A Virtual Reality Serious Game for Cognitive Assessment in Mild Cognitive Impairment and Early Alzheimer's Disease

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Abstract. Introduction: *Mild Cognitive Impairment (MCI) and early-stage Alzheimer's disease are frequently underdiagnosed in primary care despite their high prevalence. Virtual Reality (VR) serious games provide immersive environments that can enhance cognitive assessment through ecologically valid and engaging activities.* ***Objective:*** *This paper presents the design, implementation, and data collection strategy of a Unity-based VR serious game simulating a realistic supermarket, aimed at assessing route learning, spatial memory, and sequential task execution in older adults with suspected MCI or early Alzheimer's disease.* ***Methodology:*** *The system employs a two-phase navigation task (guided route learning followed by autonomous recall) together with interaction and locomotion techniques tailored to older adults, including joystick-based continuous locomotion with head-directed turning and simplified ray-based selection, plus an optional teleport locomotion mode for participants who experience cybersickness.* ***Results:*** *The implemented prototype integrates a configurable supermarket environment, a two-phase NPC-guided and autonomous route-learning task, simplified locomotion and ray-based interaction, and structured telemetry export for movement, head-directed view, timing, and item-interaction events. These outputs establish a reproducible instrument for subsequent feasibility and clinical-validation studies and for future research on AI-based screening support.*
Keywords *Virtual Reality, Serious Games, Mild Cognitive Impairment, Alzheimer's Disease, Cognitive Assessment, Spatial Navigation, Human–Computer Interaction, Healthcare AI.*

1. Introduction

Mild Cognitive Impairment (MCI) is common among older adults, although prevalence estimates vary substantially with age, education, setting, and diagnostic criteria [Salari et al. 2025]. Population aging is also increasing the global burden of dementia [World Health Organization 2026]. MCI describes a clinical state between expected cognitive aging and dementia [Petersen et al. 2014]; the amnestic subtype is associated with increased risk of progression to Alzheimer's disease dementia [Ward et al. 2013, Petersen et al. 2014]. Early detection can support timely clinical evaluation and care planning, yet detection rates remain low in United States Medicare primary care [Liu et al. 2024].

Traditional neuropsychological assessment typically relies on paper-and-pencil tests, which may have limited ecological validity for everyday behavior. In contrast, Virtual Reality (VR) environments provide immersive, controllable, and repeatable simulations of real-world scenarios, enabling detailed behavioral measurement while maintaining experimental control [Parsons 2015]. Prior work employing virtual supermarket and shopping tasks has shown that such scenarios can discriminate between cognitively healthy older adults and individuals with MCI, particularly in the context of early screening and game-based assessments [Zygouris et al. 2015, Yan et al. 2021, Porffy et al. 2022].

However, many published virtual shopping assessments emphasize aggregate task outcomes rather than continuously sampled interaction telemetry [Yan et al. 2021, Iliadou et al. 2021, Porffy et al. 2022], use desktop or tablet-based setups, or treat route learning and spatial memory as secondary outcomes. Usability constraints for older adults, including cybersickness [Porcino et al. 2022] and unfamiliar VR controllers [Baker et al. 2020], also remain challenging. At the same time, machine learning is increasingly used to classify MCI and early Alzheimer's disease from high-dimensional clinical, neuroimaging, and neuropsychological data [Zhang et al. 2021, Kurbalija et al. 2023, Liu et al. 2025].

This paper presents a VR serious game developed in Unity using the XR Interaction Toolkit, which simulates a supermarket environment for the assessment of route learning, short-term spatial memory, and sequential task execution. The primary contributions are:

- A system architecture and interaction model for a location-based VR serious game designed to support route learning and item-sequencing tasks in older adults.
- An accessibility-oriented interaction design that incorporates locomotion and interaction techniques tailored to the constraints of older VR users.
- A comprehensive data collection and metrics framework that captures spatial trajectories, head-directed view, interaction events, and error patterns, enabling future research on AI-based classification and screening support.

The supermarket scenario was chosen because grocery shopping is a familiar instrumental activity of daily living that combines route learning, prospective memory, and sequential planning. Full head-mounted immersion was adopted to support naturalistic head-directed scanning and embodied navigation, while prior work indicates that immersive spatial-orientation tasks can capture egocentric and allocentric navigation behavior [Costa et al. 2022, Hořejší et al. 2025]. Other space-oriented scenarios, such as malls, mazes, or parks, could be recreated using the same design logic.

