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Adaptation of an immersive virtual reality serious game prototype for upper limb function training in post-stroke individuals: innovations and clinical applications

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Abstract

Background

Virtual reality, particularly through the use of serious games, has emerged as a promising strategy in post-stroke rehabilitation. Adapting existing serious games may represent a viable approach to tailoring interventions to the motor demands of specific populations. Accordingly, this study described the adaptation and redesign process of an immersive virtual reality game, *Virtual Mente*, originally developed for cognitive training in older adults, for upper-limb reaching training in post-stroke individuals.

Methods

This descriptive study outlined the functional adaptation and redesign process of the *Virtual Mente* serious game for a new target population. The methodological process was divided into three main stages: (1) description and analysis of the therapeutic potential of the original game version; (2) implementation of initial adjustments and adaptations based on internal testing and iterative discussions between researchers and developers; and (3) final testing and technical refinement of the adapted version.

Results

Following meetings between developers and researchers conducted from November 2023 to October 2025, three primary adaptation axes were identified: (1) biomechanical and kinematic adjustments of movements related to task execution; (2) application of motor learning principles to enable upper-limb reaching training in post-stroke individuals; and (3) implementation of strategies to ensure user sensory comfort during immersive virtual reality exposure. These adaptations resulted in the redesign of game interactions, including the creation of a new phase with additional targets and objects, increased movement variability, and audiovisual modifications to improve interaction and sensory tolerability.

Conclusions

The adaptation process enabled the redesign of *Virtual Mente* into a prototype with characteristics more consistent with the therapeutic demands of upper-limb reaching training after stroke. By integrating clinical, biomechanical, and motor learning principles, the adapted version may represent a promising complementary tool for rehabilitation training in immersive virtual reality. Future steps include content validation by experts and usability testing with post-stroke individuals.

Background

Virtual reality (VR) has emerged as a promising strategy in neurorehabilitation, particularly when combined with conventional therapy to support the recovery upper-limb function in post-stroke individuals [1–5]. In rehabilitation settings, VR interventions are frequently delivered through digital games that create interactive environments capable of stimulating engagement and task practice during therapy [4]. These games can be broadly classified as serious games, which are developed for educational, training, or therapeutic purposes, or commercial games designed primarily for entertainment and immersive experiences [6–10]. Within therapeutic contexts, serious games have been increasingly explored as tools to support rehabilitation processes by integrating specific training objectives into structured game environments [8–11].

Despite advances in new game development of new VR-based games, the absence of standardized approaches for game design, therapeutic parameters, and outcome interpretation has limited the consistent application of these technologies in clinical practice [13–16]. In this context, adapting existing games represents a viable and sustainable strategy, allowing previously tested technological resources to be repurposed and tailored to the specific motor demands of rehabilitation. This approach can reduce development costs while facilitating the incorporation of therapeutic principles into games originally designed for other purposes, thereby expanding their clinical applicability [8, 11, 12, 16].

When appropriately adapted, serious games can incorporate kinematic and motor parameters commonly used in clinical practice, enabling alignment with game tasks and therapeutic goals according to the individual's stage of recovery [14–15]. Such integration may support different levels of motor recovery, guide the selection of more appropriate interventions, and enhance the precision of therapeutic objectives during training [15, 16]. Furthermore, understanding how these technical parameters contribute to the design and refinement of VR games may support the development of more effective interventions that promote clinically meaningful improvements in motor function while maintaining patient engagement throughout training [17, 18].

These considerations highlight the growing need not only for the development but also for the adaptation of existing serious games to address specific rehabilitation demands, such as upper-limb training in post-stroke individuals. Although this process involves technical and developmental challenges, adapting previously established digital environments may provide more accessible and targeted therapeutic tools [19–21]. Within this context, this study aims to describe the adaptation process of an immersive virtual reality (IVR) game, *Virtual Mente*, originally developed for cognitive training in older adults, for upper-limb reaching training in post-stroke individuals.

Methods

This descriptive study aimed to describe the functional adaptation and redesign process of the serious game *Virtual Mente* for upper-limb reaching training in post-stroke individuals. The project was conducted through a partnership between the Strategic Health Technologies Center (NUTES) at the State University of Paraíba (UEPB) and the Virtual Reality Intervention and Research Laboratory (LIPERV) at the

Federal University of Rio Grande do Norte (UFRN), between November 2023 and October 2025. Game testing activities were carried out internally by members of LIPERV/UFRN, while programming, implementation of modifications, and system updates were managed by the NUTES/UEPB development team.

The methodological process was organized into three main stages: (1) description and analysis of the therapeutic potential of the original game version, conducted between November 2023 and April 2024; (2) initial adjustments and adaptations of the game, carried out from August to December 2024; and (3) final testing and technical refinement of the adapted game version. The most recent version, completed in October 2025, is currently undergoing testing for content validation and usability assessment by specialists in computer science and rehabilitation. At the end of each methodological stage, multidisciplinary meetings were held to produce testing reports, ensuring integration of technical, clinical, and user-experience perspectives throughout the adaptation process for the new target population.

The study was approved by the Research Ethics Committee of the UFRN (CAAE: 85298124.6.0000.5537; Approval No. 7,682,556). Additionally, the use and storage of user data from the original version of the game for cognitive training in older adults, managed by NUTES, was approved by the Research Ethics Committee of the UEPB (CAAE: 81694124.0.0000.5187; Approval No. 7,020,886).

Results

Serious game Virtual Mente

Virtual environment and gameplay

The *Virtual Mente* prototype was originally developed to address cognitive aspects in older adults through a simulation of a virtual home environment designed to provide a familiar and pleasant experience, thereby promoting immersion and user engagement. The game takes place at a dining table, where the user remains seated centrally and interact with objects positioned on the table surface. Four plates are arranged horizontally in front of the user, while fruits and vegetables are randomly placed on a tray located to the left. The main task consists of use one hand to grasp the fruits and vegetables from the tray and place them onto the corresponding plates, one object at a time. The session is ends once all objects have been correctly placed on their respective targets.

