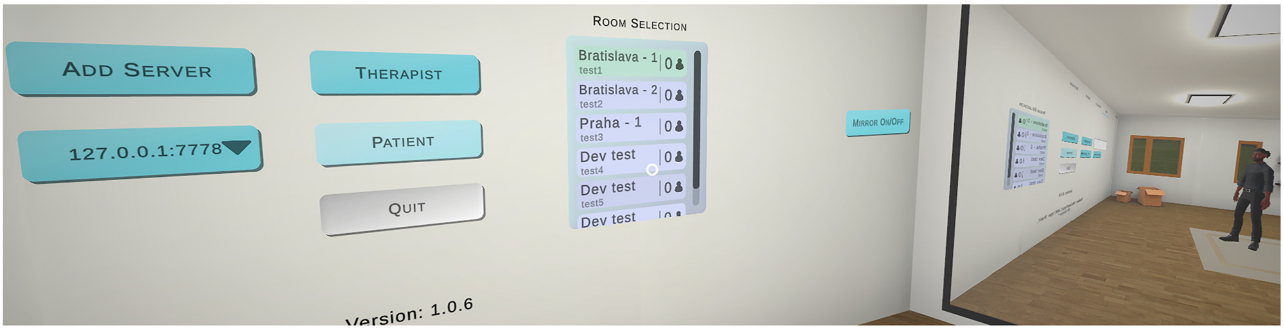
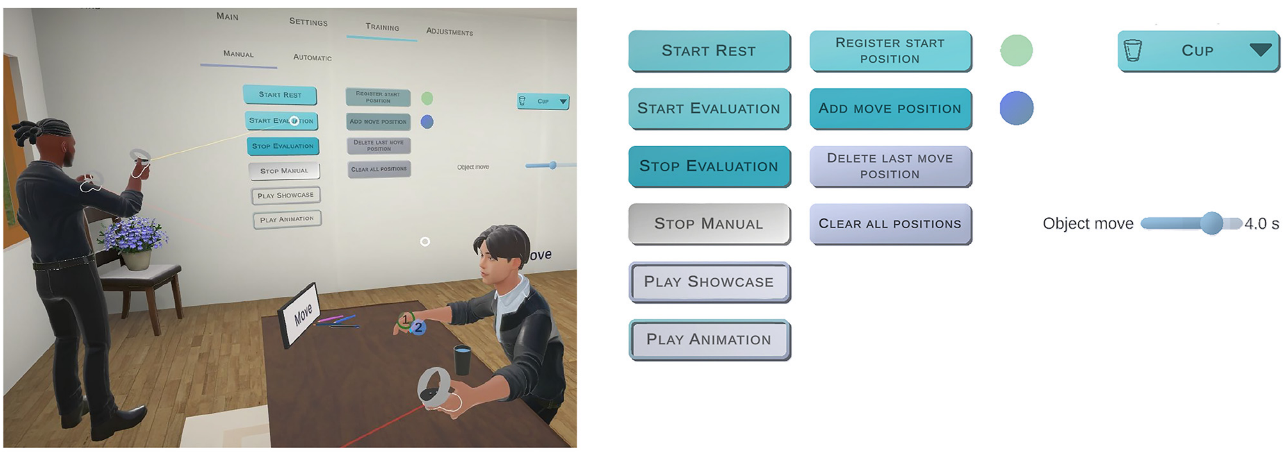


Figure 3: A part of the lobby with the wall menu (left) and mirror (right) from the user's point of view. The big paper box, visible in the mirror, contains objects used in the second evaluation scenario.



a) b)

Figure 4: The training room from a third-person view with both the therapist's (left, standing) and patient's (right, sitting) avatar visible (a) and a condensed view on the manual training controls (b).

repetitions of the basic training procedure (Section 5). In the manual mode, the therapist controls when the periods of the procedure start. In the automatic mode, the period durations and the number of repetitions of the whole procedure are set up beforehand and the sequence of procedures is then performed automatically.