2. Related Work

This section summarizes the literature on VR cognitive assessment, serious games for MCI and Alzheimer's disease, and usability challenges for older adults.

2.1. VR-based cognitive assessment and digital markers

VR and other digital technologies have been used for cognitive assessment by deriving markers from interaction traces, sensor streams, or multimodal inputs, often analyzed with machine learning. Studies have used high-dimensional neuropsychological, imaging, and behavioral markers to distinguish MCI and Alzheimer's disease from controls [Kurbalija et al. 2023, Zhang et al. 2021], while shopping and navigation tasks combine memory, executive function, and attention demands in a single scenario [Porffy et al. 2022, Yan et al. 2021]. Deep learning has also been applied to multimodal images and metadata, although often without ecologically grounded task design [Han et al. 2024]. Closer to the present work, SOIVET derives spatial-navigation markers with concurrent validity and moderate accuracy for discriminating MCI from controls [Costa et al. 2018b, Costa et al. 2022].

2.2. VR supermarket and shopping tasks

Supermarket and shopping environments have been used to assess cognition in older adults, including game-based tests that distinguish participants with MCI from comparison groups through measures related to learning, memory, executive functions, and attention [Yan et al. 2021, Iliadou et al. 2021]. Similar paradigms in research and clinical contexts show the value of embedding assessment in everyday activities and capturing behavioral metrics [Porffy et al. 2022]. However, several implementations use desktop or tablet-based interaction, report mainly aggregate performance measures, and rarely treat route learning and route recall as central outcomes.

2.3. Spatial navigation and route-learning in VR

Spatial orientation and route-learning deficits are among the earliest cognitive changes in Alzheimer's disease and amnestic MCI. SOIVET [Costa et al. 2018b] was proposed as immersive VR tasks for these processes: initial studies reported high presence, tolerability, and usability, and later case-control results showed correlations with conventional neuropsychological measures and moderate accuracy in separating MCI from healthy controls [Costa et al. 2022]. Related work found that an immersive VR maze correlated more strongly with self-reported sense of direction than the paper Money Road-Map Test [Costa et al. 2018a], and component studies confirmed the applicability and short-term stability of SOIVET-Maze and SOIVET-Route in older adults with and without MCI [Silva et al. 2023, Santos et al. 2022].

VR locomotion studies also show trade-offs between cybersickness and spatial orientation. Teleportation can reduce cybersickness but impair spatial orientation relative to continuous controller-based locomotion [Hořejší et al. 2025]. Motivated by these findings, the present work adopts continuous joystick locomotion to support route learning and spatial updating, with optional teleportation as an accommodation for participants who report discomfort. This design also reflects the need for careful monitoring of cybersickness in older adults [Li et al. 2025].

2.4. Usability of VR for older adults

Older adults are susceptible to cybersickness and may have difficulty with complex controllers or extended VR exposure. VR studies in nursing homes report low but non-negligible cybersickness and occasional drop-out, supporting short sessions, clear multimodal instructions, and careful monitoring [Li et al. 2025, Costa et al. 2018b]. The present system applies these principles through continuous joystick locomotion with optional teleportation, limited controller input, two ray-based interaction modes, and short tasks of increasing difficulty.

2.5. Gaps identified in prior work

The literature reviewed during the design phase indicated four recurring gaps: limited route-learning tasks in ecologically valid environments, insufficient fine-grained telemetry, under-addressed usability concerns for older adults, and limited integration between HCI design and downstream AI pipelines. The present system addresses these gaps by combining a supermarket-based route-learning task, older-adult-centered interaction, and detailed telemetry logging. Compared with desktop or semi-immersive virtual-supermarket tools where navigation is secondary [Yan et al. 2021, Iliadou et al. 2021], and immersive spatial-orientation systems based on abstract mazes or routes [Costa et al. 2018b, Costa et al. 2022], this work combines head-mounted immersion, an everyday scenario, and route reproduction as the primary outcome.

3. Methodology

3.1. System architecture

The system is implemented in Unity using the XR Interaction Toolkit and is organized into modular subsystems for environment management, NPC guidance, task management, interaction handling, telemetry logging, and user interface (Figure 1).