To indicate the correct sequence of object placement, a floating panel is displayed above the table in front of the user. The order in which objects must be placed on the targets is randomized at the beginning of each new phase. The system provides visual and auditory feedback for each action. Correct placements are indicated by a green halo surrounding the target accompanied by a characteristic sound, whereas incorrect placements trigger a red halo and a different sound cue. The system also allows visualization of a virtual hand that simulates grasping and manipulation movements within the virtual

environment. After completing a phase, a congratulatory panel appears, followed by a transition to a panel showing the message “waiting for the next phase” (Fig. 1). The originally version of *Virtual Mente* was developed by NUTES/UEPB in partnership with the Study and Research Group in Neurosciences, Exercise, Health, and Sports at the State University of Montes Claros.

Figure 1. Initial version of the *Virtual Mente* game. (a) Visual feedback indicating correct and incorrect responses during task execution. (b) Virtual kitchen environment used to simulate functional reaching tasks. (c) Representation of the virtual hand during task execution. (d) Congratulatory panel displayed upon phase completion. Source: Authors’ data (Strategic Health Technologies Center, State University of Paraíba [NUTES/UEPB]; Study and Research Group in Neurosciences, Exercise, Health, and Sports, State University of Montes Claros).

Device and connectivity

The game requires a head-mounted display system, specifically the Meta Quest 2 or Quest 3 device, which enables full immersion in a virtual environment. This system tracks the user’s hand position and gestures in real-time using built-in sensors, eliminating the need for handheld controllers to capture hand movements. At the end of each phase, the generated data are collected and transmitted to an application programming interface, where they are organized and subsequently displayed on a web-based platform by NUTES. In this system, a phase corresponds to a single task cycle within the game, whereas a session refers to the complete gameplay period that may include multiple phases during a training session. Access to this platform requires prior registration and an individual password for each therapist, ensuring user data security and facilitating the use of the platform’s available resources (Fig. 2).

The web-based platform was designed as a support tool for therapists, allowing them to manage device connectivity, initiate game phases, register new users, access previously records user data, and monitor individual performance indicators. These indicators include the number of correct and incorrect responses, time spent in each phase, movement dominance, and reaching velocity (Fig. 3). During gameplay, the therapist can observe the user’s perspective through an external display using Meta’s built-in projection feature. Based on this projection, the therapist may guide the user during task execution or provide additional feedback when necessary to complete the phase. This configuration allows the user to focus exclusively on the tasks proposed by the game, while the therapist manages the technical and clinical aspects through the platform, ensuring a smoother and more efficient experience for both.

Analysis of the game’s therapeutic potential

The originally version of the game was primarily designed for cognitive training in older adults and included tasks involving visual recognition of fruits and vegetables, these tasks required users to identify objects and place them on the corresponding targets according to a predefined sequence, thereby

stimulating selective processes such as selective attention, short-term memory, and visual working memory. In addition to these cognitive demands, the game also required basic motor planning to execute the sequence of reaching and object placement actions within the virtual environment. Although the originally version demonstrated potential for cognitive training, its applicability for motor rehabilitation was limited.

The interaction tasks involved restricted upper-limb joint movements and promoted low biomechanical variability, providing limited opportunities for structured reaching practice. The interaction tasks involved restricted upper-limb joint movements and promoted low biomechanical variability, providing limited opportunities for structured reaching practice. As a result, essential elements commonly required in motor rehabilitation, such as repeated reaching movements and progressive increases in task difficulty, were not sufficiently incorporated into the game design.

Based on the limitations identified during testing of the original prototype, a series of meetings were conducted between the development team at NUTES/UEPB and researchers from LIPERV/UFRN to define the adaptation strategy for the game. During these meetings, the collaborative workflow, distribution of responsibilities between the laboratories, development timeline, testing stages, and procedures for documenting and analyzing the modifications implemented in the game were established.

Definition of the game enhancement axes

During the initial internal analyses conducted by the LIPERV research team, the original version of the game was examined through exploratory internal testing performed by laboratory members. As part of the laboratory's routine development activities, researchers and students scheduled individual testing sessions to interact freely with the virtual environment and explore the game tasks and system functionalities. During these sessions, participants evaluated aspects related to task execution, interaction demands, usability, and potential limitations for motor training. Following these testing sessions, observations and suggestions were discussed collectively during laboratory meetings, resulting in a summary document that compiled the main strengths, limitations, and technical issues identified during testing.

This evaluation indicated that the game presented a solid design framework and coherent task structure, which facilitated its potential adaptation for motor training purposes and the integration of game-generated performance data with selected clinical assessment parameters. The primary objective of this stage was to identify components of the game that required modification to ensure its suitability for the new target population. In addition to evaluating the game's structural characteristics, this phase also involved identifying and correcting software flaws or implementation defects, commonly referred to as bugs, that could compromise system functionality. Such bugs may negatively affect user experience by interfering with usability, reducing performance stability, or compromising the accuracy of data stored on the web-based platform.

Following this initial analysis, meetings between the NUTES and LIPERV teams, conducted between November 2023 and April 2024, enabled the identification of key elements related to both training demands and user comfort. Based on these discussions, three primary enhancement axes were established to guide the adaptation process: (1) biomechanical and kinematic adjustment of movements associated with in-game task execution; (2) application of motor learning principles to support upper-limb training in post-stroke individuals; and (3) implementation of strategies to ensure user sensory comfort and adherence to IVR-based therapy.

Discussion

First game adaptation

Identification of functional errors and virtual environment suitability

To identify aspects of the game requiring adaptation for use by post-stroke individuals, internal testing was conducted by the LIPERV research team between November 2023 and April 2024. This exploratory phase allowed the researchers to examine the technical performance, interaction dynamics, and environmental characteristics of the original game version. The analysis indicated that the virtual environment presented a coherent structural organization and stable interaction framework, which are important prerequisites for the implementation of rehabilitation-oriented tasks. However, specific adjustments were required to ensure that the interaction demands of the game adequately supported upper-limb motor training in individuals with post-stroke impairments.

