TESIS DE LA UNIVERSIDAD
DE ZARAGOZA

2025

215

Jorge Luis Buele León

Soluciones tecnológicas basadas en actividades de la vida diaria para la evaluación y el entrenamiento cognitivo en pacientes con enfermedades neurodegenerativas

Director/es
Palacios Navarro, Guillermo

ISSN 2254-7606

Prensas de la Universidad
Universidad Zaragoza

Universidad de Zaragoza
Servicio de Publicaciones

ISSN 2254-7606

Universidad Zaragoza
1542

Tesis Doctoral

SOLUCIONES TECNOLÓGICAS BASADAS EN ACTIVIDADES DE LA VIDA DIARIA PARA LA EVALUACIÓN Y EL ENTRENAMIENTO COGNITIVO EN PACIENTES CON ENFERMEDADES NEURODEGENERATIVAS

Autor

Jorge Luis Buele León

Director/es

Palacios Navarro, Guillerno

UNIVERSIDAD DE ZARAGOZA
Escuela de Doctorado

2025

Tesis Doctoral

Por Compendio de Publicaciones

Soluciones tecnológicas basadas en actividades de la vida diaria para la evaluación y el entrenamiento cognitivo en pacientes con enfermedades neurodegenerativas

Autor

Jorge Luis Buele León

Director

Dr. Guillermo Palacios Navarro

Departamento de Ingeniería Electrónica y Comunicaciones

2025

AGRADECIMIENTOS

Agradezco profundamente a Dios, por las oportunidades y bendiciones que me ha brindado en cada paso de este camino.

Quiero expresar mi más sincero reconocimiento a mi director de tesis, el Dr. Guillermo Palacios, por confiar en mí e invitarme a soñar con llegar a esta meta que personalmente no creía posible. Gracias por el respaldo, por la dedicación y compromiso conmigo y mi familia.

A mi esposa Fátima, quien ha estado a mi lado durante estos años de estudio, en el desarrollo de los experimentos y en los momentos de sacrificio. Me ha brindado su apoyo incondicional y es mi mayor fuente de motivación y la amo por eso.

A mis padres, Luis y Anita, por formar en mí un espíritu de lucha y responsabilidad que me ha impulsado a seguir adelante. A mi hermano Pablo, por su apoyo incondicional y constante. Su amor y enseñanzas han contribuido en mi vida, y les debo gran parte de lo que hoy soy.

Al Dr. José Varela, un gran amigo que no solo me ha ayudado con la parte técnica de esta investigación, sino que me ha mostrado su respaldo durante estos años. Estoy muy agradecido por su generosidad que ha enriquecido mi vida personal y profesional.

A mis amigos, compañeros de trabajo, estudiantes y a todos los participantes de los estudios. Su colaboración y disposición permitieron el desarrollo de esta tesis.

CONTENIDOS

LISTA DE FIGURAS

LISTA DE TABLAS

RESUMEN

El deterioro cognitivo en adultos mayores es un desafío creciente en geriatría, ya que impacta de manera negativa en la capacidad para realizar actividades de la vida diaria, limitando su independencia. Estas actividades, como preparar alimentos, tomar medicamentos o realizar compras, requieren habilidades cognitivas complejas como la memoria, la atención y la planificación. Aunque la neurociencia ha tenido avances en la comprensión de este deterioro, todavía se necesitan herramientas de evaluación e intervención que sean realistas y aplicables en entornos cotidianos para promover mejoras funcionales. Esta tesis presenta un compendio de publicaciones centrado en el desarrollo y evaluación de aplicaciones tecnológicas, con énfasis en la realidad virtual como herramienta innovadora. Esta investigación incluyó el diseño de un ejercicio de cribado cognitivo en un entorno real, utilizando sensores inteligentes, que simuló una actividad de la vida diaria. Posteriormente este fue adaptado a un entorno de realidad virtual inmersivo para el cribado cognitivo y como parte de una intervención dual que integra tanto aspectos motores como cognitivos. Los resultados de esta tesis muestran que la integración de la tecnología permite una evaluación precisa de funciones cognitivas como la atención y memoria. Los participantes que fueron parte del experimento en el entorno virtual presentaron mejoras en su cognición y estado emocional, lo cual respalda la evidencia actual sobre el uso de la realidad virtual como una herramienta innovadora y segura. La investigación desarrollada en esta tesis establece una base sólida para futuras aplicaciones clínicas más ecológicas y adaptadas a las necesidades del usuario. Además, se detallan los componentes necesarios para implementar estas intervenciones, incluyendo la frecuencia, duración de las sesiones y el nivel de inmersión requerido.

ABSTRACT

Cognitive impairment in older adults is a growing challenge in geriatrics, as it negatively impacts the ability to perform activities of daily living, limiting their independence. These activities, such as preparing food, taking medication or shopping, require complex cognitive skills such as memory, attention and planning. Although neuroscience has made progress in understanding this impairment, assessment and intervention tools that are realistic and applicable in everyday environments are still needed to promote functional improvements. This thesis presents a compendium of publications focused on the development and evaluation of technological applications, with an emphasis on virtual reality as an innovative tool. This research included the design of a cognitive screening exercise in a real environment, using smart sensors, which simulated an activity of daily living. This was later adapted to an immersive virtual reality environment for cognitive screening and as part of a dual intervention that integrates both motor and cognitive aspects. The results of this thesis show that the integration of technology allows for an accurate assessment of cognitive functions such as attention and memory. Participants who took part in the experiment in the virtual environment showed improvements in their cognition and emotional state, which supports the current evidence on the use of virtual reality as an innovative and safe tool. The research developed in this thesis establishes a solid foundation for future clinical applications that are more ecological and adapted to the needs of the user. In addition, the components necessary to implement these interventions are detailed, including the frequency, duration of the sessions and the level of immersion required.

INTRODUCCIÓN 1

1.1. Introducción general

Este capítulo ofrece una visión general de la investigación llevada a cabo en esta tesis, con el contexto, una revisión bibliográfica de los conocimientos previos, las preguntas y objetivos de investigación y los resultados más relevantes de las publicaciones incluidas en el compendio.

1.1.1. Deterioro cognitivo

A medida que la esperanza de vida aumenta en muchas regiones del mundo, surge un desafío importante: vivir más años no siempre significa que se tenga una buena calidad de vida. Con el envejecimiento de la población, los casos de deterioro cognitivo aumentan, pasando de un proceso de envejecimiento normal hacia formas patológicas de deterioro. Entre estos, existen estados intermedios como el deterioro cognitivo leve (DCL), donde las personas experimentan una disminución en la memoria o en otras funciones cognitivas, pero en algunos casos conservan su independencia. Sin intervención, el DCL puede progresar hacia formas más graves de demencia. Según un estudio publicado por *The Lancet: Public Health*, en 2019 se estimó que 57 millones de personas vivían con demencia en todo el mundo, y se proyecta que esta cifra aumente a 153 millones para el año 2050 [1].

La demencia es un término que abarca diversas condiciones clínicas como la enfermedad de Alzheimer (EA), el Parkinson, la demencia vascular, la demencia frontotemporal, la enfermedad de Huntington y la demencia por cuerpos de Lewy, cada una con sus causas y factores de riesgo específicos. Iribarne et al. [2] señalan que el Alzheimer es la causa más común de demencia, representando el 80% de los casos en personas mayores de 65 años, seguido de la demencia vascular, la frontotemporal y la de cuerpos de Lewy. Según la revisión de Zhang et al. [3], el Alzheimer en sus primeras etapas lidera entre las causas de demencia, abarcando entre el 50% y el 70% de los casos. Asimismo, se debe puntualizar que si bien el Alzheimer es la causa principal de demencia diagnosticada clínicamente en los países occidentales, la demencia vascular podría ser más frecuente en el este de Asia [4]. Aunque no se conoce una cura definitiva para la demencia, existen tratamientos disponibles que pueden mejorar algunos síntomas, dependiendo de la etapa de la enfermedad en la que se encuentre la persona [5].

