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Immersive virtual reality serious game adaptation for upper limb rehabilitation after stroke

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Abstract

Virtual reality has emerged as a promising approach for post-stroke rehabilitation, although many existing serious games were not originally designed to meet the motor demands of upper-limb rehabilitation. This study describes the adaptation and redesign of the immersive virtual reality serious (IVR) game *Virtual Mente*, originally developed for cognitive training in older adults, for upper-limb reaching training in post-stroke individuals. The adaptation process was conducted through iterative collaboration between rehabilitation researchers and software developers, supported by internal testing and multidisciplinary discussions. Three main adaptation axes were identified: biomechanical and kinematic optimization of reaching movements, integration of motor learning principles, and implementation of strategies to improve sensory comfort during IVR exposure. These modifications resulted in redesigned game interactions, including a new training phase with additional targets and objects, greater movement variability, progressive task demands, and audiovisual adjustments to improve interaction fidelity and user comfort. The adapted prototype provides a more clinically oriented framework for task-specific upper-limb rehabilitation by incorporating therapeutic principles into game design while preserving the immersive characteristics of the original system. Future studies will focus on expert content validation, usability testing with post-stroke individuals, and clinical evaluation to determine the feasibility and therapeutic potential of the adapted system.

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 [2, 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 [8–12].

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, based on the identification of biomechanical demands, movement characteristics, motor learning principles, interaction requirements, and sensory aspects relevant to upper-limb rehabilitation after stroke; (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 original version of game underwent exploratory internal testing conducted by members of the LIPERV research team as part of the game's development process. Researchers and students individually interacted with the virtual environment to explore the game tasks and system functionalities. Upper-limb movements required during gameplay were analyzed through direct observation and audiovisual recordings obtained during internal testing sessions. Recordings were reviewed to identify segmental movement phases, joint participation, and motor demands associated with each task.

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.

Virtual Mente serious game

The game prototype was originally developed for cognitive training in older adults using an immersive virtual home environment designed to promote familiarity, immersion, and user engagement. The game was developed by NUTES in partnership with the Study and Research Group in Neurosciences, Exercise, Health, and Sports of the State University of Montes Claros. The game takes place at a dining table where the user remains seated and interacts with virtual objects positioned on the table. Four plates are arranged horizontally in front of the user, while fruits and vegetables are randomly displayed on a tray positioned to the left. Using one hand, the user grasps each object and places it on the corresponding plate. The phase ends when all objects have been correctly positioned.

A floating panel displayed above the table indicates the object to be placed. The presentation order is randomized at the beginning of each phase. Correct object placement triggers a green visual cue and an auditory signal, whereas incorrect placement activates a red visual cue and a different sound. The game also displays a virtual hand synchronized with the user's hand movements to provide real-time visual feedback during reaching and grasping tasks. At the end of each phase, a congratulatory message is displayed, followed by a transition screen indicating the start of the next phase (Fig. 1).

Virtual reality system, software architecture and web platform

The game is compatible with the Meta Quest 2 and Meta Quest 3 head-mounted displays, which provide immersive visualization and optical hand tracking through integrated sensors without requiring handheld controllers. Hand movements are captured in real time and represented within the virtual environment through a virtual hand synchronized with the user's movements. The game was developed using the Unity game engine with C# scripts that control the game logic, manage each training phase, and process user interactions, including random object generation, hand and controller tracking, grasping and object manipulation, hit and error detection, and data acquisition.

During gameplay, the system automatically records performance and kinematic data, including task completion time, hand position and movement trajectories, reaching velocity, interaction events, and controller input when Meta Touch controllers are used. At the end of each phase, these data are automatically transmitted through an application programming interface to a secure web-based platform developed by NUTES/UEPB. In the system, a *phase* corresponds to a single task cycle, whereas a *session* comprises one or more consecutive phases performed during a training session. The system supports interaction using either optical hand tracking or Meta Touch controllers, depending on the experimental configuration.

The platform requires individual therapist authentication and allows user registration, device connectivity management, phase initiation, access to previously recorded sessions, and visualization of performance indicators, including task completion time, correct and incorrect responses, movement dominance, and reaching velocity (Figs. 2 and 3). During gameplay, the therapist can monitor the user's view through Meta's built-in casting function on an external display, enabling task supervision and guidance while the user remains focused on the virtual environment.

The study was approved by the Research Ethics Committee of the Federal University of Rio Grande do Norte, CENTRAL (Universidade Federal do Rio Grande do Norte, UFRN); CAAE: 85298124.6.0000.5537; Approval No. 7,682,556. All methods were performed in accordance with the relevant guidelines and regulations. The internal testing procedures conducted by LIPERV members were exclusively exploratory prototype development and technical evaluation activities aimed at identifying software and hardware issues and improving system functionality. Laboratory members were not recruited as research participants, and no personal, clinical, behavioral, or identifiable data were collected or analyzed. Therefore, informed consent was not applicable to this stage of the study.