For the manual mode, it is necessary to choose the arm movement to be imagined by the patient and to configure how it will be animated. There are four options for the movement, each with a different set of objects and animation. These are to move a block, to move a cube, to drink from a cup, and to open a box with a key. Figure 4(a) shows the cup option. The animations can be customized by adding several "move positions". During the animation, the avatar's arm will move the object through all the "move positions" and an additional movement with the object is performed at each position. The animation setup controls can be seen in Figure 4(b) (all controls, except the first column).

For the automatic mode, the period durations and the number of the procedure repetitions are set. The movement and animation setup is taken from the manual mode.

5 Basic training procedure

The basic training procedure contains one motor imagery task. For the patient, there are three periods, or states, differing in the mental activity performed:

Resting, where the patient should relax and not imagine any movement and their mental activity should be minimal;

Motor Imagery (MI), where the patient should imagine performing the desired movement with their disabled arm; and

Pause, where the patient's mental activity does not matter as the EEG signal is not processed by the P-EEG.

In this section, we describe the procedure as performed in the manual mode. The user perspective is captured by the UML state machine in Figure 2, while the sequence diagram in Figure 5 provides a detailed view of the interaction between all the actors and software components involved. For the sake of clarity, Figure 5 does not show the EEG

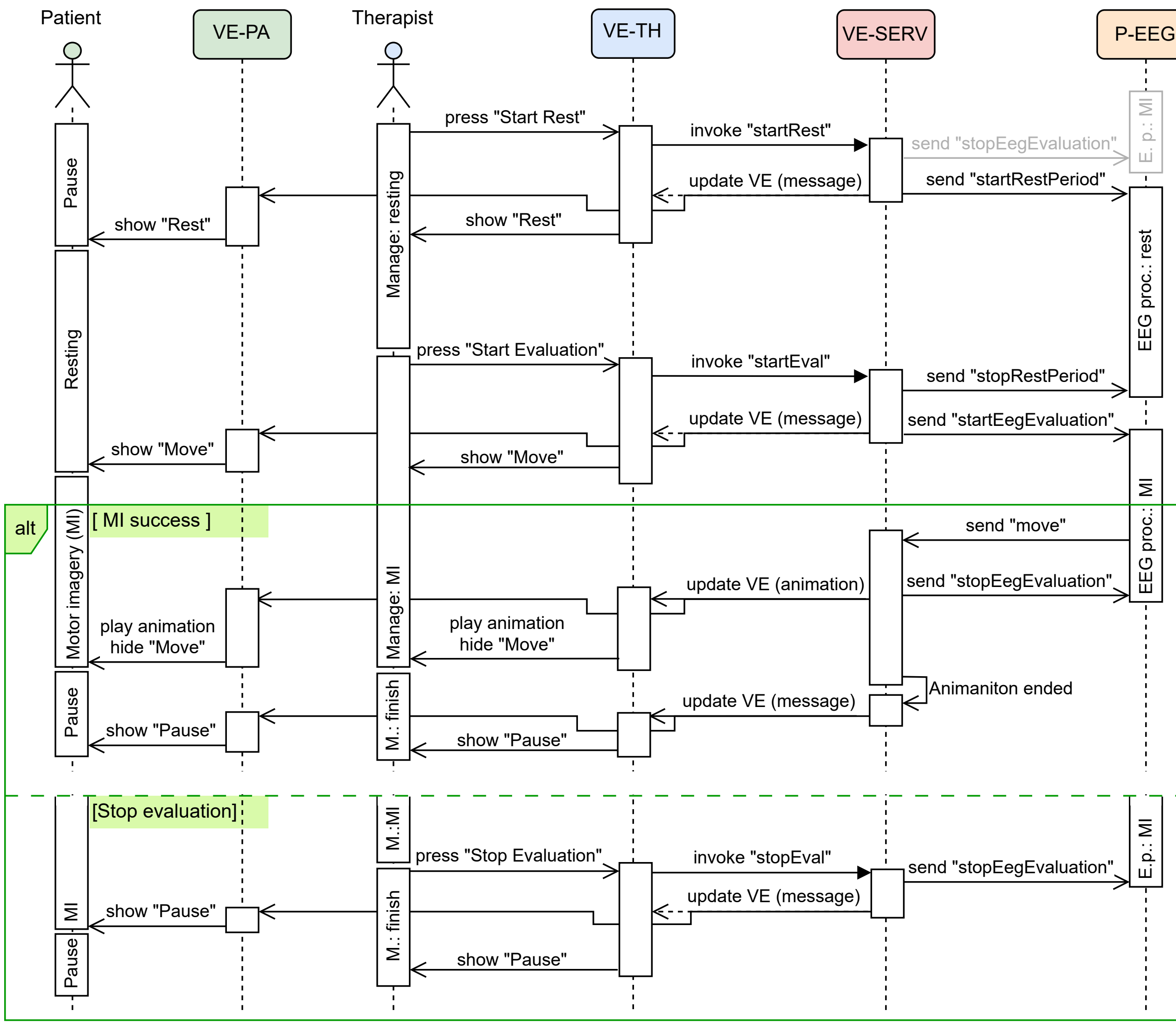


Figure 5: UML sequence diagram depicting the interaction between the L-NeRVEn components and users during the basic training procedure.

signal flow. During the whole training, the patient wears an EEG cap and the signal from the cap is fed to the P-EEG instance connected to the same server and virtual room as the patient's and therapist's VE.

At the beginning of the procedure, the patient is in the pause period. This can be the pause during which the training setup is carried out (the "Training setup (pause)" state in Figure 2) or the pause after the previous run of the procedure (the "Pause" state in Figure 2). The procedure starts when the therapist presses the *Start Rest* button in the wall menu of their VE-TH instance (the first button in Figure 4(b)). Then, the corresponding event (*startRest*) is invoked to notify the VE-SERV instance that the resting period should start. The VE-SERV responds by checking whether there is no previous MI task running. If yes, the VE-SERV sends the *stopEegEvaluation* command to the P-EEG. Then the VE-SERV sends *startRestPeriod* to notify the P-EEG that it should treat the EEG signal as the one coming from a relaxing (resting) person. The VE-SERV also updates both the VE-TH and VE-PA with the "Rest" and the "Training started" messages. While the "Rest" message is displayed during the whole period, the second one disappears after a while. Seeing the "Rest" message, the patient starts resting.