1.1.2. Funciones cognitivas

Las funciones cognitivas son habilidades que se necesitan para llevar a cabo cualquier tarea, independientemente de su complejidad. Permiten almacenar, comprender y relacionar la información que proporcionan los sentidos y ser usada en el presente o en el futuro para realizar tareas. Están relacionadas con los mecanismos de aprendizaje, recuerdos, resolución de problemas, prestar atención, etc. [6]. Dentro de las mismas se incluyen la percepción, la atención, la conciencia, el lenguaje, la memoria, las funciones ejecutivas (FE), entre otras.

La atención es un proceso mental que permite enfocar los recursos cognitivos en estímulos específicos, filtrando la información irrelevante y priorizando aquello que es importante según la tarea [6], [7]. Las personas con trastornos de atención suelen tener dificultades para ignorar estímulos irrelevantes, lo que puede provocar una sobrecarga de información [8]. La capacidad de enfocar, mantener y alternar la atención se manifiesta en los diferentes tipos de atención: selectiva, dividida, sostenida y alterna. Cada una de estas se utiliza en diferentes situaciones y contextos cognitivos, lo que asegura una gestión eficiente de los recursos mentales [6], [9].

La memoria es otra función que complementa la atención, permitiendo la retención y recuperación de experiencias pasadas, así como el aprendizaje y la adaptación [9]. Entre sus sistemas, la memoria episódica destaca por almacenar eventos específicos con detalles contextuales y emocionales, pero es la primera en declinar durante el envejecimiento normal o patológico [10], [11]. Los cambios neurofibrilares iniciales en la demencia afectan estructuras del lóbulo temporal medial, como el hipocampo y la corteza entorrinal, interrumpiendo redes neuronales y deteriorando la memoria episódica. Esto limita la capacidad de relacionarse con el entorno, afectando identidad y conexión con el pasado. Por otro lado, el lenguaje y la memoria semántica sostienen la interacción social y el razonamiento complejo. Esta última almacena conocimientos generales, independientes de experiencias personales, esenciales para la comunicación y comprensión del entorno [12]. En la demencia, se pierden asociaciones semánticas, esto dificulta el acceso a palabras y conceptos, afectando la fluidez verbal y la resolución de problemas cotidianos [13].

Las funciones ejecutivas y la memoria de trabajo son responsables de la manipulación de la información en el presente y la planificación futura. Estas habilidades de orden superior, que incluyen el control inhibitorio, la flexibilidad cognitiva y el razonamiento, son la base del comportamiento orientado a metas [13]. Cuando estas funciones comienzan a deteriorarse, como en el caso de la demencia, la persona experimenta dificultades para organizar actividades, tomar decisiones y adaptar su comportamiento a nuevos contextos. El modelo de memoria de trabajo de Baddeley [14], con componentes como el bucle fonológico y el bloc de dibujo visual, ilustra cómo estas funciones colaboran para mantener activa la información relevante, que se usa en la resolución de problemas en tiempo real [12]. La memoria de trabajo interactúa constantemente con la memoria a largo plazo, facilitando el aprendizaje y la adaptación a situaciones nuevas, permitiendo el desarrollo personal y profesional a lo largo de la vida.

Por otro lado, las habilidades visoespaciales permiten al individuo interpretar y moverse eficazmente en el espacio, están presentes en la navegación y la percepción de profundidad [15]. Cuando aparecen los trastornos cognitivos, la capacidad visoespacial puede reducirse, haciendo que tareas como la búsqueda visual se vuelvan desafiantes y requieran tiempos de respuesta prolongados. Esto puede ser debido a problemas de atención y procesamiento en áreas cerebrales específicas encargadas de la percepción visual [16]. La reducción en la detección de movimiento y en el reconocimiento de objetos sugiere que estas dificultades visoespaciales podrían usarse como un marcador temprano de deterioro cognitivo, ya que afectan la interacción con el entorno. Este deterioro puede limitar la independencia de la persona, ya que impacta en el desarrollo de sus actividades cotidianas.

1.1.3. Actividades de la vida diaria

Las actividades de la vida diaria (AVD) son acciones que el ser humano realiza en su día a día relacionadas con el autocuidado, alimentación, vestimenta y mantener la higiene personal. Cuando las capacidades visoespaciales y otras funciones cognitivas comienzan a deteriorarse, estas tareas se vuelven cada vez más desafiantes [17]. Se pueden clasificar en dos subgrupos: actividades básicas de la vida diaria (ABVD) y actividades instrumentales de la vida diaria (AIVD), aunque algunos autores también mencionan que existen las actividades avanzadas (AAVD) [18].

Según la Asociación Americana de Terapia Ocupacional (AOTA), existen 11 actividades instrumentales de la vida diaria (AIVD) que son más complejas, y por lo tanto, pueden representar un desafío para algunos adultos mayores [19]. Estas actividades incluyen: (i) cuidado de otras personas; (ii) cuidado de mascotas y animales; (iii) crianza de hijos; (iv) gestión de la comunicación; (v) conducción y movilidad en la comunidad; (vi) gestión financiera; (vii) organización y mantenimiento del hogar; (viii) preparación y limpieza de comidas; (ix) expresión religiosa y espiritual; (x) mantenimiento de seguridad y manejo de emergencias; y (xi) compras. Por su naturaleza, requieren habilidades motoras y cognitivas avanzadas, además de una buena adaptación al entorno, planificación y resolución de problemas. Aunque no son fundamentales para la supervivencia, estas actividades permiten a la persona desenvolverse de manera autónoma en su entorno, sin requerir asistencia constante.

Por esto, las AIVD son especialmente vulnerables a los déficits cognitivos que se agravan con el avance de enfermedades neurodegenerativas. En las etapas iniciales de la demencia, la memoria episódica se ve afectada, lo que impide que las personas recuerden eventos recientes o adquieran nueva información. En etapas más avanzadas, los déficits se extienden a la memoria semántica, el lenguaje, las habilidades visuoespaciales y afectan el desarrollo de las AIVD [20], [21]. La pérdida de estas capacidades impacta negativamente en el bienestar emocional y puede llevar al aislamiento social, acelerando el deterioro cognitivo y afectando significativamente la calidad de vida [18]. La incapacidad para completar AVD básicas, como bañarse o vestirse, señala una fase avanzada de la enfermedad y la necesidad de cuidados más intensivos.

1.1.4. Tecnología en el diagnóstico cognitivo

Para identificar la aparición de problemas en las funciones cognitivas, se han desarrollado diferentes instrumentos destinados a su evaluación. Estas pruebas permiten la detección temprana de trastornos en dichas funciones [22]. En neuropsicología, las pruebas de lápiz y papel se emplean actualmente para realizar un cribado o evaluación rápida de habilidades cognitivas como la memoria, atención y lenguaje. Ejemplos destacados incluyen el evaluación cognitiva de Montreal (MoCA) [23], el examen mini-mental (MMSE) [24], la prueba de modalidades de símbolos y dígitos (SDMT) [25], la prueba de aprendizaje auditivo verbal de Rey (RAVLT) [26], cuestionario de memoria multifactorial (MMQ) [27] y la prueba de trazado de caminos (TMT) [28], todos útiles para obtener una visión general de la cognición humana [29].

El MoCA es una herramienta diseñada para detectar deterioro cognitivo leve, es valorada por su capacidad de evaluar memoria, habilidades visuoespaciales, atención y lenguaje y cuenta con varias adaptaciones culturales y lingüísticas [23]. Otro test que resalta es el Mini-Examen Cognoscitivo (MEC-35), el cual cuenta con una alta confiabilidad (r=0,87; p<0,001) que permite discriminar pacientes con déficit cognitivos de aquellos que tienen rendimiento normal [30]. Por su parte, el MMSE, es ampliamente utilizado en contextos clínicos, aunque su sensibilidad puede verse limitada en personas con bajo nivel educativo o diferencias culturales marcadas [24]. Para complementar esta evaluación, se pueden incorporar otras pruebas ampliamente utilizadas. La escala breve de depresión geriátrica (SGDS) es adecuada para identificar síntomas de depresión [31], mientras que la escala de AIVD de Lawton y Brody [32] evalúa la capacidad para realizar actividades cotidianas, como el manejo de finanzas o la preparación de alimentos.