These considerations are particularly relevant because post-stroke individuals frequently present with combined sensory, perceptual, and motor deficits that require carefully structured and stable virtual environments. Previous studies have demonstrated that virtual environments should minimize sensory overload by maintaining clear visual organization, controlled stimulus presentation, and environmental stability during task execution. These characteristics are essential to facilitate attention, movement planning, and safe task performance in users with neurological impairments [20–23]. Furthermore, accurate real-time tracking of user movements and stable device connectivity represent critical factors for ensuring safety and reliability during virtual environment–based interventions [22, 23].

At the end of the testing phase, a structured report was prepared to document the main observations identified during internal evaluation, encompassing five main evaluation dimensions. The final report was developed based on the observations and suggestions reported during internal testing sessions. These observations were subsequently discussed in laboratory meetings, and the most frequently reported issues and adaptation needs were consolidated to guide the modification process.

The five dimensions included: (1) platform and game connectivity; (2) virtual environment design; (3) game initiation, interactivity, and completion; (4) bug identification and correction; and (5) additional

improvement suggestions (Table 1). These dimensions allowed the research team to systematically identify both technical issues and interaction aspects requiring modification, which subsequently informed the definition of the game enhancement axes, including biomechanical and kinematic adjustments of movement execution, the incorporation of motor learning principles for upper-limb rehabilitation, and strategies to promote sensory comfort and adherence during IVR-based therapy.

Table 1
Evaluated dimensions and proposed improvements in the initial version of the *Virtual Mente* game.

GAME ASPECTS	OBSERVATIONS
Platform and game connectivity	• Instabilities in synchronization between the device and the platform, affecting bidirectional communication
Virtual environment design	• Excessive brightness and high sound volume at the beginning of the phase
Game initiation, interactivity, and completion	• Fruits and vegetables positioned too close to each other on the tray. • Congratulatory panel and "waiting for the next phase" message panel with dimensions disproportionate to the virtual environment. • Virtual hand displaying a standardized grasping movement, regardless of the manipulated item. • High sound volume at phase initiation and during item interaction. • Presence of black lines on some fruits.
Bug identification and correction	• Duplication of the virtual hand when grasping items on the tray.
Additional improvement suggestions	• Inclusion of a chair as a reference for user positioning. • Development of an informational panel displaying phase duration, number of errors, and correct responses. • Addition of focused lighting over the table and reduction of background brightness. • Inclusion of a panel considering not only correct item placement but also the layout of the plates on the table. • Replacement of the external landscape visible through the window with a more realistic environment. • Development of a new phase with nine plates and the addition of new fruits and vegetables.

Note: Data were derived from internal testing conducted by researchers from the LIPERV, focusing on functional adaptation for upper-limb reaching training in post-stroke individuals. The table summarizes identified issues and corresponding improvements related to technical, aesthetic, and interaction aspects of the game.

Adaptation to movement biomechanics and kinematics

To analyze the biomechanical and kinematic movement demands associated with task execution in the game, the potential ranges of joint of the upper-limb were initially identified, including movements at the shoulder, elbow, wrist, and fingers. These movements comprised flexion, extension, abduction, adduction, internal and external rotation, pronation, supination, and radial and ulnar deviation [25]. Mapping these possible joint actions allowed the research team to determine which motor components were required to perform each game phase and how they contributed to task completion.

The analysis of movement organization was conducted according to the continuous movement framework, which considers the sequential organization of motor behavior during task execution. Within this model, movement is analyzed across different stages, including the initial condition, preparation, initiation, execution, and termination of the task. The initial condition refers to both the environmental context and the individual's posture before movement onset, whereas preparation involves non-observable processes related to movement planning and motor programming. The observable components include initiation, corresponding to the moment when body segments begin to move; execution, defined as the period during which effective segment displacement occurs; and termination, marking the completion of the movement [25–29].

Biomechanical and kinematic evaluations of upper-limb movements were conducted through direct observation and audiovisual recordings obtained during gameplay. For this purpose, LIPERV researchers interacted with the game while movements were recorded from multiple angles. This procedure allowed a detailed examination of how each virtual task element influenced the organization of movement in the real environment. The recordings were subsequently reviewed to identify motor patterns, segmental movement phases (initiation, execution, and termination), and the specific demands imposed by interactions with virtual objects.

Video analysis indicated that, during the reaching phase, movements were predominantly characterized by shoulder flexion and abduction combined with elbow extension, enabling hand transport toward the target. During the prehension preparation phase, fine adjustments in hand positioning were observed, involving forearm pronation or supination and subtle wrist flexion and extension movements. At the moment of grasping, finger flexion and wrist stabilization occurred, requiring coordinated activation of intrinsic and extrinsic hand muscles. During item manipulation, precise and coordinated finger movements were required, accompanied by postural adjustments of the shoulder and elbow to maintain grip stability and proximal control (Table 2).

Table 2
Joint movements and motor demands identified in the *Virtual Mente* game tasks.