After a while, the therapist decides to stop the resting period and start the MI one by pressing the *Start Evaluation* button. The subsequent event (*startEval*), commands (*stopRestPeriod*, *startEegEvaluation*), and VE updates cause the EEG processing at the P-EEG to switch from the resting to the MI recognition mode, and the "Rest" message is replaced by "Move" in the VE-TH and VE-PA. Now, the patient starts the MI task, i.e., imagining the desired movement of their paralyzed limb.

As it is evident from the "alt" fragment in Figure 5, there are two ways in which the MI period may end. The first one is the success of the task: When the P-EEG recognizes that the patient imagined the movement properly, it sends the *move* command to the VE-SERV. The VE-SERV then acknowledges the P-EEG that the period dedicated to the MI task ended (with the *stopEegEvaluation* command) and lets the VE-TH and VE-PA play the animation of the movement. After the animation, both the VE-TH and VE-PA are updated again, with the "Pause" message. The signal processing at P-EEG may end immediately after it sends the *move* command. The second way is a failure of the MI task: If the patient is not able to successfully imagine the movement within a reasonable time frame, the therapist presses the "Stop Evaluation" button in their VE-TH. Then the VE-TH invokes the *stopEval* event to notify the VE-SERV that the MI task evaluation should end. The VE-SERV sends the *stopEegEvaluation* command to P-EEG to stop the EEG signal processing and updates the VE-TH and VE-PA with the "Pause" message. In both cases, the procedure ends with the patient in the pause period, where P-EEG is not processing the EEG signal. Therefore, a new training procedure may start immediately after the previous one ended.

As it is evident from Figure 2, the procedure may be terminated within any period. The termination is executed by the therapist pressing the "Stop Manual" button. It sets the system to the training setup activity.

6 Experimental evaluation

The main goal of the experimental evaluation was to assess the usability, presence, and cognitive workload within the virtual environment provided by L-NeRVEn. This was achieved by defining a set of scenarios and letting a group of participants fulfill these scenarios within the VE. Subsequently, the participants expressed their opinions using standardized questionnaires. The scenarios, questionnaires, and objective methods used are described in Section 6.1. The basic information about the participants is given in Section 6.2. The questionnaire results are presented and discussed in Section 6.3 and the results of the objective evaluation in Section 6.4.