A pesar de su utilidad, Na et al. [33] señalan que las pruebas estandarizadas, en especial las de evaluación cognitiva general, pueden no ser lo suficientemente sensibles ni precisas para detectar de manera temprana enfermedades como la EA, limitando así su efectividad en las primeras etapas. Además, algunas de estas evaluaciones son percibidas como invasivas, generando incomodidad y estigma, lo que puede llevar a que los pacientes eviten realizarlas. Esto obstaculiza la detección temprana y por ende, el inicio oportuno del tratamiento [34]. Estas limitaciones ponen en evidencia la necesidad de contar con herramientas más aceptables y representativas.

Un aspecto asociado a estas deficiencias es su baja validez ecológica. Este concepto, se refiere a la correspondencia entre los resultados obtenidos en las evaluaciones y el desempeño del participante al realizar AVD [35]. Según Chaytor y Schmitter-Edgecombe [36], la utilidad de las pruebas no solo debe medirse en términos de resultados clínicos, sino también por su capacidad para predecir las dificultades que los pacientes enfrentan en su día a día [37]. Sin embargo, sus hallazgos mostraron que algunos participantes que obtuvieron buenos resultados en las pruebas estandarizadas, presentaron deficiencias significativas al realizar sus actividades diarias [37].

Actualmente, los instrumentos de evaluación pueden apoyarse en la tecnología, mejorando la eficacia de los resultados. En 2002 ya aparecieron instrumentos computarizados, como el test de acción naturalista, propuesto por Schwartz et al. [38]. Los resultados indicaron que los errores de omisión se asociaron con problemas en la memoria episódica, mientras que los errores de comisión reflejaron alteraciones en las funciones ejecutivas. Aunque este enfoque se aplicó en contextos reales, también se señalaron limitaciones, como la falta de atractivo y efectividad en comparación con herramientas tecnológicas más avanzadas [39].

O'Leary et al. [40] desarrollaron una plataforma con pantalla táctil para evaluar la cognición, demostrando ser mejor que los laberintos tradicionales al permitir comparaciones directas con pruebas neuropsicológicas estandarizadas. Pitteri et al. [41] crearon un videojuego diseñado para detectar deterioro cognitivo en la velocidad de procesamiento de la información. Los resultados revelaron que aquellos pacientes con esclerosis múltiple mostraron un menor desempeño en comparación con los sanos. Se encontraron correlaciones significativas con el SDMT, confirmando su validez como herramienta diagnóstica. Por su parte, Khaligh-Razavi et al. [42] desarrollaron una prueba cognitiva basada en tecnología móvil para evaluar la velocidad y precisión del procesamiento visual, con una duración de solo 5 minutos. Esta herramienta, orientada a la detección temprana de alteraciones cognitivas en trastornos como la demencia, mostró una precisión comparable con el MMSE o MOCA.

1.1.5. Realidad virtual en el diagnóstico cognitivo

En este contexto, realidad virtual (RV) surge como una tecnología emergente con un alto potencial para aumentar la validez ecológica en la evaluación cognitiva. La RV consiste en la creación de entornos simulados generados por computador que buscan replicar situaciones del mundo real de manera interactiva e inmersiva. Popularizada a finales de la década de los años 2000, esta tecnología ha despertado un creciente interés en diversos campos del conocimiento, incluida la neuropsicología [35] (Figura 1).

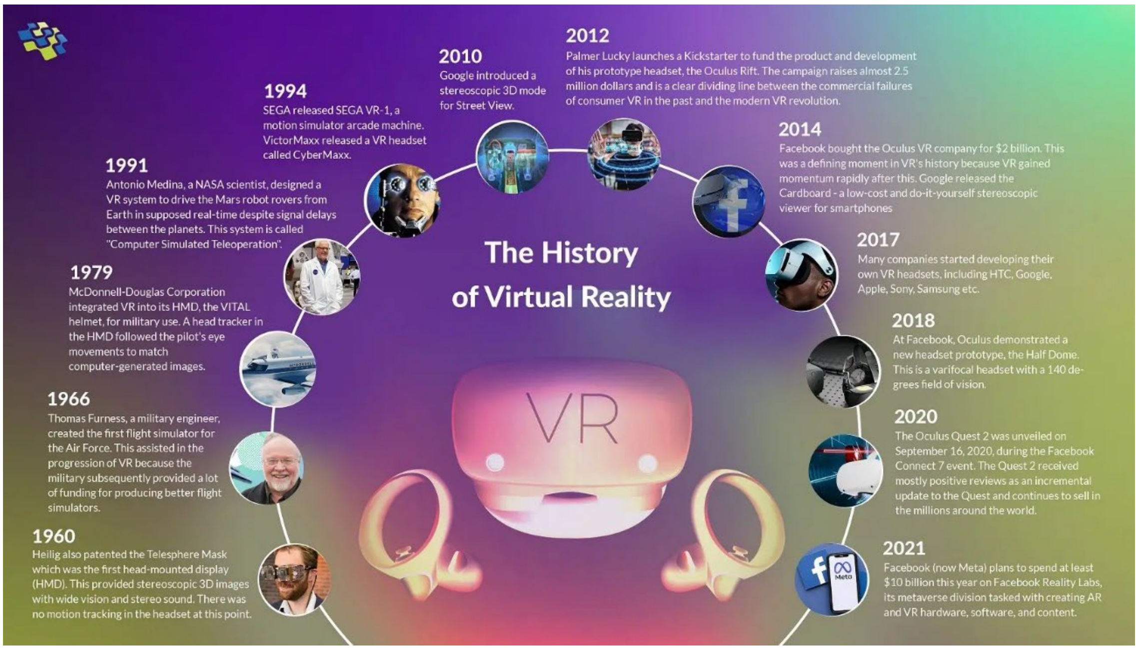


Figura 1. Evolución de la realidad virtual [43].

En la evaluación cognitiva mediante RV, el nivel de inmersión es un parámetro que define la interacción del usuario con el entorno virtual. Según el grado de inmersión, las aplicaciones se pueden clasificar en no inmersivas, semi-inmersivas e inmersivas, cada una con características específicas que se ajustan a lo que se desea medir. Las propuestas no inmersivas se desarrollan en entornos con interacción limitada, donde no se genera una sensación de presencia total. Estas actividades suelen utilizar pantallas como computadoras o tablets, ofreciendo un enfoque más accesible para participantes con restricciones físicas o tecnológicas.

Por otro lado, las aplicaciones semi-inmersivas combinan elementos visuales y sensoriales más avanzados, como proyectores panorámicos, sistemas de audio especializados y controladores básicos que permiten una interacción más directa con el entorno, que permiten una mayor conexión con las tareas virtuales. Por su parte, las inmersivas se caracterizan por utilizar tecnologías avanzadas como dispositivos de seguimiento corporal y gafas de RV (Head-Mounted Displays, HMD), que permiten una interacción completa con el entorno y experiencia altamente realista [44]. Esto podría generar una ventaja significativa frente a los métodos tradicionales, al evaluar habilidades y funciones cognitivas en contextos más realistas y dinámicos. Además, se puede llevar un control riguroso de las condiciones de los experimentos, lo que facilita la replicabilidad y consistencia de los resultados.

Un beneficio adicional de la RV es su integración con plataformas que optimizan la adquisición y análisis de datos en tiempo real, proporcionando información más precisa y útil para los profesionales de la salud. Muchas aplicaciones basadas en RV parten de instrumentos previamente validados, adaptándolos al entorno virtual para conservar su validez. Por ejemplo, el Método de Loci (MoL), una técnica mnemotécnica que fue virtualizada por Vindenes et al. [45]. De forma similar, Caplan et al. [46] reemplazó el recorrido físico por un castillo, por un recorrido virtual. En este contexto, la capacidad de navegación de los participantes influyó directamente en su habilidad para recordar los elementos asociados al recorrido.

Sin embargo, no todas las aplicaciones de RV se limitan a la virtualización de pruebas clásicas. En muchos casos, se diseñan ejercicios completamente nuevos para aprovechar al máximo las capacidades únicas de esta tecnología. Davison et al. [47] evaluaron las funciones ejecutivas mediante tareas en un laboratorio de química virtual y un simulador de estacionamiento. Los resultados demostraron que la evaluación desarrollada fue ligeramente más efectiva que las pruebas neuropsicológicas tradicionales para predecir el deterioro cognitivo relacionado con la edad.