Results

Analysis of the therapeutic potential of the original game

The analysis of the original version of *Virtual Mente* showed that its tasks primarily targeted cognitive functions through object recognition and sequential placement activities. These tasks required users to identify fruits and vegetables and place them on the corresponding targets, engaging selective attention, short-term memory, visual working memory, and basic motor planning. Despite these characteristics, the game showed limited applicability for upper-limb rehabilitation after stroke. The interaction tasks involved a restricted range of upper-limb movements and low biomechanical variability, providing limited opportunities for repetitive reaching practice, progressive task difficulty, and functional motor training.

The findings obtained during the initial analysis guided discussions between the LIPERV/UFRN and NUTES/UEPB teams regarding the adaptations required for the new target population. The original game architecture was considered suitable for adaptation because it already incorporated a structured task sequence, immersive interaction, and integration with a web-based platform for performance monitoring. However, the analysis also identified software bugs and interaction limitations that could affect usability, movement execution, and the reliability of recorded performance data.

Based on these findings, three enhancement axes were defined to guide the redesign process: (1) biomechanical and kinematic adjustment of movement demands; (2) incorporation of motor learning principles for upper-limb rehabilitation after stroke; and (3) implementation of strategies to improve sensory comfort during IVR exposure.

First game adaptation of the game

The exploratory internal testing demonstrated that the original version of the game presented a coherent virtual environment, stable interaction framework, and satisfactory technical performance, providing a suitable foundation for adaptation to upper-limb rehabilitation after stroke. However, the analysis also identified specific technical limitations and interaction characteristics that required modification to better support rehabilitation-oriented tasks.

The findings were consolidated into a technical report comprising five evaluation dimensions: (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). Together, these dimensions enabled the systematic identification of technical issues, interaction limitations, and opportunities for functional improvement. The resulting findings guided the definition of the three enhancement axes adopted during the redesign process: (1) biomechanical and kinematic adjustment of movement execution; (2) incorporation of motor learning principles for upper-limb rehabilitation; and (3) implementation of strategies to improve sensory comfort and adherence during IVR 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.

The biomechanical analysis demonstrated that the original version of the game incorporated reaching, grasping, and object manipulation tasks involving coordinated movements of the shoulder, elbow, forearm, wrist, and fingers. During reaching, movement was predominantly characterized by shoulder flexion and abduction combined with elbow extension to transport the hand toward the target. The grasp preparation phase involved forearm pronation or supination with fine wrist adjustments, whereas grasping required coordinated finger flexion and wrist stabilization. Object manipulation further required coordinated finger movements associated with proximal stabilization of the shoulder and elbow to maintain grip 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

Although these movement components were present, the analysis demonstrated that the original game provided limited biomechanical demands for upper-limb rehabilitation after stroke. The tasks exhibited low movement variability, limited target spatial distribution, reduced requirements for trunk and upper-limb dissociation, minimal forearm pronation and supination, and relatively simple interaction patterns. Consequently, the game offered limited opportunities to progressively challenge motor performance and promote the movement variability required for rehabilitation. These findings supported the implementation of structural modifications to increase biomechanical complexity and better align the game with the therapeutic objectives of upper-limb rehabilitation.

Based on the limitations identified during the initial analysis, several adaptations grounded in motor learning principles were implemented to optimize upper-limb rehabilitation after stroke. Although the original version already incorporated task-oriented practice with immediate visual and auditory feedback, additional modifications were introduced to increase movement variability, practice progression, and sensorimotor demands.

A second game phase was developed while maintaining the original version as Phase 1. Phase 2 incorporated additional reaching targets distributed across different spatial locations, enabling multitarget reaching and increasing movement variability through different directions, ranges of motion, and joint combinations. Fourteen fruits and vegetables were randomly distributed between two trays positioned on opposite sides of the table, allowing bilateral training and task execution with either upper limb. Object presentation was randomized at the beginning of each phase to reduce movement predictability and increase cognitive-motor demands (Fig. 4).

These modifications established together a graded progression of task difficulty. Targets positioned farther from the user or contralateral to the active upper limb required larger reaching amplitudes and greater motor control than proximal or ipsilateral targets, providing progressively greater biomechanical and functional demands throughout training. Several adaptations also were implemented to improve sensory comfort during IVR exposure (Table 1).

These adaptations included focused lighting over the table, reduced background illumination, balanced sound effects, and lower-contrast color schemes. These modifications were designed to reduce visual

discomfort and facilitate interaction for post-stroke individuals during gameplay. These changes were intended to minimize visual discomfort and facilitate interaction for post-stroke individuals, who may present increased sensitivity to visual stimuli, slower sensory integration, spatial disorientation, and greater visual or cognitive fatigue.