6.1 Materials and methods

Inspired by the works [18], [33], [34], the development of testing scenarios focused on introducing users to the virtual environment and establishing fundamental interaction skills, essential for the training procedure. Given that users may have no prior experience with VR headsets, the test scenarios were designed to demonstrate the capabilities of L-NeRVEn while guiding users in learning its fundamental functions. Four scenarios were prepared:

1. movement and spatial orientation,
2. interaction with objects,
3. navigation in the wall menu, and
4. patient-therapist collaboration.

This structured approach allowed evaluating how efficiently the users adapt to the virtual environment, perform essential tasks, and interact with the system. The first three scenarios take place in the lobby, while the last one is carried out in the training room.

The participants have evaluated their experience using the three questionnaires mentioned in Section 2.2: SUS for usability, IPQ for immersion and NASA-TLX for workload. The scenarios are in more detail described in Section 6.1.1 and the questionnaires in Section 6.1.2.

In addition to the questionnaires, which represent subjective methods of evaluation, the participants' performance during the evaluation was captured in the form of video recordings and observer's notes. Additional interviews were carried out with some participants, where the subsequent analysis of the recordings and notes revealed ambiguities and atypical behavior.

Before the evaluation, all the participants signed a written consent form with information about the experiment and the data collected. The methods used comply with all the relevant national regulations, institutional policies and are in accordance with the tenets of the Helsinki Declaration. Ethical review and approval were waived for this study as it presents no more than minimal risk of harm to the participants and involves no procedures for which written consent is normally required outside the research context.

6.1.1 Scenarios

The *Movement and Spatial Orientation* scenario evaluates users' ability to navigate and orient themselves within the VE. Inspired by [34], it focuses on various 3D interaction techniques, such as walking, teleportation, and object recognition. This scenario makes the user familiar with the basic navigation and allows them to determine their preferred movement techniques. The following tasks are included:

1. identifying objects in the VE, namely locating doors, finding shelves and objects placed on them, identifying a window, and observing one's avatar;

2. moving with joystick;
3. rotating around their own axis;
4. using teleportation for movement;
5. activating the wall mirror and observing the avatar's reflection; and
6. moving towards an open box on the floor.

The *Interaction with Objects* scenario examines how effectively the users interact with virtual objects. It assesses their ability to pick up, manipulate, and use the virtual objects while identifying potential usability issues related to the interaction mechanics. The objects to be manipulated with are in one of the paper boxes in the lobby (Figure 3). The tasks included are:
1. identifying objects inside the box;
2. picking up an object using a raycaster;
3. extracting objects from the box and placing them on the floor;
4. grabbing an object with a virtual hand;
5. transferring an object from one hand to another;
6. throwing an object;
7. placing objects on a shelf; and
8. handling two objects simultaneously.

The *Navigation in the Wall Menu* scenario focuses on evaluating menu accessibility, ease of use, and how quickly users can locate and modify settings necessary for their VR experience. Its tasks are:
1. changing the language of the application;
2. changing the avatar;
3. enabling background music;
4. adjusting brightness;
5. modifying rendering scale, setting the scale to the minimum value, and setting the scale to the maximum value;
6. changing the aiming reticle;
7. managing server settings: changing, removing, and adding a new server IP address and port;
8. selecting the "Dev Test 4" virtual room; and
9. connecting to the server as a patient.

The *Patient-Therapist Collaboration* scenario is the only one taking place in the training room. It analyzes the interaction between a patient and a therapist within the VR system. It evaluates how well the users communicate, follow instructions, and engage in collaborative tasks, providing insights into the effectiveness of the VE. The test includes:
1. testing headset speaker volume;
2. testing headset microphone sensitivity;
3. checking the therapist's position within the scene;
4. observing the therapist's motion;
5. naming objects the therapist points to;
6. sitting at the table; and
7. starting the training procedure.