Las aplicaciones que simulan AVD podrían ofrecer una ventaja adicional al replicar actividades cotidianas con alta validez ecológica, evaluando las capacidades cognitivas y motoras en contextos funcionales más representativos de la vida real. Por ejemplo, Barnett et al. [48] emplearon un entorno de cocina virtual para tareas relacionadas con la organización y preparación de alimentos. Los resultados mostraron la sensibilidad de estas actividades para detectar diferencias de desempeño según la edad y el estado cognitivo. Por su parte, Allain et al. [49], evaluaron la capacidad para elaborar una taza de café en un entorno virtual y se comparó su desempeño con el de la misma actividad realizada en un entorno real. Este tipo de estudio resulta útil para analizar las AIVD en pacientes con EA, identificando diferencias en el rendimiento entre los contextos virtual y real.

Ouellet et al. [50] desarrollaron una tienda virtual para evaluar tareas de compras, en la que participaron 20 adultos jóvenes y 19 mayores. Los resultados mostraron que este tipo de ejercicios son sensibles a la edad, ya que, aunque todos los participantes completaron la tarea con éxito, las diferencias en el desempeño entre los grupos permitieron validar el constructo de la evaluación. Además, Martis et al. [51] compararon cuantitativa y cualitativamente dos aplicaciones de RV que simulaban un supermercado virtual (una en un computador y la otra en una tablet). Este estudio demostró que los juegos serios basados en RV pueden ser más efectivos que los enfoques tradicionales basados en cuestionarios, mejorando tanto el rendimiento en la evaluación clínica como la motivación de los pacientes.

1.1.6. La realidad virtual en el entrenamiento y rehabilitación cognitiva

Posterior al diagnóstico de los problemas cognitivos o de una enfermedad ya definida se debe plantear el tratamiento respectivo. Por lo general, se prescribe una receta médica de medicamentos con dosis ajustadas al caso específico. Sin embargo, es común que los pacientes, especialmente aquellos con deterioro cognitivo, olviden seguir las indicaciones farmacológicas, lo que puede comprometer la efectividad del tratamiento [52].

Esta problemática impulsó la búsqueda de alternativas que complementen las terapias tradicionales, y la tecnología está presente para generar soluciones. Aunque inicialmente se enfocó en la rehabilitación de funciones motoras, las investigaciones recientes han ampliado su alcance hacia el entrenamiento y la rehabilitación de las habilidades cognitivas. Este cambio responde a la necesidad de abordar los desafíos asociados al tratamiento de pacientes con deterioro cognitivo. La revisión reciente de Chan et al. [53] indicó que la mayoría de las intervenciones en adultos mayores ha venido utilizando computadoras de escritorio tradicionales, seguidas de computadoras de pantalla táctil y entornos de realidad virtual inmersiva (RVI), representando esta última solo el 5,7% del total. Estos resultados son consistentes con la revisión de Carroll et al. [54], que indicaron que solo el 9% de las aplicaciones de RV que reportaron son totalmente inmersivas.

Previamente se presentó evidencia del uso de la RV basada en AVD para el diagnóstico, pero también se puede utilizar para el tratamiento de trastornos cognitivos. Estas simulaciones, al estar basadas en escenarios familiares fortalecen la validez ecológica de la tarea, al reflejar con mayor precisión las demandas y contextos de la vida cotidiana [55]. En el estudio de Grewe et al. [56], los participantes sanos debían memorizar una lista de compras y adquirir los artículos correspondientes, acercando la experiencia a situaciones de la vida real. De manera similar, Parsons et al. [57] desarrollaron una tienda de comestibles en un entorno virtual, que integró el aprendizaje de una lista de compras como parte del entrenamiento cognitivo. Por otro lado, Chatterjee et al. [58] desarrollaron una cocina virtual inmersiva en la que los participantes prepararon alimentos, incluyendo carne y pasta. Los resultados fueron prometedores, mostrando mejoras en las funciones cognitivas y una posible reducción en el tiempo de estancia en la unidad de accidentes cerebrovasculares de un gran hospital en Reino Unido. Sin embargo, también existen estudios que consideran que las pruebas de su efectividad aún son limitadas [59].

A medida que aumentó el número de aplicaciones experimentales, surgieron nuevos desafíos, como la aparición de síntomas de malestar asociados a la RV. Estos síntomas son conocidos como efectos inducidos por la RV o ciberenfermedad (cybersickness en inglés), que incluyen mareos, desorientación, dolores de cabeza, dolor ocular y otros dolores relacionados [60]. Como destacaron Marson et al. [61] en su revisión, se requieren investigaciones adicionales para evaluar las capacidades y limitaciones de estas herramientas alternativas en el tratamiento de enfermedades neurodegenerativas.

1.1.7. Intervenciones basadas en realidad virtual y motora

En las intervenciones dirigidas a adultos mayores, los videojuegos activos (exergames, en inglés) se distinguieron por integrar tareas combinadas que incluyen elementos cognitivos y motores. Además de entrenar funciones cognitivas como la memoria, la atención y la flexibilidad cognitiva, los exergames añaden un componente físico que mejora la coordinación motriz y la condición general del usuario. Joubert y Chainay (2018) descubrieron en su estudio que el entrenamiento combinado mejoró entre un 25 y 30% más la flexibilidad cognitiva y la atención en comparación con intervenciones que se centran en un solo aspecto. El componente motor incrementa el flujo sanguíneo cerebral, lo que contribuye a una mejor oxigenación y nutrición neuronal, favoreciendo así cambios adaptativos en el cerebro, incluso en edades avanzadas [62].

Las intervenciones que incorporaron actividades motoras han mostrado su efectividad para mejorar las capacidades funcionales de las personas. La revisión sistemática realizada por Zhu et al. [63] analizó 11 ensayos controlados aleatorizados, evidenciando un impacto moderado en el desempeño motor y cognitivo de los participantes, especialmente en pacientes con deterioro cognitivo leve y demencia. Estas intervenciones demostraron ser particularmente efectivas en áreas relacionadas con la coordinación y la estabilidad física. Gao et al. [64] presentaron seis programas que combinaban RV con rehabilitación tradicional, reportando beneficios en la capacidad de los participantes para realizar tareas específicas y mejorar su bienestar emocional. Sin embargo, no se observaron mejoras significativas en la autonomía y en la funcionalidad motora general.

Adams et al. [65] utilizaron el sistema de software SaeboVR basado en RV y AIVD para la recuperación de la función motora después de un accidente cerebrovascular. Los resultados mostraron una mejora clínicamente importante tanto en la función motora como en el desempeño cognitivo asociado. Guidali et al. [66] presentaron un sistema de rehabilitación que permite el entrenamiento de AVD con el apoyo de un robot de asistencia. Esto nace por la evidencia de varios estudios que respaldan el efecto positivo que los juegos serios podrían aumentar la motivación. De esta manera se ofrece una ayuda adicional para personas que poseen dificultades motoras, con resultados prometedores. Estas intervenciones también han mostrado una capacidad destacada para aumentar la motivación y adherencia, como lo reportaron Park et al. [67], al comparar la RV con enfoques convencionales.

Estas aplicaciones basadas en AVD podrían complementar las terapias formales y ofrecer al personal de salud un recurso adicional para responder a la creciente demanda de servicios de rehabilitación. A medida que la tecnología avance, se espera que estas herramientas puedan adaptarse al progreso de cada paciente, superando las limitaciones de las pruebas de laboratorio, las cuales no reflejan las condiciones de vida cotidiana [68]. Por ello, esta tesis doctoral presenta una base estructurada para el diseño de aplicaciones en el diagnóstico e intervención de adultos mayores con deficiencias cognitivas, fortaleciendo su aplicabilidad en contextos de la vida real.

1.2. Preguntas de investigación y objetivos

Esta tesis doctoral se centra en explorar preguntas de investigación fundamentadas en la necesidad de implementar soluciones tecnológicas basadas en actividades de la vida diaria que permitan realizar tanto el diagnóstico como la intervención cognitiva motora en la población adulta mayor. A continuación, se presentan las preguntas y objetivos de investigación.