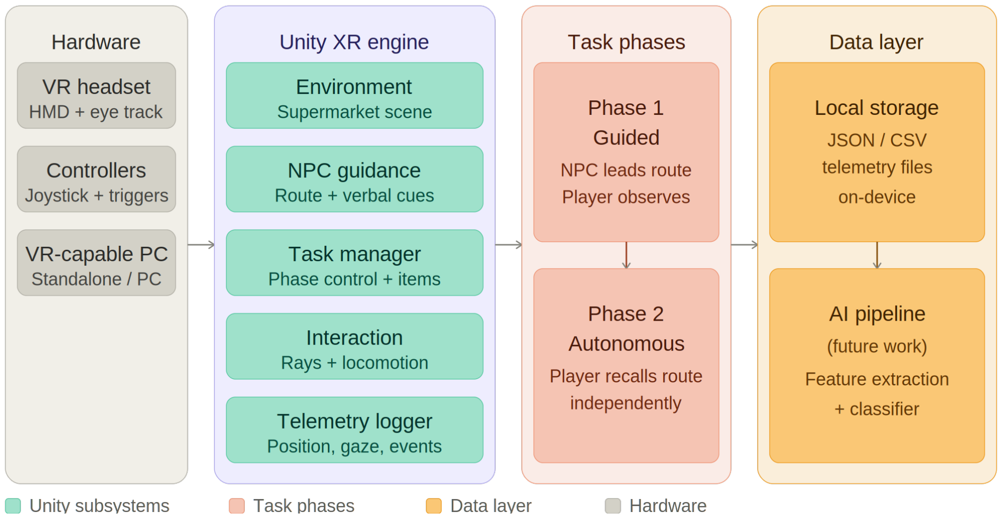

Figure 1. High-level system architecture: VR client, NPC/task controller, telemetry logging, and data export for offline analysis.

The system runs locally on a VR-capable device (e.g., standalone headset or PC-based VR), with all telemetry logs stored on-device in structured files for subsequent offline analysis.

3.2. VR supermarket environment design

The virtual environment simulates a medium-sized supermarket with aisles, shelves, product categories, and a checkout area. Salient visual landmarks, such as signage and color-coded sections, are consistent with design features used in prior virtual shopping tasks [Yan et al. 2021, Porffy et al. 2022]. Routes are short and confined to selected aisles to reduce fatigue while engaging spatial memory, and environmental complexity can be parameterized to adjust task difficulty (Figure 2).

Figure 2. Top-down view of the virtual supermarket environment.

3.3. Route-learning and recall task design

The core assessment consists of a two-phase navigation task designed to probe route learning, spatial memory, and sequential task execution.

Guided phase: An NPC leads the player along a predefined route, stopping near each target item and verbally indicating that this is an item that should later be collected, while at the beginning of the task, explicitly informing the participant that the route should be reproduced as closely as possible during the subsequent autonomous phase. The player observes the path and item locations but does not perform autonomous navigation. Key landmarks are placed near decision points to support landmark-based navigation strategies. Figure 3 illustrates the NPC guiding the player and verbally indicating the target items.

Autonomous recall phase: The NPC is removed and the player must reproduce the same route independently, collecting items in the correct order from the same starting position. The system records the player's trajectory, deviations from the original route, dwell times at intersections, item selections (correct and incorrect), and temporal order of interactions. The task ends when all items are collected. If a participant chooses to stop before completing the route, the task can be manually terminated by the examiner and the partial data are still logged.

3.4. Interaction techniques

The interaction model minimizes complexity while supporting reliable item selection. Joystick-based continuous locomotion is the primary movement technique, with head-oriented rotation and optional teleportation for participants who report discomfort. Evidence on locomotion trade-offs and tolerability in older adults informed this design [Hořejší et al. 2025, Li et al. 2025, Costa et al. 2018b]. Controller input is limited to locomotion, optional teleport activation, and ray triggering. Two ray modes are available:

Figure 3. NPC guiding the player along the route, verbally indicating which items should be collected.

a fingertip ray for precise point-and-select interactions and a palm-based ray for steadier pointing. Items are selected by ray intersection and trigger press, with visual highlighting and auditory confirmation (Figure 4).

Figure 4. Ray-based item selection: players interact with items at a distance using a ray pointer, without requiring physical proximity.