6.1.2 Questionnaires

As a standard method for gathering subjective feedback from users regarding their experiences, perceptions, and satisfaction with the system, questionnaires provide a structured way to collect both qualitative and quantitative data, enabling us to evaluate usability, immersion, and workload.

The first one used in our evaluation is the *SUS questionnaire*, which consists of 10 items (questions) rated on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). The final score s_{sus} is calculated as follows:
1. For odd-numbered questions, the response value is subtracted by 1.
2. For even-numbered questions, the response value is subtracted from 5.
3. The adjusted values are summed and multiplied by 2.5, resulting in the final score $s_{sus} \in [0, 100]$.

The score s_{sus} is usually interpreted as follows:
- $s_{sus} \geq 80$ means an excellent usability,
- $s_{sus} \in [70, 80)$ means a good usability,
- $s_{sus} \in [50, 70)$ is an average usability, and
- $s_{sus} < 50$ is a poor usability.

The *IPQ questionnaire* assesses the subjective sense of presence in the VR environment. It consists of 14 items, categorized into four key aspects: the three dimensions mentioned in Section 2.2, and a general presence, which provides an overall measure of presence. The items are rated on a 7-point Likert scale (1 = Strongly Disagree, 7 = Strongly Agree). For each dimension, the score is calculated as the average of the ratings of its items. And the final score is the average over all dimensions. Higher scores indicate a stronger sense of presence or immersion in a VE. The scores range from 1 to 7 and are interpreted as follows:
- scores close to 1 mean a very low presence,
- scores around 4 mean a moderate presence, and
- scores close to 7 mean a high presence.

Finally, the *NASA-TLX questionnaire* assesses six key dimensions of workload:
- *mental demand* – the cognitive effort required to complete the task;
- *physical demand* – the physical effort needed for task execution;

- *temporal demand* – the time pressure experienced during the task;
- *performance* – the user's self-assessment of task success;
- *effort* – the amount of exertion required to complete the task; and
- *frustration* – the emotional impact, including irritation and confusion.

Each dimension is represented by a question, rated on a scale from 0 to 100, with 5-point steps. The questionnaire supports two scoring methods: the *Raw NASA-TLX* with the final score computed as a simple average of all six dimensions and *Weighted NASA-TLX*, where participants also rank the dimensions by importance. In this study, we opted for the *Raw NASA-TLX*, as we consider all dimensions equally important. The final score is interpreted as follows
- *0 to 20* as a very low workload,
- *21 to 50* as a low to moderate workload, and
- *51 to 100* as a high workload.

6.2 Participants

A total of 18 participants took part in the study, covering a diverse range of demographics and experience levels. The participants' age ranges from 19 to 67 years old, with 13 males and 5 females. Their experience with VR varied significantly from complete beginners (Level 1) to advanced users (Level 4). Detailed participant characteristics are listed in Table 1. The abbreviations used in Table 1 have the following meaning:
- UNI = University,
- HS = High school,
- CS = Computer Science,
- MED = Medicine,
- ME = Mechanical Engineering,
- NA = Nutrition Assistant,
- CYB = Cybersecurity,
- PA = Public Administration,
- ME = Mechanical Engineering,
- PHIL = Faculty of Philosophy,
- PSY = Psychology,
- LAW = Faculty of Law,
- Eye s. = Eye surgery,
- MY = Myopia,
- MS = Motion Sickness, and
- Dia = Diabetes.

6.3 Questionnaire results

The scores for each questionnaire, achieved by the evaluation participants, are given in Table 2 and the interpretation of the results is provided in the following paragraphs.

System Usability Scale (SUS): The average SUS score was 63.47, indicating that the application achieved moderate usability. Although this suggests that the system is usable, there is still room for improvement, particularly in user interface intuitiveness and interaction design.