Second game adaptation of the game

Evaluation of the redesigned version of the game identified additional technical and interaction issues requiring refinement before expert validation. The findings primarily involved platform connectivity, virtual environment design, interaction fidelity, and software stability. Regarding platform connectivity, improvements included enhanced device synchronization and the addition of user management filters on the web platform. Modifications to the virtual environment focused on refining the textures and shapes of fruits and vegetables, adjusting plate design, and optimizing lighting and visual contrast. Interaction improvements included refinements to object manipulation, visualization of pinch and palmar grasp representations, object placement logic, and reduced transition time between consecutive phases.

Additional software corrections addressed interaction inconsistencies during object manipulation, errors in recording successful and unsuccessful task completion, and synchronization failures when generating or resuming phases. Further refinements included redesigning the virtual chair, adding a performance summary panel displaying phase duration, number of correct and incorrect responses, and overall performance, and replacing object cues on the targets with translucent reference images positioned above each plate. The final version of the prototype was delivered to the research team in October 2025 and is currently undergoing content validation and usability assessment by specialists in computer science and rehabilitation prior to clinical testing.

Discussion

This study describes the functional adaptation and redesign of the *Virtual Mente* serious game, originally developed for cognitive training in older adults and subsequently reconfigured for upper-limb rehabilitation in post-stroke individuals. While preserving the original virtual environment, the game was redesigned to incorporate new interaction tasks and therapeutic components that better reflect the motor and functional demands of upper-limb rehabilitation. These modifications were implemented through an iterative collaboration between developers and rehabilitation researchers, guided by clinical and biomechanical principles while incorporating motor learning concepts, resulting in a prototype with greater potential to support task-oriented training in IVR.

The adaptation of the game followed an adaptation process guided by clinical objectives, ensuring that game modifications were clinically driven while remaining technically feasible. This approach is consistent with current frameworks for the development of serious games, which recommend integrating clinical requirements, patient-centered principles, and motivational strategies throughout the design process [10–13]. Accordingly, a movement analysis framework commonly adopted in

neurological rehabilitation was adopted to identify the biomechanical and kinematic requirements of reaching, grasping, and object manipulation, providing the clinical rationale for redesigning the game mechanics [22–27]. This approach may also enable clinicians to observe task-specific motor patterns during gameplay, supporting qualitative assessment of motor performance during rehabilitation [25–27].

In addition to motor training, the redesign also considered factors that may influence user engagement and the clinical feasibility IVR interventions. Accurate synchronization between users' real movements and their virtual representation, together with immediate visual feedback, is essential to support natural interaction, minimize perceptual-motor discrepancies, and reduce sensory discomfort during IVR exposure [21, 28–38, 40]. These aspects are particularly relevant for post-stroke individuals, who may present increased susceptibility to sensory overload and cybersickness. By improving movement tracking, interaction fidelity, and feedback, the redesigned game becomes more responsive to users' motor and sensory needs, allowing therapists to deliver rehabilitation in a more structured, safe, and clinically applicable virtual environment [37–40].

The adaptation of the game represents an important step toward the development of clinically oriented IVR interventions for upper-limb rehabilitation after stroke. By integrating clinical reasoning, biomechanical analysis, motor learning principles, and user-centered design, the adapted prototype provides a structured framework or clinically oriented upper-limb rehabilitation in IVR. Nevertheless, this study has some limitations. The adaptation process was based exclusively on internal testing conducted by the research and development teams, and the prototype has not yet undergone formal content validation or usability testing with post-stroke individuals. Future studies will therefore focus on expert content validation, usability assessment, and subsequent clinical evaluation to determine the feasibility, acceptability, and potential therapeutic effects of the adapted system in individuals after stroke.

Conclusions

This study described the adaptation of the IVR serious game for upper-limb rehabilitation in post-stroke individuals. The adaptation process incorporated clinical, biomechanical, and motor learning principles to improve movement precision, increase the variability of reaching tasks, and enhance sensory comfort within the virtual environment. These modifications resulted in a prototype with greater potential to support task-oriented rehabilitation in IVR. Future studies should focus on expert content validation, usability testing with post-stroke individuals, and clinical evaluation to determine the feasibility, acceptability, and therapeutic potential of the adapted system.

Declarations

Declarations

Ethics approval and consent to participate

The study was approved by the Research Ethics Committee of the Federal University of Rio Grande do Norte, CENTRAL (Universidade Federal do Rio Grande do Norte, UFRN); CAAE: 85298124.6.0000.5537; Approval No. 7,682,556. All methods were performed in accordance with the relevant guidelines and regulations. The internal testing procedures conducted by LIPERV members were exclusively exploratory prototype development and technical evaluation activities aimed at identifying software and hardware issues and improving system functionality. Laboratory members were not recruited as research participants, and no personal, clinical, behavioral, or identifiable data were collected or analyzed. Therefore, informed consent was not applicable to this stage of the study.