1.2.1. Preguntas de Investigación

La pregunta de investigación es la siguiente: ¿Cómo pueden las soluciones tecnológicas basadas en AVD contribuir a la detección temprana de déficits cognitivos y mejorar las intervenciones de funciones cognitivo-motoras en adultos mayores? Esta pregunta se desglosa en tres preguntas de investigación específicas que guían los objetivos y contribuciones de esta tesis. A saber:

1. Pregunta de Investigación 1 (PI1): ¿Es viable desarrollar una solución tecnológica basada en AVD que permita un cribado de las funciones cognitivas?
2. Pregunta de Investigación 2 (PI2): ¿Cuál es el estado actual de las aplicaciones de RV basadas en AIVD para la intervención cognitiva-motora en adultos mayores con deterioro cognitivo?
3. Pregunta de Investigación 3 (PI3): ¿Cómo influye una intervención de RV que integra entrenamiento motor y cognitivo en las funciones cognitivas de adultos mayores con deterioro cognitivo leve?

1.2.2. Objetivos de investigación

Para responder a estas preguntas, la tesis se estructura en los siguientes objetivos:

1. Objetivo 1 (OBJ1): Desarrollar un ejercicio de cribado basado en una AVD con elementos físicos y sensores inteligentes.
2. Objetivo 2 (OBJ2): Implementar una aplicación de RV basada en una AVD que permita realizar un cribado efectivo de las funciones cognitivas.
3. Objetivo 3 (OBJ3): Examinar la utilidad de aplicaciones de RV basadas en AIVD para la intervención cognitiva en adultos mayores con deterioro cognitivo.
4. Objetivo 4 (OBJ4): Investigar las aportaciones de las intervenciones cognitivo-motoras de RV que utilizan AIVD en los adultos mayores con trastornos neurodegenerativos.

- Objetivo 5 (OBJ5): Diseñar una intervención de RV para adultos mayores con deterioro cognitivo leve, integrando los componentes metodológicos necesarios para su implementación efectiva.
- Objetivo 6 (OBJ6): Evaluar la efectividad de una intervención que combine entrenamiento motor y cognitivo en RV basado en una AIVD en adultos mayores con deterioro cognitivo leve.

1.3. Listado del compendio de publicaciones

Esta tesis doctoral se presenta como formato de compendio de publicaciones, integrando seis artículos científicos previamente publicados. A continuación, se detallan las referencias completas de los artículos que conforman el cuerpo de la tesis.

I. Palacios-Navarro, G., **Buele, J.**, Gimeno Jarque, S., & Bronchal García, A. (2022). Cognitive Decline Detection for Alzheimer's Disease Patients Through an Activity of Daily Living (ADL). IEEE Transactions on Neural Systems and Rehabilitation Engineering, 30, 2225-2232. IEEE Transactions on Neural Systems and Rehabilitation Engineering. https://doi.org/10.1109/TNSRE.2022.3196435
II. Varela-Aldás, J., **Buele, J.**, Amariglio, R., García-Magariño, I., & Palacios-Navarro, G. (2022). The cupboard task: An immersive virtual reality-based system for everyday memory assessment. International Journal of Human-Computer Studies, 167, 102885. https://doi.org/10.1016/j.ijhcs.2022.102885
III. Varela-Aldás, J., **Buele, J.**, López, I., & Palacios-Navarro, G. (2023). Influence of Hand Tracking in Immersive Virtual Reality for Memory Assessment. International Journal of Environmental Research and Public Health, 20(5), Article 5. https://doi.org/10.3390/ijerph20054609
IV. **Buele, J.**, Varela-Aldás, J. L., & Palacios-Navarro, G. (2023). Virtual reality applications based on instrumental activities of daily living (iADLs) for cognitive intervention in older adults: A systematic review. Journal of NeuroEngineering and Rehabilitation, 20(1), 168. https://doi.org/10.1186/s12984-023-01292-8
V. **Buele, J.**, & Palacios-Navarro, G. (2023). Cognitive-motor interventions based on virtual reality and instrumental activities of daily living (iADL): An overview. Frontiers in Aging Neuroscience, 15. https://doi.org/10.3389/fnagi.2023.1191729
VI. **Buele, J.**, Avilés-Castillo, F., Del-Valle-Soto, C., Varela-Aldás, J., & Palacios-Navarro, G. (2024). Effects of a dual intervention (motor and virtual reality-based cognitive) on cognition in patients with mild cognitive impairment: A single-blind, randomized controlled trial. Journal of NeuroEngineering and Rehabilitation, 21(1), 130. https://doi.org/10.1186/s12984-024-01422-w

Asimismo, se consideró pertinente incluir los artículos presentados en revistas y conferencias internaciones que formaron parte de la base formativa del doctorando.

VII. **Buele, J.**, Varela-Aldás, J., & Palacios-Navarro, G. (2022). Virtual Reality applications based on activities of daily living (ADL) for cognitive diagnosis and rehabilitation. 2022 Congreso de Tecnología, Aprendizaje y Enseñanza de la Electrónica (XV Technologies Applied to Electronics Teaching Conference), 1-5. https://doi.org/10.1109/TAEE54169.2022.9840591
VIII. **Buele, J.**, Labre-Tarco, V. E., López-Albuja, M. A., Tapia-Ramos, V., & Palacios-Navarro, G. (2023). Advancements in Virtual Reality for Elderly Care: A Two-Decade Journey. 2023 IEEE Seventh Ecuador Technical Chapters Meeting (ECTM), 1-6. https://doi.org/10.1109/ETCM58927.2023.10309039
IX. Varela-Aldás, J. L., **Buele, J.**, Pérez, D., & Palacios-Navarro, G. (2023). Memory rehabilitation during the COVID-19 pandemic. BMC Medical Informatics and Decision Making, 23(1), 195. https://doi.org/10.1186/s12911-023-02294-1

1.4. Trabajos realizados

Explicamos a continuación los principales resultados obtenidos en todos y cada uno de los artículos que componen este compendio. Nos referimos a los artículos según el orden establecido en el apartado anterior.

El primer artículo evaluó la efectividad de una tarea basada en una AVD como herramienta para la detección del deterioro cognitivo en pacientes con Alzheimer. La propuesta se diseñó considerando la necesidad de aumentar la validez ecológica de los métodos de diagnóstico actuales, ofreciendo una alternativa no invasiva y práctica. Se emplearon dos armarios, cada uno con dos puertas, equipados con una tarjeta Raspberry Pi 3 y sensores, basado en el experimento de Landero et al. [69]. En cada uso, los armarios contenían un conjunto de objetos diferente, organizados en cuatro categorías o subtareas: cocina, higiene personal, costura y elementos del aula. La actividad consistía en dos fases: en la fase de codificación, los participantes memorizaban la ubicación de los objetos dentro de los compartimentos; en la fase de recuperación, debían identificar el compartimento correcto que contenía el objeto solicitado dentro de un tiempo limitado. Los sensores instalados en las puertas permitieron registrar de manera automática las respuestas y los tiempos de reacción, facilitando un análisis detallado y preciso de los resultados.

El experimento incluyó 24 adultos mayores, divididos en un grupo con EA (ADG) y un grupo sano (HG). Los resultados mostraron que, en el ADG, no hubo correlación significativa entre la precisión y variables como edad, nivel educativo o tiempo desde el diagnóstico, pero se encontró una asociación positiva significativa entre la tarea y la escala MEC-35 (rho=0,71, p=0,01), lo que validó su capacidad para detectar deterioro cognitivo. En el HG, la edad se asoció negativamente con la precisión (rho=-0,736, p=0,006), y aunque no hubo relación con el nivel educativo ni género, se observaron diferencias significativas entre subtareas (p<0,001), Entre estas, la subtarea de cocina presentó los mejores resultados, lo que sugiere que fue percibida como la más sencilla o accesible para los participantes.