Core Task	Phase	Shoulder	Elbow	Wrist	Fingers
REACHING TASK	**Initiation**	Flexion; Abduction; External rotation	Extension	Flexion; Extension; Pronation; Supination	Flexion; Extension
	Execution	Flexion; Abduction; External rotation	Extension	Flexion; Extension; Pronation; Supination	Flexion; Extension
	Termination	Flexion; Abduction; External rotation	Extension	Flexion; Extension; Pronation; Supination	Flexion; Extension
GRASPING TASK	**Initiation**	Flexion; Abduction; Adduction; Internal rotation; External rotation	Flexion; Extension	Flexion; Extension; Pronation; Supination; Ulnar deviation; Radial deviation	Flexion; Extension; Abduction; Adduction; Thumb opposition
	Execution	Flexion; Abduction; Adduction; Internal rotation; External rotation	Flexion; Extension	Flexion; Extension; Pronation; Supination; Ulnar deviation; Radial deviation	Flexion; Extension; Abduction; Adduction; Thumb opposition
	Termination	Flexion; Abduction; Adduction; Internal rotation; External rotation	Flexion; Extension	Flexion; Extension; Pronation; Supination; Ulnar deviation; Radial deviation	Flexion; Extension; Abduction; Adduction; Thumb opposition
MANIPULATION TASK	**Initiation**	Flexion; Extension; Abduction; Adduction; Internal rotation; External rotation	Flexion; Extension	Flexion; Extension; Pronation; Supination; Ulnar deviation; Radial deviation	Flexion; Extension; Abduction; Adduction; Thumb opposition
	Execution	Flexion; Extension; Abduction; Adduction; Internal	Flexion; Extension	Flexion; Extension; Pronation; Supination; Ulnar deviation;	Flexion; Extension; Abduction; Adduction;

Core Task	Phase	Shoulder	Elbow	Wrist	Fingers
		rotation; External rotation		Radial deviation	Thumb opposition
	Termination	Flexion; Extension; Abduction; Adduction; Internal rotation; External rotation	Flexion; Extension	Flexion; Extension; Pronation; Supination; Ulnar deviation; Radial deviation	Flexion; Extension; Abduction; Adduction; Thumb opposition

Note: Shoulder, elbow, wrist, and finger movements required for reaching, grasping, and manipulation tasks were analyzed across task phases (initiation, execution, and termination), based on the model proposed by Hedman [28].

This analysis also revealed limitations of the original game for motor training purposes. Although the original version incorporated reaching, grasping, and manipulation actions, the tasks did not provide sufficient biomechanical challenges for post-stroke individuals. The activities exhibited limited variability in range of motion, lacked spatial variation of targets, imposed low demands on trunk and upper-limb dissociation, required minimal pronation and supination movements, and relied on relatively simple interaction tasks with limited potential to promote neural adaptation. These findings highlighted the need for structural modifications to ensure that the game could generate motor stimuli aligned with the therapeutic goals of upper-limb rehabilitation.

Application of motor learning principles

After identifying the motor demands with task execution in the game, motor learning principles were considered to guide the adaptation of the system for upper-limb reaching training in post-stroke individuals. The literature describes four primary mechanisms that contribute to motor learning: use-dependent learning, instruction-based learning, reinforcement learning, and sensorimotor adaptation. In the game context, use-dependent learning is promoted through the repeated execution of reaching, grasping, and manipulation actions involving virtual objects. Instruction-based learning is conveyed through visual and auditory cues, as well as performance-related feedback provided to the user during interaction with the virtual environment. Reinforcement learning occurs through success and error signals and progression between phases that inform users about their performance. Finally, sensorimotor adaptation is triggered when users must adjust their movements in response to changes in the virtual environment, such as item location, response timing, or interaction dynamics [30, 31].

The logic of the original game version already incorporated some fundamental motor learning mechanisms, such as task-oriented practice combined with immediate visual and auditory feedback. These elements allow users to monitor their performance and adjust movements during task execution, supporting the formation of stable motor memories and facilitating neural plasticity processes essential

for motor recovery after stroke [30, 32, 33]. However, functional analysis of the original version revealed important limitations, particularly the need to increase the number of targets and introduce randomization in object presentation to strengthen key elements associated with neural reorganization in post-stroke individuals.

Increasing the number of targets was considered essential to enhance motor exploration. New targets were therefore added at different spatial locations on the table, enabling multitarget reaching and stimulating movements across multiple directions, ranges of motion, and joint combinations. This modification enriched the diversity of trained motor patterns and expanded the functional motor repertoire required for post-stroke recovery. In addition, randomization of object presentation disrupted predictable movement sequences, increased cognitive-motor demands, and strengthened sensorimotor adaptation processes, thereby contributing to cortical reorganization and improved generalization of motor learning [34, 35].

Based on these considerations, the developers implemented a new game phase. The original version was maintained as Phase 1, while Phase 2 incorporated additional motor demands. Although the virtual environment remained unchanged, five additional plates were introduced, resulting in a total of nine targets distributed according to the model adapted from Stewart's study [36]. The increased number of targets promoted greater movement variability by encouraging reaching across multiple directions, ranges of motion, and joint combinations. Additionally, 14 different types of fruits and vegetables were introduced and randomly distributed across two trays positioned at the left and right corners of the table, facilitating bilateral training and enabling task execution with either upper limb.

This adaptation aimed to increase the complexity of the reaching task by establishing a graded progression of difficulty. Targets located closer to the user require smaller joint excursions and lower motor effort compared with more distant targets. Similarly, targets positioned on the ipsilateral side of the affected limb allow gradual increases in reaching difficulty. To further introduce practice variability, a randomization model was applied to object placement on the targets, ensuring that the arrangement changes at the beginning of each phase and thereby increasing task complexity and variability (Fig. 4).

Strategies to ensure user sensory comfort

Audiovisual adaptations of the VR environment were also implemented to enhance user comfort and reduce the risk of sensory discomfort during gameplay. Factors influencing sensory discomfort during VR exposure are commonly grouped into three main categories: content-related factors, hardware-related factors, and user-related characteristics. Content-related factors include the design of visual elements as well as camera movement, speed, and direction within the virtual environment. Hardware-related factors involve characteristics such as display type, field of view, interaction range, and frame rate. Finally, user-related factors include individual characteristics such as sex, age, prior VR experience, susceptibility to motion sickness, and duration of exposure to the virtual experience [36–39].

Sensory discomfort associated with VR exposure, commonly referred to as cybersickness, is characterized by symptoms such as sweating, yawning, dizziness, spatial disorientation, fatigue, nausea, and vomiting during or after exposure to virtual environments [36, 40, 41]. Among the theoretical explanations for these symptoms, sensory conflict theory proposes that cybersickness arises from a mismatch between incoming sensory information and prior bodily experiences [42–44]. In contrast, multisensory reweighting theory suggests that these symptoms may result from discrepancies between expected and perceived sensory stimuli, indicating that susceptibility to cybersickness may depend on an individual's capacity to rapidly resolve conflicting multisensory signals generated during VR interaction [45].