NASA-Task Load Index (NASA-TLX): The average final score was 29.54, which falls within the low to moderate workload range. This suggests that the cognitive effort required to use the VR system is manageable and does not impose excessive strain on users. Regarding the dimensions, the results can be interpreted as follows:
- Mental Demand (MD), average score (avg.sc.) = 32.5: The tasks required cognitive effort, but were not excessively challenging to process mentally.
- Physical Demand (PD), avg.sc. = 19.17: Low physical strain, indicating that interaction with the VR system was not physically demanding.
- Temporal Demand (TD), avg.sc. = 32.78: Participants experienced some time pressure, suggesting that time-limited tasks included mild stress.
- Performance (P), avg.sc. = 37.22: Participants rated their performance positively, indicating that the tasks were achievable.
- Effort (E), avg.sc. = 14.44: The effort required to complete the tasks was relatively low, meaning that the tasks were manageable.
- Frustration (F), avg.sc. = 14.21: Participants reported mild frustration, possibly due to usability issues or interaction difficulties.

Igroup Presence Questionnaire (IPQ): The average final score was 4.81, indicating a moderate to strong sense of presence in the virtual environment. However, there is room for improvement in realism and user engagement to enhance immersion. Per dimension, the scores were similar, except the Realism:
- General Presence (GP) – Average Score: 5.67 – Participants reported a strong sense of presence, perceiving the virtual world as authentic and immersive.
- Spatial Presence (SP) – Average Score: 5.10 – Users felt physically present in the virtual environment, suggesting a high-quality interaction with their surroundings.

Table 1: List of the evaluation participants and their basic information. The column title abbreviations are “Gnd.” for gender, “E.VR” for experience with VR, “Heal.” for health, “Edu” for education, and “Heig.” for height.

ID	*Age*	*Gnd.*	*E.VR*	*Heal.*	*Edu.*	*Field*	*Heig.*
T01	25	M	3	x	UNI	CS	188
T02	20	M	3	x	HS	–	185
T03	19	F	2	x	HS	–	183
T04	26	M	4	MY	UNI	CS	182
T05	27	F	4	MY, MS	UNI	MED	164
T06	27	M	1	x	UNI	TECH	187
T07	24	M	1	MY	UNI	CS	175
T08	19	M	1	Dia	HS	PA	179
T09	19	F	2	x	HS	–	169
T10	25	M	1	x	UNI	ME	183
T11	24	M	4	x	UNI	CS	190
T12	23	F	1	x	HS	NA	173
T13	23	M	3	x	UNI	CYB	183
T14	67	M	2	Ey.S.	UNI	ME	175
T15	19	M	1	x	UNI	PHIL	189
T16	23	M	1	x	UNI	PSY	184
T17	24	M	4	x	UNI	ME	179
T18	20	F	1	x	UNI	LAW	167

- Involvement (INV) – Average Score: 4.87 – Participants were engaged and their actions in the virtual world had meaning; however, there is still room for improvement to enhance overall engagement.
- Realism (REAL) – Average Score: 3.52 – The lower score in this category indicates that the users did not find the virtual environment entirely realistic. Factors such as graphics quality, interaction mechanics, or environmental design contributed to this perception.

6.4 Objective evaluation

Video recordings and direct observations provided further insights into participants’ performance and difficulties experienced. The recording analysis revealed several recurring issues that participants encountered during their interactions with the VE. For instance, 66 % of participants experienced difficulties with the button layout, as indicated by visible frustration and multiple unsuccessful attempts to perform actions such as grabbing objects or selecting options in the wall menu. The participants struggled to remember the specific functions assigned to the controller

Table 2: Scores of the evaluation participants for the SUS, NASA-TLX, and IPQ questionnaires, including dimensions. The column title abbreviations are: “SUS” – System Usability Scale, “TLX” – the final NASA-TLX score, “MD” – mental demand, “PD” – physical demand, “TD” – temporal demand, “P” – performance, “E” – effort, “F” – frustration, “IPQ” – the final IPQ score, “GP” – general presence, “SP” – spatial presence, “INV” – involvement, “REAL” – perceived realism.