Respecto a los tiempos de reacción, el ADG mostró diferencias significativas en función de la presencia de comorbilidades (p=0,026), siendo estos tiempos más largos en participantes con afecciones adicionales. En el HG, no se hallaron asociaciones significativas entre los tiempos de reacción y las variables evaluadas. La fiabilidad del test-retest se confirmó con un coeficiente de correlación intraclase (ICC) excelente en ambos grupos (ADG: 0,757; HG: 0,821), sin diferencias significativas entre las medidas iniciales y posteriores (p>0,05).

La comparación entre grupos evidenció que el HG tuvo un desempeño significativamente mejor, con una precisión promedio del 78,35%, frente al 54.10% del ADG (t=5,969, p<0,001). El tamaño del efecto fue grande (d=2,42), lo que refuerza la capacidad discriminativa de la tarea. Aunque se identificaron efectos techo en la subtarea de cocina del HG, el diseño general de la tarea logró evitar este problema al considerar el rendimiento total. Estos resultados respaldan el uso de esta tarea como una herramienta válida y práctica para la detección temprana del deterioro cognitivo.

En el segundo artículo se presentó un sistema basado en RVI para evaluar la memoria mediante una tarea llamada "Cupboard Task." El sistema virtualizó la misma tarea presentada en el estudio anterior, como una alternativa inmersiva a los métodos tradicionales. Se diseñó para proporcionar una evaluación más ecológica y automatizada de funciones cognitivas, especialmente la memoria. La interfaz se controla mediante las gafas Oculus Go y un puntero manual, además, posee retroalimentación auditiva en el caso de aciertos o errores. El sistema permite el ingreso del nombre del participante y registra automáticamente los tiempos de reacción y respuestas de cada uno en tiempo real, así como en la memoria interna del dispositivo.

El estudio involucró a 22 participantes sanos, seleccionados con criterios como una puntuación mínima de 26 en el MMSE y edades entre 18 y 65 años. Se aplicaron dos niveles de dificultad con diferentes cantidades de objetos para memorizar (7 y 9), permitiendo analizar la relación entre desempeño y variables como edad, tiempo de reacción y nivel educativo. Los datos recolectados se analizaron mediante correlaciones de Pearson, pruebas ANOVA y el ICC, lo que permitió validar el sistema frente al MoL.

Los resultados mostraron una alta concordancia entre ambas herramientas, con un ICC de 0,614 para el nivel 1 y 0,662 para el nivel 2, considerados clínicamente significativos. No se encontraron diferencias significativas en el desempeño según género o nivel educativo, pero sí se observó una correlación negativa significativa entre la edad y el desempeño en la tarea, lo que confirma la sensibilidad del sistema a los efectos típicos del envejecimiento en tareas de memoria episódica. Además, se encontró una relación negativa entre el tiempo total de reacción y el desempeño, indicando que un tiempo más prolongado está asociado con peores resultados. En cuanto a la usabilidad, el sistema obtuvo una alta puntuación en el cuestionario breve para la evaluación de la satisfacción con los sistemas de rehabilitación virtual (USEQ) [70] con un 96,3%.

En el tercer artículo se evaluó la influencia del seguimiento de manos (hand tracking) en sistemas de RVI para la evaluación de la memoria. Se utilizó la tarea de los armarios, comparando dos métodos de interacción: controles tradicionales de Oculus Quest 2 y el seguimiento de manos. Los datos recopilados incluyeron precisión en las respuestas, tiempo de reacción y percepción de presencia, usabilidad y satisfacción. El experimento incluyó a 20 participantes sin deterioro cognitivo, seleccionados con base en una puntuación mínima de 26 en el MoCA. Validar el sistema en una población más joven garantiza que existen las condiciones adecuadas para su aplicación en adultos mayores o con DCL.

Al realizar las pruebas experimentales se utilizó un nivel de dificultad de 7 objetos, y cada sesión tuvo una duración promedio de 25 minutos. Los resultados revelaron que, aunque el método con controles mostró una precisión promedio 7,08% mayor y tiempos de respuesta 0,27 segundos más rápidos, no hubo diferencias estadísticamente significativas entre ambos métodos. En cuanto a la presencia, usabilidad y satisfacción, las puntuaciones fueron similares entre ambos, aunque el control manual se percibió ligeramente más intuitivo.

En el cuarto trabajo, se realizó una revisión sistemática para analizar el uso de aplicaciones de RV basadas en AIVD en intervenciones cognitivas. La revisión abarcó un total de 19 estudios, con una muestra de 590 participantes, mayoritariamente mujeres (72,67%), que incluyó tanto adultos sanos como personas diagnosticadas con DCL o EA. Los estudios seleccionados implementaron intervenciones con niveles variados de inmersión y analizaron diversas tareas relacionadas con las AIVD como compras en supermercados, preparación de alimentos y manejo de medicamentos.

Se utilizó una estrategia de búsqueda sistemática en cinco bases de datos principales (Scopus, PubMed, IEEE Xplore, Web of Science y APA PsycNet) hasta abril de 2023. Los criterios de inclusión consideraron estudios originales, revisados por pares, que involucraron intervenciones basadas en RV diseñadas para rehabilitación, entrenamiento o estimulación cognitiva, excluyendo investigaciones descriptivas o enfocadas únicamente en rehabilitación motora. La calidad metodológica se evaluó mediante la escala PEDro, donde los estudios obtuvieron puntajes promedio de 6,16, indicando buena calidad, aunque con limitaciones en aspectos como el cegamiento de participantes y terapeutas.

Los resultados indicaron que la mayoría de las intervenciones basadas en RV y AIVD produjeron mejoras significativas en dominios como memoria, atención y funciones ejecutivas, superando los resultados obtenidos por los grupos de control. Las tareas realizadas en entornos inmersivos tendieron a mostrar un impacto mayor, posiblemente debido a su mayor validez ecológica, al replicar con mayor precisión las condiciones de la vida cotidiana. Sin embargo, las intervenciones semi inmersivas y no inmersivas demostraron su efectividad en diferentes funciones cognitivas específicas, lo cual demuestra las múltiples potencialidades de esta tecnología. Entre las principales limitaciones identificadas en los estudios revisados, se destacó la falta de seguimiento a largo plazo para evaluar la transferencia de habilidades al entorno real, así como la necesidad de muestras más homogéneas y numerosas.

Posterior al análisis de aplicaciones enfocadas exclusivamente en la rehabilitación cognitiva y considerando la evidencia obtenida durante dicho proceso, se planteó la necesidad de realizar una nueva revisión centrada en intervenciones que integran tanto componentes cognitivos como motores (quinto artículo). Este trabajo presentó una mini revisión que evaluó el impacto de aplicaciones de RV que combinan tareas cognitivo-motoras basadas en AIVD en adultos mayores sanos, con DCL y demencia, utilizando RVI y no inmersiva.

La revisión incluyó ocho estudios donde los participantes realizaron actividades motoras como caminar, realizar ejercicios de equilibrio, y manipular objetos en entornos simulados. Estas actividades se combinaron con tareas cognitivas como planificación, resolución de problemas y memoria a corto plazo. Los resultados demostraron que estas intervenciones generan mejoras en funciones ejecutivas, memoria, atención, velocidad de marcha y equilibrio, lo que se traduce en un aumento de la independencia en las actividades cotidianas. Además, se observaron beneficios adicionales en la transferencia de habilidades adquiridas en los entornos virtuales hacia contextos reales, potenciando la calidad de vida de los participantes.

Un hallazgo destacado fue la capacidad de estas aplicaciones para promover la neuroplasticidad, evidenciada por mejoras en el flujo sanguíneo cerebral en áreas prefrontales y cinguladas, asociadas con funciones ejecutivas y memoria. Sin embargo, la heterogeneidad de los estudios en cuanto a diseños metodológicos, duración de las intervenciones y características de los participantes, limitó las conclusiones generalizables.

En el sexto estudio se consideró la evidencia observada en trabajos previos sobre la efectividad de intervenciones cognitivo-motoras. Hasta ahora, la mayoría de las investigaciones en este campo se habían realizado en países desarrollados con contextos socioeconómicos y culturales propios [53], [64] El estudio presentado fue el primero en América Latina que estimuló y evaluó la cognición, depresión y autonomía funcional usando RV que simula una AIVD. Este enfoque fue diseñado para adultos mayores con DCL y se llevó a cabo en un centro comunitario en un pueblo de Ecuador.