Based on these considerations, several adaptations were implemented in the game to improve sensory comfort (Table 1). These modifications included adjustments to lighting, sound, and visual design, such as adding focused lighting over the table, reducing background scene brightness, balancing sound effects, and using lower-contrast colors schemes. These modifications are particularly relevant for post-stroke individuals, who often exhibit increased sensitivity to brightness and contrast, slowed sensory integration, susceptibility to spatial disorientation, and increased visual or cognitive fatigue. By reducing peripheral stimuli, stabilizing the virtual environment, and minimizing sensory overload, these adaptations improve tolerability for users with lower sensory thresholds, decrease the risk of cybersickness, and enhance the safety, comfort, and clinical feasibility of using the game in rehabilitation [7, 46, 47].

Second game adaptation

Final testing and technical improvements of the game's final version

After receiving the new version of *Virtual Mente*, which incorporated the proposed adaptations, redesign, and creation of Phase 2, additional internal testing was conducted by members of the LIPERV research team following the same exploratory procedures adopted in the previous testing stage. During this stage, new demands related to Phase 2 were identified, particularly regarding object design, correction of additional bugs, interaction challenges, platform connectivity, and synchronization between real-world movements and their virtual representations. Observations from this phase informed final adjustments to optimize the user experience, improve fidelity between real and virtual motor execution, and prepare the prototype for expert validation.

Key outcomes encompassed various aspects of the game and web platform. For the platform and connectivity, improvements included the addition of filters to locate or exclude users on the web platform, as well as enhancements in device connectivity and synchronization. Concerning the game environment design, corrections were requested for the textures and shapes of fruits and vegetables, adjustments to plate design, and modifications to the light–dark contrast within the game environment. Regarding game initiation, interactivity, and completion, adjustments included object manipulation,

adaptations of virtual hand visualization according to grasp type (pinch and palmar), improvements in the logic for object placement on the plates, and a reduction in waiting time between the end of one phase and the start of the next.

For bug correction, issues were identified in object interactions during manipulation, errors in counting hits and mistakes within the game, and inconsistencies in the virtual environment when generating or resuming the same phase. Finally, additional recommendations included replacing the chair design with a standard dining chair model, creating an informational panel for the user to display data on phase duration, number of errors, successes, and final percentage, and modifying object presentation on the targets using translucent images positioned above each plate.

The new improvement demands for Phase 2 targeted key aspects of the clinical applicability of VR games for post-stroke rehabilitation. Accordingly, the adjustment of the synchronization and tracking of user movements in the real environment and their corresponding representation in the virtual environment can minimize perceptual–motor discrepancies, ensuring that accurate feedback is provided for each action, which is essential for promoting motor learning processes [21]. Similarly, modifications to contrast, lighting, and visual stability of the scenario can reduce perceptual fatigue and prevent the sensory overload commonly experienced by post-stroke individuals [45, 47, 48].

By controlling these aspects, the virtual environment becomes more tolerable, safe, and functionally oriented toward motor performance, reducing sensory input that can impair motor planning. These adjustments make the game more responsive to the user's motor and sensory needs, allowing therapists to conduct training in a more structured and safe manner, thereby increasing the clinical applicability of VR-based rehabilitation [47, 48]. The latest version of the game prototype was delivered to LIPERV in October 2025 and is currently undergoing testing for content validation and usability assessment by professionals with expertise in computer science and rehabilitation. These procedures correspond to the subsequent phases of the study and aim to evaluate the clarity, relevance, and usability of the system before its application with end users.

Theoretical perspectives and evidence on the development and use of serious games in rehabilitation

This study describes the functional adaptation and redesign of the *Virtual Mente* game, originally developed for cognitive training in older adults and subsequently reconfigured for functional upper-limb training in post-stroke individuals. While retaining the original virtual environment, the game was expanded to include a new phase with additional plates, fruits, vegetables, and trays, thereby increasing interaction opportunities and motor demands. These modifications were implemented collaboratively between developers and researchers through an iterative process guided by clinical and biomechanical principles, resulting in a tool better aligned with the requirements of motor and functional training in individuals with upper-limb impairments.

Current frameworks for the development of serious games in rehabilitation emphasize two main axes: the standardization of the design process based on clinical requirements and patient-centered principles, along with the incorporation of motivational elements to enhance therapeutic adherence [10–13]. Redesigning IVR serious games for rehabilitation requires integrating kinetic-functional and biomechanical demands into game tasks. In parallel, strategies for sensory comfort within virtual environments must be incorporated to reduce cybersickness symptoms and ensure a clinically oriented and tolerable user experience. Following a framework similar to that proposed by Ambros-Antemate [10], the adaptation of *Virtual Mente* adopted an iterative and collaborative workflow between physiotherapists and programmers, ensuring alignment between clinical objectives and game design and reinforcing the practical applicability of conceptual models in the creation and development of IVR serious games.

One of the theoretical approaches frequently used to understand engagement and motivation in digital rehabilitation games is the Self-Determination Theory [50]. This theory proposes that motivated behavior is sustained by the fulfillment of three basic psychological needs: autonomy, competence, and relatedness. Autonomy refers to the perception of control over one's actions, competence emerges from successfully performing appropriately challenging tasks, and relatedness reflects the sense of connection with a meaningful context. In the redesign of *Virtual Mente*, these principles were considered to support engagement during training. Direct interaction with game elements encourages a sense of autonomy, progressive increases in task difficulty support the perception of competence, and immersion in a familiar and coherent virtual environment may facilitate the user's sense of connection with the task context.