Participant	*SUS*	*NASA-TLX scores*							*IPQ scores*				
ID		*TLX*	*MD*	*PD*	*TD*	*P*	*E*	*F*	*IPQ*	*GP*	*SP*	*INV*	*REAL*
T01	80	33.33	40	40	50	50	10	10	6.80	7.00	7.00	7.00	6.25
T02	42.5	30.0	20	20	50	50	10	30	4.06	4.50	4.50	5.50	1.75
T03	65	31.67	30	30	40	40	10	20	5.13	6.50	5.00	6.50	2.50
T04	50	23.33	10	10	10	10	10	10	5.56	7.00	5.00	7.00	3.25
T05	50	21.67	10	10	20	30	10	10	3.06	4.00	4.00	1.00	3.25
T06	65	35.0	50	40	40	40	10	10	5.13	7.00	7.00	3.25	3.25
T07	77.5	40.0	70	10	50	50	50	10	4.29	5.67	3.67	5.33	2.50
T08	77.5	18.33	0	0	90	100	10	10	4.88	6.67	4.67	4.50	3.67
T09	60	25.0	0	10	10	10	30	10	5.00	5.33	5.33	5.33	4.00
T10	55	23.33	0	20	10	20	0	10	4.83	6.33	5.00	5.00	3.00
T11	50	30.0	50	0	40	40	20	10	4.29	6.33	5.00	3.33	2.50
T12	72.5	30.0	30	20	10	10	10	20	4.04	4.33	5.00	4.33	2.50
T13	27.5	31.67	30	30	20	10	10	10	4.25	4.33	4.33	4.33	4.00
T14	67.5	40.0	40	40	40	40	20	40	4.25	4.33	4.33	4.33	4.00
T15	100	11.67	10	0	0	50	10	0	4.75	6.00	5.00	5.00	3.00
T16	57.5	41.67	70	20	50	30	10	30	4.75	6.00	5.00	4.00	4.00
T17	65	36.67	65	25	50	40	10	10	4.75	5.00	5.00	5.00	4.00
T18	80	28.33	60	20	10	50	20	10	6.75	7.00	7.00	7.00	6.00
Average	63.47	29.54	34.41	19.17	32.78	37.22	14.44	14.44	4.81	5.67	5.10	4.87	3.52

buttons and 22 % also accidentally teleported to an unintended location while attempting to grab an object on the floor. This occurred because the teleport function is mapped to the same button as object grabbing. When a participant aims at an object and presses the "Grip" button, the object is successfully grabbed. However, if the same button is pressed while aiming at the floor, the teleport function is triggered instead. This issue arises when the users struggle to precisely target an object and inadvertently shift their aim slightly to the floor while pressing the button, resulting in an unintended teleportation.

To mitigate this challenge, an effective improvement could be the integration of a visual aid, such as an annotated drawing of the controller with labeled buttons and their corresponding functions, enabling the users to familiarize themselves with the controls more efficiently and reducing cognitive load during interactions. Additionally, reassigning the button functions could play a crucial role in minimizing accidental interactions.

Moreover, non-verbal clues such as prolonged pauses, repeated gestures, or erratic movements indicated areas where the interface or interaction mechanics were not intuitive. These observations highlight usability challenges that may not have been fully captured in the self-reported questionnaire data. A notable example of this occurred during the task of adding a server, using the wall menu captured in Figure 3. Participants were instructed to enter a new server (this consists of typing a new IP address and pressing the "Add server" button to add it to the system). However, many remained silent for an extended period, and their interactions with the interface included visibly frustrated button presses. The subsequent video analysis revealed that participants mistakenly attempted to press the "Add Server" button instead of selecting the designated text box to input the IP address. This finding highlights a substantial flaw in the wall menu design, where the system fails to adequately inform users about the need to interact with the empty text field before pressing the button.

Another notable issue observed in real-time was the intensive breathing and excessive sweating exhibited by 11 participants (approximately 61 %) while navigating using the controller joystick. These were the participants with the self-assessed level of VR experience (the "E.VR" column in Table 1) equal to 1 or 2. Among them, 64 % experienced symptoms of motion sickness within the first 10 min of the VR experience, while the remaining 36 % reported experiencing the same symptoms during its final minutes. The presence of deep breathing and frequent wiping of sweat suggests that participants were experiencing increasing dizziness and growing frustration as a result. Although an alternative teleportation-based movement method was available, the strong sensation of dizziness persisted throughout the entire testing session, indicating that joystick-based movement significantly contributed to discomfort and potential simulator sickness.