3.5. Accessibility and adaptation for older adults

Table 1 summarizes accessibility decisions based on evidence that cybersickness, fatigue, and controller unfamiliarity are barriers for older adults [Costa et al. 2018b, Li et al. 2025]. The system uses short sessions, joystick locomotion with head-based rotation and optional teleportation [Hořejší et al. 2025], simplified input, multimodal instructions, and error-tolerant logging.

3.6. Implementation status

Table 2 separates implemented prototype components from planned work. The contribution claimed here is the implemented instrument—architecture, older-adult-centered interaction, and telemetry-and-metrics framework—whereas empirical validation and the AI classifier are future work (Section 7).

4. Data Collection and Metrics

The current prototype captures movement, head-directed view, interaction, and timing telemetry during both phases. Interaction events are timestamped relative to session start,

Table 1. Accessibility and usability design decisions.

Design Decision	Motivation	Reference
Short sessions	Reduce exposure burden and support tolerability	[Li et al. 2025, Costa et al. 2018b]
Teleport locomotion	Provide an alternative when continuous locomotion causes discomfort	[Hořejší et al. 2025]
Head-based rotation	Maintain a simple, view-directed turning scheme	—
Simplified controller input	Reduce cognitive and motor demands	[Baker et al. 2020, Costa et al. 2018b]
Two ray-based modes	Accommodate motor differences	—
Multimodal instructions	Support sensory/cognitive limits	[Costa et al. 2018b]
Error-tolerant logging	Reduce stress, preserve data	—

while continuous streams (player position and head/camera data) are sampled at a configurable interval, currently 0.5 s (2 Hz). Records are stored as newline-delimited JSON for append-safe writing and offline parsing. The same schema is designed to accommodate gaze vectors or fixation points after compatible eye-tracking hardware is integrated in future work.

4.1. Raw data streams

- **Player movement:** 3D position over time, enabling trajectory reconstruction and spatial deviation analysis.
- **Head-directed view:** Camera look-at point from the headset forward ray, supporting scanning-pattern and disorientation analysis independent of eye tracking.
- **Planned eye-tracking stream:** When compatible hardware is integrated, gaze vectors or fixation points will support attention-allocation analysis.
- **Interaction events:** Timestamp, item identifier (-1 for invalid interactions), correctness, and intended sequence position.
- **Task timing:** Completion time, phase durations, and dwell times at key zones.

4.2. Derived metrics

Table 3 summarizes the derived metrics computed from raw data.

These metrics support both traditional statistical group comparisons and feature extraction for machine learning models.

5. Discussion

The design addresses the gaps identified in Section 2 across ecological validity, usability, data richness, and AI-oriented analysis.

Table 2. Implemented components versus planned future work.

Implemented in this prototype	Planned (future work)
Supermarket environment, start menu, and tutorial scenes	AI-based analysis pipeline (feature extraction and classifiers)
Two-phase task: NPC-guided route with per-waypoint narration and visual item highlighting/arrows, plus autonomous recall with ordered collection, error counting, and completion detection	Feasibility/usability pilot and clinical validation with healthy older adults and MCI patients
Joystick continuous locomotion with head-directed rotation and optional teleport mode	Encrypted data transmission, electronic-health-record integration, and data-protection governance
Two ray-based interaction modes; item selection with visual highlight, audio confirmation, and VFX	Adaptive route difficulty based on ongoing performance
Telemetry layer: event-driven grab/interaction logging and fixed-interval position and camera recorders, written as newline-delimited JSON	Eye-tracking/gaze capture and multi-modal, explainable models
Editor-side heatmap visualization of the logged data	

5.1. Ecological validity and route learning

Embedding assessment in a realistic supermarket supports ecologically grounded spatial-orientation measures. Unlike systems where navigation is secondary to item selection, the two-phase design makes route reproduction the central outcome and records head-directed scanning and locomotion behavior relevant to allocentric and egocentric orientation [Porffy et al. 2022, Yan et al. 2021, Costa et al. 2018b]. Comparing guided and autonomous phases can reveal error patterns such as wrong turns and repeated backtracking.

5.2. Usability and data richness

The system balances older-adult usability (short sessions, simplified controls, multimodal instructions, and optional teleportation) with detailed behavioral telemetry [Costa et al. 2018b, Li et al. 2025, Hořejší et al. 2025]. This provides a richer behavioral record than assessments that report only aggregate completion time, score, or error counts.