In addition to theoretical aspects related to motivation and engagement, the identification and correction of bugs played an important role in the adaptation process of the game for post-stroke individuals. In IVR systems, the integration between hardware and software requires high levels of stability and synchronization to ensure that user actions are accurately represented in the virtual environment [49, 51]. Addressing technical inconsistencies during the development process therefore contributes to improving interaction reliability and supports the iterative cycles commonly involved in the design and refinement of serious games for rehabilitation. Similarly, considering the joint demands involved in reaching and object manipulation tasks allowed the redesign of game interactions to incorporate movements requiring different ranges of motion and joint combinations. This approach may provide clinicians with observable motor patterns during task execution that could support qualitative observations of motor control during rehabilitation training [28, 29, 52].

The gamification strategies incorporated into serious games aim to promote and sustain engagement during repetitive motor training tasks. One mechanism frequently discussed in the literature is the promotion of a state of flow, characterized by deep involvement in the activity when task difficulty is balanced with the user's abilities [13]. and immediate visual feedback can act as reinforcing signals for correct movement execution. In *Virtual Mente*, the use of visual feedback and gradual adjustments in the spatial distribution and distance of reaching targets sought to maintain an appropriate balance between

challenge and ability. his approach may help prevent common responses associated with repetitive training, such as boredom when tasks are overly simple or frustration when they are excessively difficult, thereby supporting motivation and engagement during practice and potentially facilitating motor learning processes and neuroplasticity [21, 28, 53].

A limitation of this study is that, to date, the validation process has been conducted only internally. Although this approach allowed close alignment with the perspectives of the development and research teams, the absence of usability testing with post-stroke individuals and formal validation by field experts remains an important limitation. The subsequent phases of the study will involve content validation by specialists and usability testing with the target population. These stages aim to evaluate system clarity, usability, and acceptance, as well as to explore its potential effects on upper-limb motor performance in post-stroke individuals.

Conclusions

This study described the functional adaptation and redesign of the IVR game *Virtual Mente*, integrating clinical, biomechanical, and motor learning principles into its redesign to better address the therapeutic demands of upper-limb reaching in post-stroke individuals. The implemented modifications improved aspects related to movement precision, variability of reaching tasks, and sensory conditions within the virtual environment, highlighting the potential applicability of the prototype as a complementary tool for rehabilitation training. Future steps include content validation by experts, usability testing with post-stroke individuals, and the integration of kinematic and clinical measures to further investigate its potential effectiveness and applicability in therapeutic contexts.

Abbreviations

LIPERV
Virtual Reality Intervention and Research Laboratory
NUTES
Strategic Health Technologies Center
VR
Virtual Reality
IVR
Immersive Virtual Reality
UEPB
State University of Paraíba
UFRN
Federal University of Rio Grande do Norte

Declarations

Ethics approval and consent to participate

The study related to the redesign and adaptation of the serious game *Virtual Mente* for post-stroke individuals was approved by the Research Ethics Committee (CEP) of Federal University of Rio Grande do Norte (UFRN; CAAE: 85298124.6.0000.5537, Opinion No. 7,682,556), and the use and storage of user data from the original version of the game for cognitive training in older adults by Strategic Health Technologies Center (NUTES) was approved by the CEP of State University of Paraíba (UEPB; CAAE: 81694124.0.0000.5187, Opinion No. 7,020,886).

Consent for publication

Not applicable.

Availability of data and materials

No datasets were generated or analyzed during the current study.

Competing interests

The authors declare no competing interests.

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Authors’ contributions

LCAC and VLC conceived the study, contributed to the design of the adaptation process, and drafted the manuscript. PESB contributed to the development of the virtual reality system and implementation of game modifications. DJSS and LBAF participated in the methodological design and analysis of the therapeutic framework. LBAF and VLC contributed to data interpretation and critical revision of the manuscript. FACC supervised the study and critically revised the manuscript. All authors read and approved the final manuscript.