These findings emphasize the importance of incorporating objective methodologies, as they revealed usability issues that participants did not explicitly mentioned in the questionnaires. Future studies should further explore these aspects by integrating techniques such as eye-tracking analysis or motion tracking to quantify user difficulties more precisely.

7 Conclusions

The L-NeRVEn virtual environment software for upper limb neurorehabilitation, presented here, has been designed and implemented as a distributed and configurable solution. The recommended setup is for both the therapist and the patient to use VR headsets. This will maximize the immersion and minimize distraction from the surrounding environment. As their VEs, VE-TH and VE-PA, communicate over a network, L-NeRVEn also allows them to occupy physically distinct places during the therapy. The P-EEG component is connected via a network, too, so it may run at a completely different location. Considering the limitations given by the physical distance and the number of suitable therapists, solutions like L-NeRVEn may improve the availability of the therapy. However, a trained personnel member is still required to assist the patient, for example, when placing the EEG cap. The P-EEG component also needs partial manual control, such as starting it and connecting to the corresponding virtual room. Therefore, under the current circumstances, the most economical way of L-NeRVEn utilization is for both the therapist and the patient to be present at the same location, together with the hardware to run all the components of L-NeRVEn.

One of the promising ways of L-NeRVEn future development is the gamification of the training sessions. Instead of utilizing the basic training procedure for repetitive movements of objects on a table, it can be adjusted for a more variable set of actions, necessary to make progress in a game-like story of the session. Such actions may include movements like opening doors, picking up an object, or starting a vehicle. The collaboration between the patient and the therapist should also be enhanced. For example, the patient may be asked to imagine helping the therapist to lift a heavy object.

The evaluation of L-NeRVEn provided satisfactory results with some room for improvement. The SUS questionnaire results indicate that the system is functional but could benefit from usability improvements to enhance efficiency and user satisfaction. Refining the interface, improving navigation clarity, and optimizing interaction mechanics could further increase usability and enhance the overall user experience. The IPQ questionnaire results suggest that the virtual environment provides a strong sense of presence, especially in general and spatial presence. However, improving realism could significantly enhance the overall immersive experience. The NASA-TLX results indicate that the VR system imposed a manageable cognitive workload and that the participants did not feel overly strained or frustrated. However, time pressure and minor usability challenges contributed to some stress during the tasks. The objective evaluation revealed certain suboptimal choices in the wall menu design and movement and object manipulation controls, especially in server selection, object grabbing, and teleportation.

Most of the deficiencies revealed can be easily corrected. One exception is the realism, where the limited performance of current VR headsets presents a serious issue. Thanks to its simple yet consistent design, L-NeRVEn maintains stable performance with 60–70 frames per second (FPS) on the Oculus/Meta Quest family of VR headsets, including the older Quest 2 models. In its current version, its smooth performance and user experience are threatened primarily by low network speed and bandwidth, resulting in delayed updates of VEs and responses from P-EEG. This presents one more argument for running all the L-NeRVEn components within the same location. However, upgrading the VE to a more realistic version means using more detailed models with higher polygon count and high-resolution textures, which may cause the frame rate to drop below 30 FPS. Regarding future development, potential frame-rate-related risk is in the need for very detailed avatar models when incorporating hand tracking. A believable capture of hand gestures will require more detailed hand models and keeping the whole avatar model consistent may require its upgrade to a more detailed version as well.

In addition to L-NeRVEn updates, based on the findings described here, the evaluation itself will continue with a larger and more diverse sample of participants and scenarios closely resembling the intended behavior of the patient and the therapist.

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Author contribution: All authors have accepted responsibility for the entire content of this manuscript and approved its submission. ŠK managed the manuscript preparation and created or edited its content in the original and revised versions. ŠK also managed the L-NeRVEn system development. JM, in cooperation with BS and ŠK, designed and carried out the experimental elevation and processed its results (Section 6). BS also contributed to the structure of the manuscript and its final form. DC was one of the most prominent developers of L-NeRVEn and contributed to its description in Sections 3 and 4, including the diagrams in Figures 2 and 5. RR and MV were responsible for the P-EEG component development, the basic training procedure design, and contributed to corresponding descriptions in Sections 3 and 4, including the diagrams in Figures 2 and 5.
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