Journal Name: Neuropsychology Review

Immersive virtual reality in neuropsychological assessment of acquired brain injury: a systematic review and meta-analysis

Nicola Davide Cavallo[1+], Federica Amitrano[1+], Armando Coccia[1*], Carlo Miccio[2], Gabriella Santangelo[3], Laura Marcuccio[2], Giovanni D'Addio[1], Pasquale Moretta[2].

[1] Istituti Clinici Scientifici Maugeri IRCCS, Movement Analysis and Robotic Laboratory (MARLab), Institute of Telese Terme (Benevento), Italy.

[2] Istituti Clinici Scientifici Maugeri IRCCS, Department of Neurorehabilitation, Institute of Telese Terme (Benevento), Italy.

[3] Università della Campania Luigi Vanvitelli, Department of Psychology, Caserta, Italy.

***Corresponding author**: Armando Coccia, Istituti Clinici Scientifici Maugeri IRCCS, Via Bagni Vecchi 1, 82037 - Telese Terme, Italy. E-mail: armando.coccia@icsmaugeri.it; phone number: +39 0824 909641.

[+] these authors equally contributed to this work.

Supplementary Materials

Table S1 - Assessment risk of bias of primary studies included in the systematic review.

	JBI CRITICAL APPRAISAL CHECKLIST FOR ANALYTICAL CROSS SECTIONAL STUDIES							
Authors	Were the criteria for inclusion in the sample clearly defined?	Were the study subjects and the setting described in detail?	Was the exposure measured in a valid and reliable way?*	Were objective, standard criteria used for measurement of the condition?	Were confounding factors identified?	Were strategies to deal with confounding factors stated?	Were the outcomes measured in a valid and reliable way?	Was appropriate statistical analysis used?
Belger et al. (2024)	Y	Y	N/A	Y	Y	Y	Y	Y
Brouwer et al. (2022)	Y	Y	N/A	Y	Y	Y	Y	Y
Costa Sousa et al. (2024)	Y	Y	N/A	Y	Y	Y	N	Y
Deblock-Bellamy et al. (2022)	Y	Y	N/A	Y	Y	Y	Y	Y
Dehn et al. (2020)	Y	Y	N/A	Y	Y	Y	Y	Y
Hougaard et al. (2021)	Y	Y	N/A	Y	Y	Y	Y	Y
Jager et al. (2015)	Y	Y	N/A	Y	N	N	Y	Y
Jannink et al. (2009)	Y	Y	N/A	Y	Y	Y	Y	Y
Kang et al. (2008)	Y	Y	N/A	Y	Y	Y	Y	Y
Kim et al. (2004)	Y	Y	N/A	Y	Y	Y	Y	Y
Kim et al. (2007)	N	Y	N/A	Y	Y	Y	Y	Y
Kim et al. (2021)	Y	Y	N/A	Y	Y	Y	Y	Y
Specht et al. (2021)	Y	Y	N/A	Y	Y	Y	Y	Y
Thomasson et al. (2024)	Y	Y	N/A	Y	Y	Y	Y	Y
Uimonen et al. (2024)	Y	Y	N/A	Y	Y	Y	Y	Y
Ulm et al. (2013)	Y	Y	N/A	Y	Y	Y	Y	Y
Zhang et al. (2001)	Y	Y	N/A	Y	Y	Y	Y	Y

* In the studies included in the meta-analysis the population is not exposed to a treatment and/or intervention

Table S2 – Description of virtual reality tasks employed to assess cognitive functions in selected studies.