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Figures

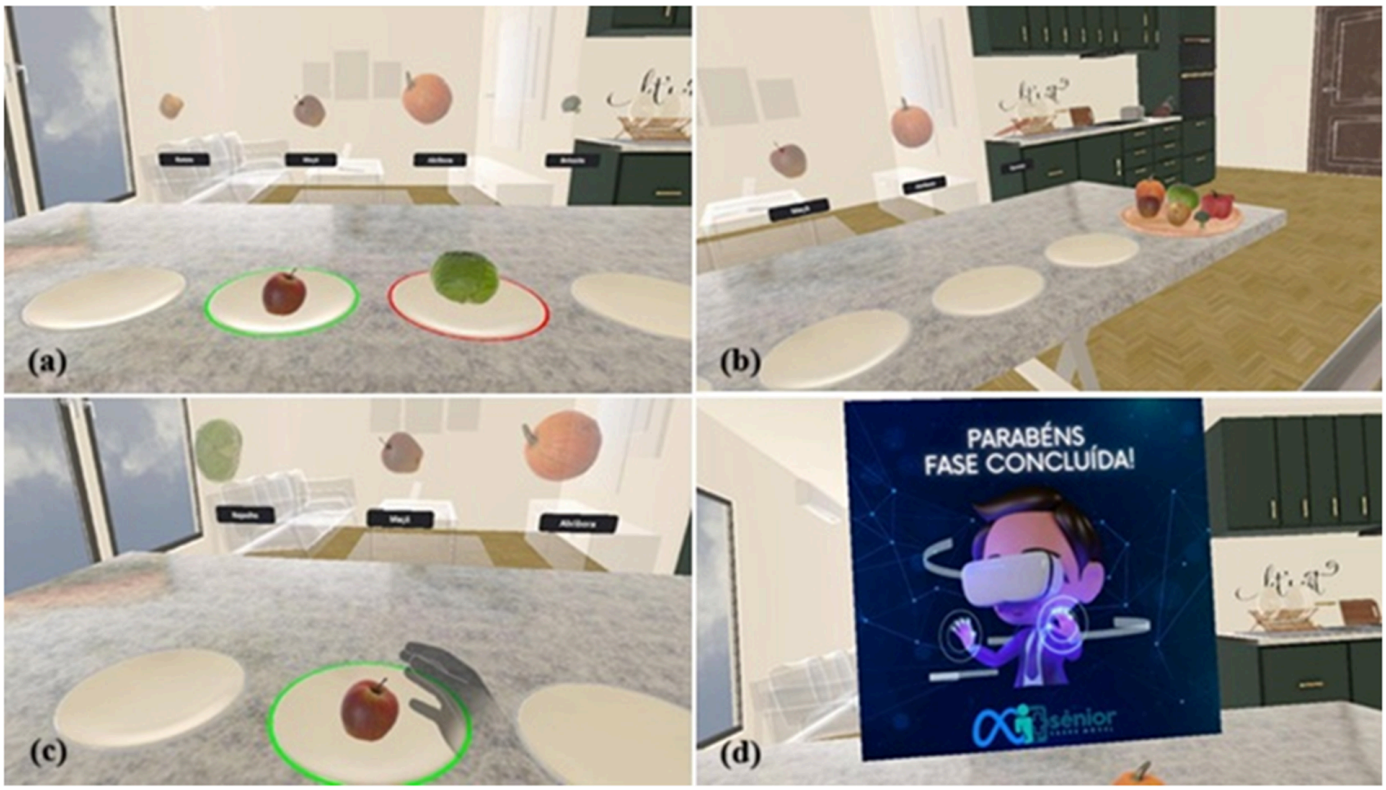


Figure 1

Initial version of the *Virtual Mente* game. (a) Visual feedback indicating correct and incorrect responses during task execution. (b) Virtual kitchen environment used to simulate functional reaching tasks. (c) Representation of the virtual hand during task execution. (d) Congratulatory panel displayed upon phase completion. Source: Authors' data (Strategic Health Technologies Center, State University of Paraíba [NUTES/UEPB]; Study and Research Group in Neurosciences, Exercise, Health, and Sports, State University of Montes Claros).

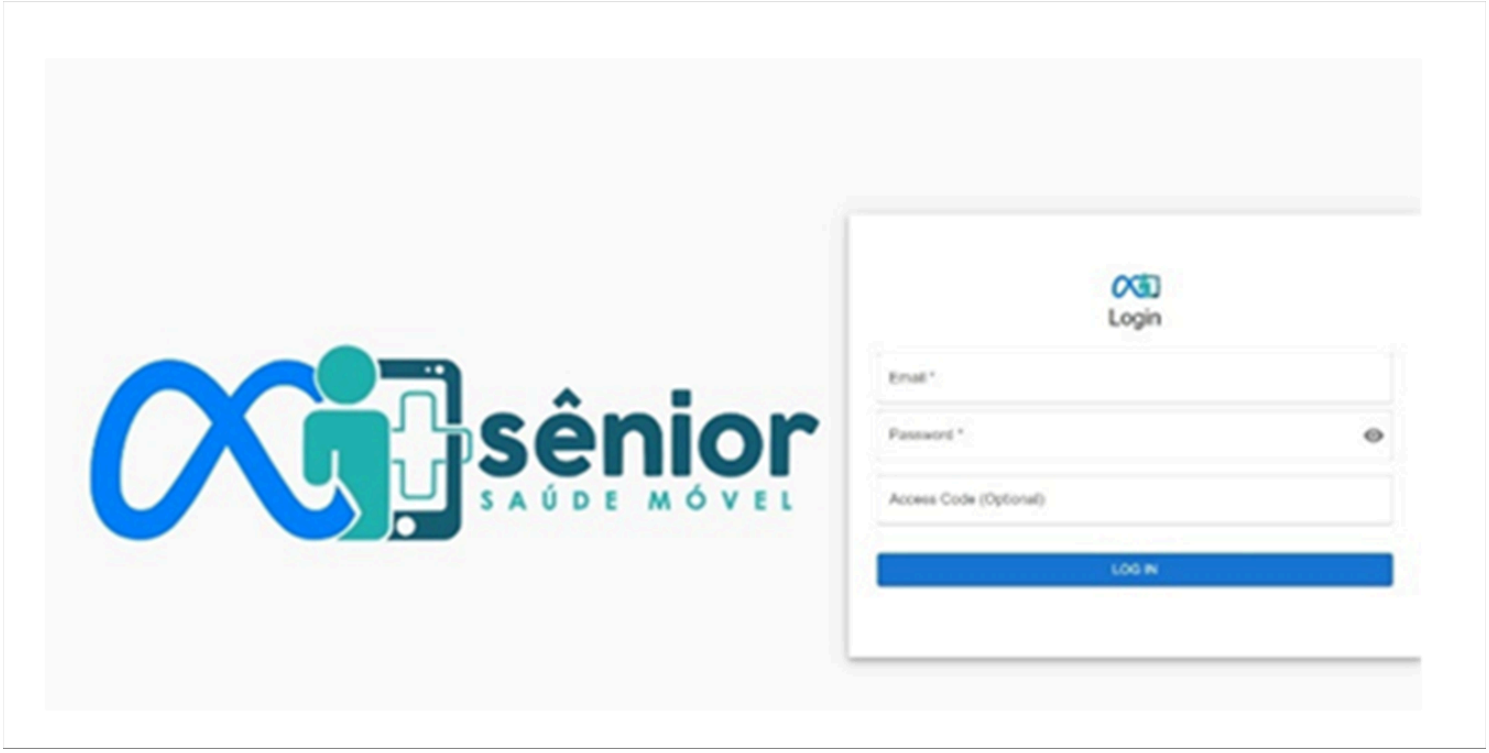


Figure 2

Senior Saúde Móvel platform. Access interface of the web-based platform used to monitor and manage user participation in the intervention. Source: Authors' data (NUTES/UEPB).