El estudio incluyó a 34 participantes mayores de 65 años, divididos aleatoriamente en dos grupos: un grupo experimental que recibió entrenamiento cognitivo mediante un sistema de RVI y un grupo control que realizó tareas tradicionales basadas en papel y lápiz. Ambos grupos participaron previamente en actividades físicas moderadas como ejercicios de equilibrio, resistencia y aeróbicos, estimulando la función motora. En el grupo experimental, el entrenamiento cognitivo se realizó usando la tarea de los armarios, utilizando las gafas Oculus Quest 2 y controladores manuales.

Los resultados demostraron mejoras significativas en las funciones cognitivas evaluadas mediante el MoCA-S (versión en español), con un aumento promedio en ambos grupos. El grupo experimental mostró una mayor adherencia y motivación hacia la tarea, alcanzando niveles más altos de dificultad y tiempos de respuesta más rápidos en comparación con el grupo control. Ambas intervenciones también redujeron los síntomas de depresión, evaluados por la escala SGDS-S. La evaluación de habilidades funcionales mediante la escala IADL-S no mostró diferencias significativas entre los grupos. Esto aporta al estado del arte actual que demuestra como la RV puede proporcionar un entrenamiento motivador y adaptado a las necesidades de los adultos mayores.

1.5. Relación de los artículos con las preguntas de investigación

La estructura de la investigación se fundamenta en la combinación de objetivos que permitieron desarrollar herramientas prácticas y establecer una base metodológica para la implementación futura de soluciones tecnológicas basadas en AIVD, como se presenta en la Tabla 1.

Tabla 1. Relación entre las preguntas de investigación, objetivos y publicaciones

N°	Publicación	PI1		PI2		PI3	
		OBJ1	OBJ2	OBJ3	OBJ4	OBJ5	OBJ6
1	Cognitive Decline Detection for Alzheimer's Disease Patients Through an Activity of Daily Living (ADL)	X					
2	The Cupboard Task: An Immersive Virtual Reality-Based System for Everyday Memory Assessment	X	X				
3	Influence of Hand Tracking in Immersive Virtual Reality for Memory Assessment		X				
4	Virtual Reality Applications Based on Instrumental Activities of Daily Living (iADLs) for Cognitive Intervention in Older Adults: A Systematic Review			X			
5	Cognitive-Motor Interventions Based on Virtual Reality and Instrumental Activities of Daily Living (iADL): An Overview				X		
6	Effects of a dual intervention (motor and virtual reality-based cognitive) on cognition in patients with mild cognitive impairment: a single-blind, randomized controlled trial					X	X

Las publicaciones incluidas en esta tesis están orientados a responder preguntas específicas planteadas previamente, basándose en los objetivos alcanzados:

PI1: ¿Es viable desarrollar una solución tecnológica basada en AVD que permita un cribado de las funciones cognitivas?

Las tres primeras publicaciones respaldan la viabilidad de desarrollar soluciones tecnológicas basada en AVD para el cribado cognitivo. La publicación 1 identificó las limitaciones de las herramientas actuales y validó una tarea física de AVD en adultos mayores con EA, demostrando sensibilidad para diferenciar estados cognitivos mediante la evaluación de memoria y atención en un contexto realista. La publicación 2 trasladó esta tarea a un entorno de RVI (Cupboard Task), validándola frente a métodos tradicionales como el MoL, y destacando su capacidad para detectar diferencias cognitivas relacionadas con el envejecimiento. La publicación 3 evaluó el impacto del seguimiento de manos en RV en el cribado cognitivo, confirmando que esta solución mantiene precisión, tiempos de respuesta adecuados, usabilidad y satisfacción en los participantes.

En conjunto, estos estudios demostraron que las soluciones tecnológicas basadas AVD permiten una evaluación efectiva y ecológicamente válida de las funciones cognitivas. Esto responde afirmativamente a la primera pregunta de investigación, además se dio cumplimiento a:

- OBJ1: Desarrollar un ejercicio de cribado basado en una AVD con elementos físicos y sensores inteligentes.
- OBJ2: Implementar una aplicación de RV basada en una AVD que permita realizar un cribado efectivo de las funciones cognitivas.

PI2: ¿Cuál es el estado actual de las aplicaciones de RV basadas en AIVD para la intervención cognitiva-motora en adultos mayores con deterioro cognitivo?

Las dos revisiones de literatura realizadas presentan el estado actual y el potencial de las aplicaciones de RV basadas en AIVD para la intervención cognitivo-motora en adultos mayores con DCL. La publicación 4 revisó sistemáticamente las intervenciones cognitivas destacando sus beneficios en memoria, atención y funciones ejecutivas al simular escenarios cotidianos Mientras que la publicación 5 describió las intervenciones combinadas (cognitivo-motoras), con un impacto positivo en la independencia funcional de los participantes. El efecto está relacionado con un aumento en el flujo sanguíneo y en una mayor motivación al ser parte de ejercicios físicos donde pueden tener mayor interacción social. Ambas publicaciones concluyen que estas aplicaciones son herramientas prometedoras para mejorar tanto la cognición como la funcionalidad física en adultos mayores, respondiendo al planteamiento de la PI2 y cumpliendo con los siguientes objetivos:

- OBJ3: Examinar la utilidad de aplicaciones de RV basadas en AIVD para la intervención cognitiva en adultos mayores con deterioro cognitivo.
- OBJ4: Investigar los aportes de las intervenciones cognitivo-motoras de RV que utilizan AIVD en los adultos mayores con trastornos neurodegenerativos.

PI3: ¿Cómo influye una intervención de RV que integra entrenamiento motor y cognitivo en las funciones cognitivas de adultos mayores con deterioro cognitivo leve?

Las publicaciones previas establecieron la base para diseñar una intervención combinada en RV para el entrenamiento de adultos mayores con DCL. La metodología detallada en la publicación 6 incluyó sesiones de 30 minutos, dos veces por semana durante seis semanas, ajustando gradualmente la dificultad de las tareas según las capacidades de los participantes. Esta intervención coincidió con lo que indica la literatura mejorando significativamente funciones cognitivas como memoria, atención y funciones ejecutivas, además de reducir síntomas de depresión geriátrica, lo que refleja un impacto positivo en el bienestar general. La intervención demostró ser una herramienta prometedora para una rehabilitación integral, lo que abre el camino a desarrollos futuros con mayor validez ecológica.

En conjunto, estos resultados responden el planteamiento de la PI3: una intervención de entrenamiento motor y cognitivo en RV impacta positivamente en las funciones cognitivas de adultos mayores con DCL e incluso puede reducir los síntomas depresivos y mejorar la aceptación tecnológica. Con ello se cumplieron los objetivos siguientes:

- OBJ5: Diseñar una intervención de RV para adultos mayores con deterioro cognitivo leve, integrando los componentes metodológicos necesarios para su implementación efectiva.
- OBJ6: Evaluar la efectividad de una intervención que combine entrenamiento motor y cognitivo en RV basado en una AIVD en adultos mayores con deterioro cognitivo leve.

1.6. Estructura de la tesis

La estructura de esta tesis se organiza en cuatro capítulos. El capítulo 1 ofrece un panorama general del contexto de la investigación y una revisión de la literatura relevante. También expone las preguntas y objetivos de investigación que guiaron el desarrollo de la investigación, junto con una descripción de las tres fases que constituyen este estudio doctoral. Además, se describen las seis publicaciones que conforman el compendio y que cumplen con los requisitos establecidos en la normativa para una tesis por compendio de publicaciones. Los resultados de este trabajo doctoral también generaron otras contribuciones adicionales en revistas y conferencias internacionales que se presentan en uno de los apéndices.

El capítulo 2 presenta una copia de las seis publicaciones que forman parte de este compendio. El capítulo 3 está dedicado a la discusión general, en la que se presentan y analizan los principales hallazgos de esta tesis, así como las aplicaciones prácticas en entornos clínicos y de investigación. El capítulo 4 ofrece las conclusiones generales, limitaciones, así como posibles direcciones para futuros estudios, motivando a continuar investigando en este campo. La última sección incluye las referencias bibliográficas citadas a lo largo del documento.