Generative AI Use Disclosure

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely for language editing and improvement of readability. All scientific content, interpretations, and conclusions were developed by the authors, who reviewed and approved the final manuscript.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Author Contribution

L.C.A.C. and V.L.C. conceived the study, contributed to the design of the adaptation process, and drafted the manuscript. P.E.S.B. contributed to the development of the virtual reality system and implementation of game modifications. D.J.S.S. and L.B.A.F. participated in the methodological design and analysis of the therapeutic framework. L.B.A.F. and V.L.C. contributed to data interpretation and critical revision of the manuscript. F.A.C.C. and E.R.V. supervised the study and critically revised the manuscript. All authors read and approved the final manuscript.

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Data Availability

All data supporting the conclusions of this study are included within this published article. The main findings related to the game adaptation process are presented in Tables 1 and 2, and the implemented game adaptations are illustrated in Figures 1, 2, 3, and 4. No additional datasets were generated or analyzed beyond those presented in this article.

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Figures

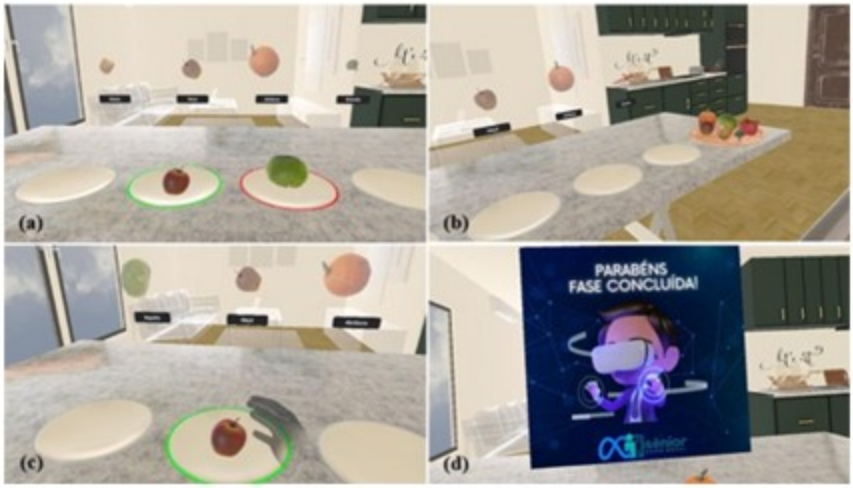


Figure 1

Original version of the immersive virtual reality serious game *Virtual Mente*. (a) Visual feedback indicating correct and incorrect responses. (b) Virtual kitchen environment. (c) Virtual hand used for object interaction. (d) Congratulatory panel displayed after phase completion. **Source:**Authors.



Figure 2

Web-based platform for therapist management of the *Virtual Mente* IVR serious game. **Source:** Authors.



Figure 3

User performance indicators displayed on the web-based platform of the *Virtual Mente* IVR serious game. **Source:** Authors.

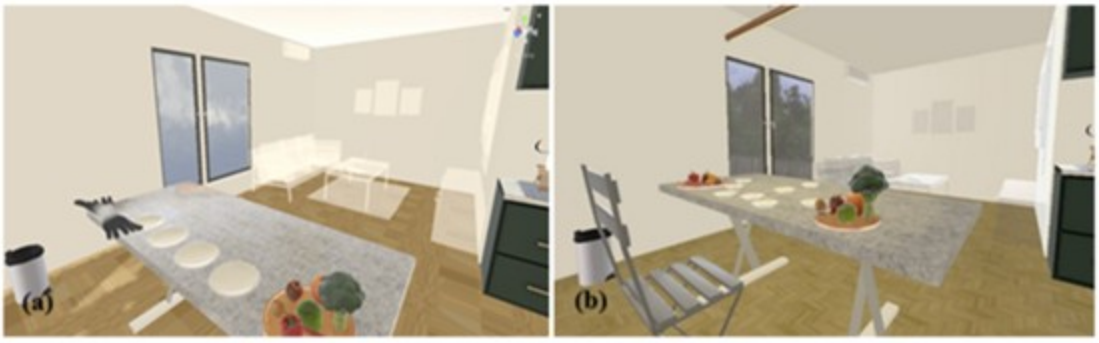


Figure 4

Comparison of the virtual environments in Phase 1 (a) and Phase 2 (b) of the IVR serious game *Virtual Mente*. **Source:**Authors.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.docx
- Table2.docx
- Figure1.tif
- Figure2.tif
- Figure3.tif
- Figure4.tif