Author(s)	Task Description	Type of cognitive process
Belger *et al.* 2024	The study took place in a realistic, virtual urban environment, where participants were required to safely cross two parallel, heavily traveled lanes of a road of 300 m in length to each side. The task was to observe the lanes (i.e., watching the cars), cross them safely, post a letter in a mailbox, and return by crossing the street again. Users press the controller button to start the road crossing. To drop the letter in, it is necessary to move the virtual hand near the mailbox (placed in the right or left side of the screen) and then press the trigger button again to cross the road back.	Executive functions
Brouwer *et al.* 2022	The study took place in a realistic, virtual supermarket. Participants were familiarized with a shopping list containing verbal labels and images, which they had to memorize. The list had either 3 products (short list) or 7 products (long list) and was presented three times with the experimenter naming the products aloud. Once ready, participants entered the VR supermarket, where they had to find the products on their list. They used HTC Vive controllers to navigate and select items by pointing a laser, fixating their gaze, and holding a button until the controller vibrated. The short list task allowed 15 minutes, while the long list task allowed 7 minutes. All tasks were performed while sitting on a desk chair.	Memory, Visuospatial functions
Costa Sousa *et al.* 2024	Participants were assessed while walking in a virtual environment representing a Montreal subway station. In the single motor task they had to walk towards a subway map, avoiding collisions with three female virtual characters walking at 1.2 m/s in different directions to create interference scenarios. In the single cognitive task, participants had to discriminate the pitch of words presented through a headset, ignoring the words' meanings. This task had two levels of complexity. In this task participants were assessed while seated and observing the static virtual environment in the HMD. The dual-task conditions required participants to walk and perform the cognitive task (simple and complex levels) simultaneously.	Executive functions
Deblock-Bellamy *et al.* 2022	Participants walked in a 75-meter virtual corridor of a shopping center, using a low-friction omnidirectional platform and a VR headset. The setup included sensors to track orientation and progression. Participants performed four combinations of tasks: two locomotor (simple and complex) and two cognitive (simple and complex). The simple locomotor task involved walking without avoiding virtual agents, while the complex task required avoiding three virtual agents. The simple cognitive task was to memorize and recall a 5-item shopping list, and the complex task involved memorizing a list with two items modified during the walk.	Memory
Dehn *et al.* 2020	The assessment task involved participants learning a shopping list and buying the items in a VR supermarket. Performance was measured by the number of correctly bought products and shopping time. The VR supermarket task was presented on a 360° cave made up of 8 monitors. Participants used a swivel chair and joystick for navigation, and selected products by tapping on touch-screen monitors.	Memory
Hougaard *et al.* 2021	Participants were instructed to wear a VR headset and explore a virtual museum. They underwent an eye tracking calibration before viewing three sets of pictures (faces, landscapes, or non-figurative paintings) on three walls, without any particular task. Each set was viewed for 60 seconds, totalling 180 seconds. The VR headset's position, orientation, and participants' gaze were registered.	Visuospatial functions

Author(s)	Task Description	Type of cognitive process
Jagar *et al.* 2015	Participants, either standing or in a wheelchair, were required to cross a virtual street presented in the virtual scenario. Healthy participants stepped forward when it was safe to cross, while stroke patients pressed a button. Six different street-crossing scenarios were presented, with varying car speeds and gaps.	Executive and Visuospatial functions
Jannink *et al.* 2009	The 3D neglect test involved a virtual environment resembling a bus station, where participants used a HMD to detect yellow balls coming towards them. The test had three levels of increasing difficulty, with balls appearing at various angles. Participants had to move their heads to track the balls and press a button to make the balls disappear when centered in their field of vision.	Visuospatial functions
Kang *et al.* 2008	The simulated supermarket had 50 items and included display stands and refrigerators. Users navigated using a joystick while sitting in a rotating chair and selected items by focusing on them with a HMD and pressing a button. The program had three stages of increasing difficulty to evaluate various cognitive functions. First Stage: Finding three displayed items within 10 turns. Second Stage: Selecting and placing items in the cart based on auditory and visual stimuli, responding to unexpected events (e.g., dropping an item), and selecting items in a specified category. Third Stage: Selecting a shopping item based on a given request and meeting a designated price.	Executive functions, Memory, Visuospatial functions
Kim *et al.* 2004	The virtual environment is designed to assess and train unilateral neglect patients using a branch road and a ball. It includes a calibration task to measure the patient's visual middle line and a main task where the patient must track a moving ball with the gaze. The program uses visual and auditory cues to help patients detect the ball, with difficulty levels adjusted based on patient performance. There are three stages of difficulty according to the variation in head motion (visual field angle), each with four levels with increasing target velocity, making a total of 12 difficulty levels. Patients progress through levels based on their success in completing tasks.	Visuospatial functions
Kim *et al.* 2007	The virtual environment simulates a typical Korean Seoul street for a street-crossing task. An avatar starts in the middle of the crossing, and vehicles appear randomly from the right or left when traffic lights change. Subjects use a HMD and head tracking to avoid accidents by stopping the vehicle with a mouse button. During calibration, subjects align an avatar to their visual middle line. In training, subjects detect virtual vehicles and respond by pressing a button. Visual and auditory cues help if the subject fails to notice the vehicle. The difficulty is adjusted by the vehicle's speed (level) and the distance between the avatar and the subject (stage). Subjects progress through levels and stages based on their performance, with the difficulty increasing or decreasing accordingly.	Executive functions
Kim *et al.* 2021	Participants were instructed to focus on a white fixation cross before each trial. In the FOP condition, they had to keep looking at the cross until it disappeared and the target appeared. In the FOR condition, they aligned a red cross, corresponding to the HMD centre, with the white cross in the VR before the target appeared. Targets were red or blue spheres shown at random locations, and participants were instructed to click the left or right button according to the target colour, as quickly as possible when they saw the sphere.	Visuospatial functions
Specht *et al.* 2021	In the VR application, users first go through a tutorial to learn navigation and control, including teleporting and grabbing objects. They use hand-controllers to move objects and click buttons in the virtual scene. In the memory game, users must remember and reproduce sequences of flashing lights by clicking buttons in the virtual scene in the correct order using the controllers, with increasing difficulty. In the recycling game, users sort items like glass bottles, milk cartons, and cans into	Executive functions Memory