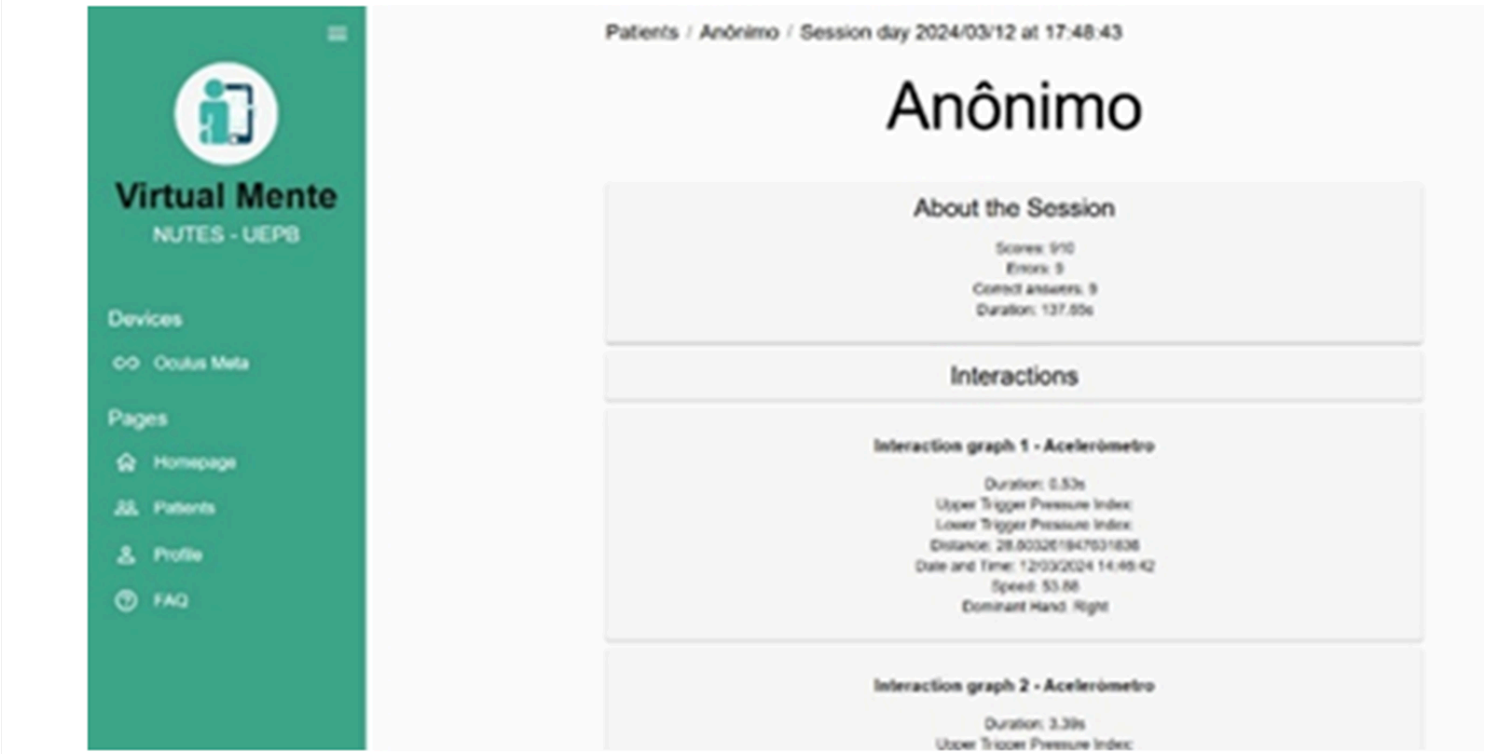


Figure 3

Senior Saúde Móvel platform. Display of user performance data, including task-related metrics used to monitor progression and support clinical decision-making. Source: Authors' data (NUTES/UEPB).

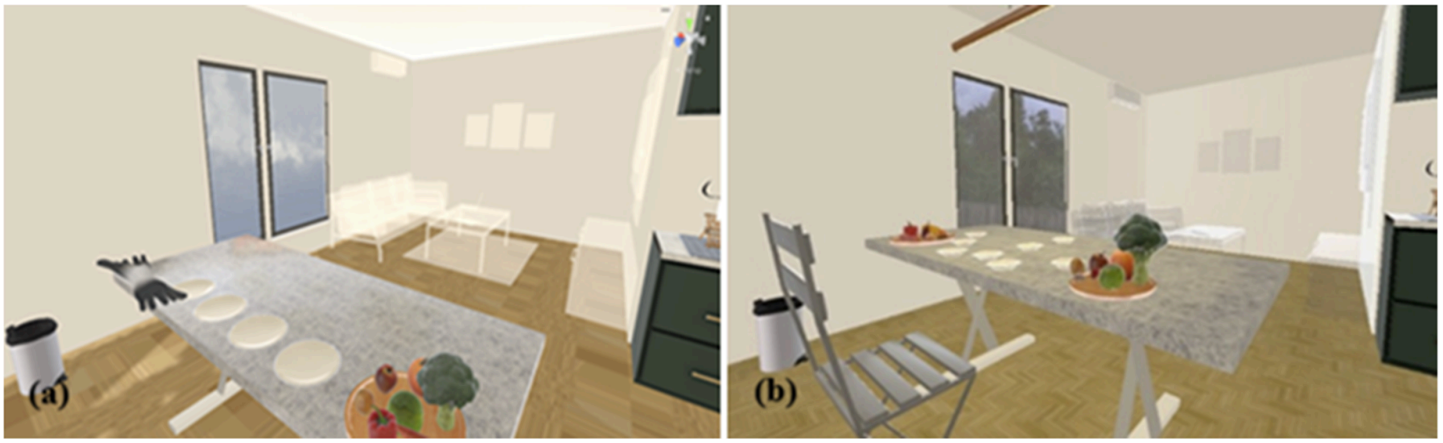


Figure 4

Differences in the virtual environment between Phase 1 (a) and Phase 2 (b) of the IVR serious game *Virtual Mente*, highlighting the increase in task complexity and interaction demands. Source: Authors' data (NUTES/UEPB).