5.3. Positioning with respect to AI-based classification research

The system complements neuroimaging, EEG, and neuropsychological approaches [Kurbalija et al. 2023, Ge et al. 2025] by providing behavioral markers tied to everyday difficulties. Although machine and deep learning models can distinguish MCI and Alzheimer's disease from controls using biomedical data [Zhang et al. 2021, Han et al. 2024, Liu et al. 2025], this work provides older-adult-oriented infrastructure—full immersion, short progressive tasks, flexible locomotion, and structured telemetry—on which such models can later be built.

Table 3. Derived metrics with definitions and cognitive interpretations.

Metric	Definition	Cognitive Interpretation
Path deviation	Mean/max distance from guided route	Route learning / disorientation
Navigation errors	Wrong aisles, backtracking count	Spatial memory deficits
Route completion	Binary success + time required	Overall spatial recall
Sequence accuracy	Levenshtein distance to target order	Executive function / planning
Item error count	Incorrect + missed items	Memory for item identity
Hesitation time	Dwell time at decision points	Decision uncertainty
Inter-item interval	Time between correct selections	Processing speed
View revisit rate	Repeated head-directed looks toward visited areas	Search inefficiency

6. Limitations

Several limitations should be noted. First, the system focuses on one environment type and task structure; additional scenarios may be needed for broader ecological assessment. Second, empirical validation with clinical populations has not yet been conducted, so usability and tolerability must be tested in line with prior VR studies on spatial orientation and cybersickness in older adults [Costa et al. 2018b, Li et al. 2025]. Third, the AI pipeline is conceptual and will require sufficient samples, confound handling, and clinical-workflow integration. Planned analyses will record prior VR familiarity, age, education, motor ability, visual impairment, cybersickness susceptibility, and supermarket familiarity as metadata; design choices such as optional teleportation, short sessions, simplified rays, and error-tolerant logging already mitigate some of these factors (Table 1). Finally, hardware and logistical constraints may limit scalability in resource-constrained healthcare settings.

7. Conclusion and Future Work

This paper presented a VR serious game for cognitive assessment in older adults, targeting route learning, spatial memory, and sequential task execution in a supermarket environment. Grounded in the reviewed literature, it combines an ecologically valid task, older-adult-centered interaction, and fine-grained telemetry on movement, head-directed view, timing, and item interactions, laying the groundwork for future AI-based screening and classification studies. Future work is organized around AI-based analysis, clinical integration, and empirical validation.

7.1. AI-based analysis pipeline (immediate next step)

The immediate continuation will implement and evaluate a research-oriented AI pipeline using logged gameplay data to investigate patterns associated with MCI or early Alzheimer's disease. Following machine-learning studies on neuropsychological, imaging, and behavioral markers [Kurbalija et al. 2023, Zhang et al. 2021] and graph-based early MCI detection [Liu et al. 2025], telemetry will be transformed into summary features, temporal sequences, and trajectory maps. Initial experiments will use conventional classifiers, followed by sequence and graph-based models for route-learning behavior.

7.2. Data transmission and clinical integration

A second direction concerns clinical deployment. Although the current prototype stores telemetry locally, future deployments may require secure transmission to hospital or clinic servers. Future work will investigate encrypted streaming, electronic-health-record synchronization, and data-protection governance.

7.3. Validation and longitudinal studies

Additional work includes empirical validation with healthy older adults and MCI patients; adaptive route difficulty; multimodal models combining gameplay, EEG, or neuropsychological scores [Ge et al. 2025, Han et al. 2024]; clinician-facing explainability tools; longitudinal studies on progression from MCI to Alzheimer's disease; and eye-tracking integration for fixation and revisit markers.

Ethics Statement

This paper reports the design and implementation of the assessment instrument; no data from human participants were collected for it. The study protocol for the planned data collection with human participants has been submitted to the research ethics committee and is awaiting approval. Data collection with participants, the feasibility/usability pilot, clinical validation, and the evaluation of any AI-based classifier will proceed only after this approval is obtained.

Data and Code Availability

To support reproducibility, the public repository (`https://github.com/Yunguer/project-mci-sbgames`) provides the VR serious game source code, a demonstration video, a reproducible sample session with raw logs and derived metrics, and setup documentation.

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