Author(s)	Task Description	Type of cognitive process
	the correct dustbins by grabbing and moving the items with the controllers. The milk carton and can need to be flattened using a press in the virtual scene before disposal. Correct sorting is indicated by a green light, while incorrect sorting shows a red light.	
Thomasson *et al.* 2024	The VR task immerses participants in a 360° virtual forest using an Oculus Rift DK2 headset. The environment includes realistic stimuli like wind and fire sounds to enhance immersion. The virtual space is divided into six columns, with target and distractor stimuli distributed across them. Participants perform four sub-tasks of increasing difficulty. In Level 1, they use a head-pointer to find 18 static targets and validate them by pressing a button. Levels 2-4 involve finding 36 moving rabbits, with distractors introduced in Level 3. In Level 4, an auditory task is added where participants report hearing a dog bark while ignoring cricket sounds. Participants use the head tracker to control a pointer or light spot and validate selections by pressing the space bar on a keyboard.	Visuospatial functions
Uimonen *et al.* 2024	In the Extinction task, participants viewed an empty room where targets appeared symmetrically in eight quadrants. They verbally reported the position of the targets, and an experimenter verified their responses using VR controllers. In the Storage task, participants searched for a specific target on a storage shelf by maintaining their gaze on it for 2.2 seconds. In the Shoot the Target task, participants in a space station environment searched for targets and selected them by orienting their gaze	Visuospatial functions
Ulm *et al.* 2013	The VR tasks are performed in a cave consisting of eight touch screens arranged in a circle, with a seat in the middle for participants. The system is connected to an external computer, and an investigator controls the session and supervises participants via a video camera. Participants use their right hand to interact with the screens. The assessment lasts 10-15 minutes and includes four tests: Star Cancellation Test: Participants touch large stars displayed among distractors on five screens, aiming for speed and accuracy; Line Bisection: Participants position a slider in the center of horizontal lines displayed on a single screen; Dice Task: Participants arrange large dots on a screen to represent dice spots; Puzzle Test: Participants select and move pieces to reconstruct a figure on the middle screen.	Visuospatial functions
Zhang *et al.* 2001	The VR tasks are performed using the virtual reality software system SOFTHAVEN designed to assess cognitive functions in daily activities. It simulates a kitchen environment where users interact using a computer cursor or touch screen. The system includes a desktop computer, head-mounted display glasses, and stereo sound. It provides visual and auditory cues to help users complete tasks, such as preparing a bowl of soup, which is divided into 30 steps. Each step is scored based on the user's performance, and the software records the number of correct responses and the time taken for each task.	Executive functions

Abbreviations: VR = Virtual Reality; HMD = Head-Mounted Device; FOP = field of perception; FOR = field of regard;

Table S3 - Results of subgroup analysis on categorial moderator variables.

Moderator Variable	**Level**	**k**	**Effect Size**	**95%-CI**	**p-val**	Q_b	**p-val Q**
Task Performance Indicator	Error-based	43	1.16	[1.02; 1.29]	<0.001	11.4	0.003
	Time-based	43	0.97	[0.71; 1.22]	<0.001		
	Body-based	10	0.50	[0.07; 0.93]	0.025		
Distractors	YES	48	0.96	[0.77; 1.15]	<0.001	0.33	0.56
	NO	48	1.04	[0.83; 1.25]	<0.001		

Abbreviations: CI = Confidence Interval

Table S4 - Results of meta-regression on continuous moderator variables.

	Slope	**SE**	**Zval**	**pval**	**95%CI -LB**	**95%CI -UB**
% of Male Patients	0.882	1.20	0.73	0.46	-1.48	3.24
Time Post Onset	-0.01	0.01	-1.18	0.24	-0.03	0.017
Patient Mean Age	-0.02	0.01	-1.66	0.09	-0.05	0.004

Abbreviations: SE = Standard Erro; CI = Confidence Interval; LB = Lower Bound; UB = Upper Bound