ARTÍCULOS PUBLICADOS 2

2.1. Artículo: Cognitive decline detection for Alzheimer's disease patients through an activity of daily living (ADL)

IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING, VOL. 30, 2022 2225

Cognitive Decline Detection for Alzheimer's Disease Patients Through an Activity of Daily Living (ADL)

G. Palacios-Navarro, J. Buele, S. Gimeno Jarque, and A. Bronchal García

***Abstract*— There are conventional screening instruments for the detection of cognitive impairment, but they have a reduced ecological validity and the information they present could be biased. This study aimed at evaluating the effectiveness and usefulness of a task based on an activity of daily living (ADL) for the detection of cognitive impairment for an Alzheimer's disease (AD) population. Twenty-four participants were included in the study. The AD group (ADG) included twelve older adults (12 female) with AD (81.75±7.8 years). The Healthy group (HG) included twelve older adults (5 males, 77.7 ± 6.4 years). Both groups received a ADL-based intervention at two time frames separated 3 weeks. Cognitive functions were assessed before the interventions by using the MEC-35. The test-retest method was used to evaluate the reliability of the task, as well as the Intraclass Correlation Coefficient (ICC). The analysis of the test-retest reliability of the scores in the task indicated an excellent clinical relevance for both groups. The hypothesis of equality of the means of the scores in the two applications of the task was accepted for both the ADG and HG, respectively. The task also showed a significant high degree of association with the MEC-35 test (rho = 0.710, p = 0.010) for the ADG. Our results showed that it is possible to use an ADL-based task to assess everyday memory intended for cognitive impairments detection. In the same way, the task could be used to promote cognitive function and prevent dementia.**

***Index Terms*—ADL, Alzheimer's disease, cognitive decline, dementia, memory assessment.**

I. Introduction

ALZHEIMER'S disease (AD) is the most common type of dementia, which produces a gradual decline in control over memory, thought and language, abruptly limiting the independence of the patient [1]. Thus, the majority of people who have mild cognitive impairment (MCI) will develop AD in the future [2], [3]. In order to identify the appearance of problems in human cognition, several tools have been developed for their evaluation [4], [5]. However, some procedures are invasive and others are part of pharmacological trials, which causes discomfort and stigma [6]. When the patient prefers not to perform them, early detection of the disease and the respective treatment are difficult. Therefore, the specialist must choose the best option according to the needs of the patient, nature of the injury and cognitive impairment.

In a conventional way, there are screening instruments that make it possible to establish whether a person suffers from a cognitive problem, even if it is not visible. In the review conducted by Roeck *et al.* [7] it is mentioned that these tests might not be as sensitive and therefore effective for the detection of AD. Examples like the Mini-Mental State Examination (MMSE), Scenery Picture Memory Test (SPMT), Memory Impairment Screen (MIS), Alzheimer Quick Test (AQT), Montreal Cognitive Assessment (MoCA), Short Test of Mental Status (STMS) and Diagnostic utility of the Addenbrooke's Cognitive Examination - III (ACE-III), stand out among the main ones. [8]. Another disadvantage of these tools is their reduced ecological validity, since they are laboratory tests that do not evaluate their interaction with situations and conditions of the daily life (ADL) [9], [10]. This could skew the obtained data, since those people with AD have difficulty performing these types of activities, as a result of cognitive impairment.

It is important that these instruments have the support of technology, making better use of the results obtained [11]. For example, *et al.* [12] pointed out in their review the potential that designs based on Innovative Assistive Technologies have to compensate for functional decline. O'Leary *et al.* [13] developed a platform that has a touch screen for cognitive evaluation in rodents, which can be compared with human neuropsychological tests, obtaining greater advantages than using standard mazes. Other studies have used classical tests as the basis for the design of new proposals to be compared. Pitteri *et al.* [14] presented a video game that sought to identify whether there was a cognitive impairment in the information processing speed (IPS). The results revealed that those patients with multiple sclerosis (MP) showed a lower performance compared to healthy ones. Significant correlations with the Symbol Digit Modalities Test (SDMT) were found,

Manuscript received 22 December 2021; revised 16 June 2022; accepted 1 August 2022. Date of publication 4 August 2022; date of current version 12 August 2022. This work was supported in part by the University of Zaragoza under Grant OTRI 2015/0409. *(Corresponding author: G. Palacios-Navarro.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Community of Aragón Institutional Review Board (CEICA) under Protocol No. PI21/326 in July 2021.

G. Palacios-Navarro is with the Department of Electronic Engineering and Communications, University of Zaragoza, 44003 Teruel, Spain (e-mail: guillermo.palacios@unizar.es).

J. Buele is with the Department of Electronic Engineering and Communications, University of Zaragoza, 44003 Teruel, Spain, and also with the Centro de Investigaciones de Ciencias Humanas y de la Educación, Universidad Tecnológica Indoamérica, Ambato 180103, Ecuador (e-mail: jorgebuele@uti.edu.ec).

S. Gimeno Jarque and A. Bronchal García are with the Teruel Center for Alzheimer's Disease, 44002 Teruel, Spain, and also with SOCIAL-CORE Ltd., 44002 Teruel, Spain (e-mail: sandragj16@gmail.com; andrea_bronchal@hotmail.com).

Digital Object Identifier 10.1109/TNSRE.2022.3196435

verifying its validity as a diagnostic tool. On the other hand, Khaligh-Razavi *et al.* [15] developed a new integrated cognitive assessment called CGN_ICA whose application lasts 5 minutes and is based on a visual categorization activity. Various natural images were presented to 448 participants to assess their cognitive performance and compared with the standard SDMT and MoCA tests. Similarly, Kalafatis *et al.* [16] used an artificial intelligence model to perform a cognitive test for cognitive impairment detection validating their efficacy in 230 participants. However, as pointed out by Marson *et al.* [17] in their review, more studies are required to evaluate the potentialities and limitations of these alternative tools during the treatment process of neurodegenerative diseases.

The aim of the study is to investigate new technological-based methods to detect cognitive decline in AD patients. The literature shows us that in spite of the acceptable results found when using technology to replace conventional methods, these alternative methods have a reduced ecological validity in predicting real-world performance [18], [19]. To accomplish that, this research proposes a more ecological task than traditional tests for cognitive impairment detection. The task represents an activity of daily living (ADL) in the sense that it is based on an activity that users can perform in their daily life. We can distinguish between basic ADL and instrumental ADL (iADL). The former include the fundamental skills needed to basic physical needs (hygiene, dressing, toileting, etc.). The latter include higher level activities such as the ability to use the telephone, shopping, food preparation, housekeeping, laundry, etc. [20]. According to Lawton [20] food preparation is an iADL and the proposed task is very close to this task. As secondary objectives, we intend to look for relationships among the obtained results and variables such as age, level of education, etc., in order to add more knowledge to the existing literature in cognitive decline.

II. Materials and Methods

This non-experimental study investigated the creation of new paradigms to detect changes in cognitive functions, such as cognitive impairment, in older adults with MCI, dementia or Alzheimer's disease through a game that emulates an activity of daily life. The study has been carried out in accordance with the Declaration of Helsinki. The protocol used in this study was approved by the Community of Aragón Research Ethics Committee (CEICA) on July 7, 2021 (protocol PI21/326) with the understanding and written consent of all the participants before the study.

A. Materials

For the development of the experiment we used a cupboard (figure 1) with the following dimensions: 120 cm width, 50 cm height, 24.5 cm depth. The cupboard was placed 102 cm above the ground so that all the participants were able to watch the inside properly. It consisted of four compartments of the same size (30 cm width, 50 cm height, 24.5 cm depth). Elements related to the kitchen, personal hygiene, sewing elements and elements found in the classroom where the participants attend their daily therapy session were also used. These elements were placed inside the compartments in the way indicated in the procedure section. Figure 1 shows the cupboard populated with elements one can find in a regular kitchen at home. Likewise, sensors were installed on the doors and a Raspberry Pi was placed under the cupboard in order to receive the inputs from each of the sensors and thereby store the data. Figure 2 depicts the main components used in the experiment (a Raspberry Pi 3, door sensors and cables).

Fig. 1. Cupboards compartments with kitchen elements.

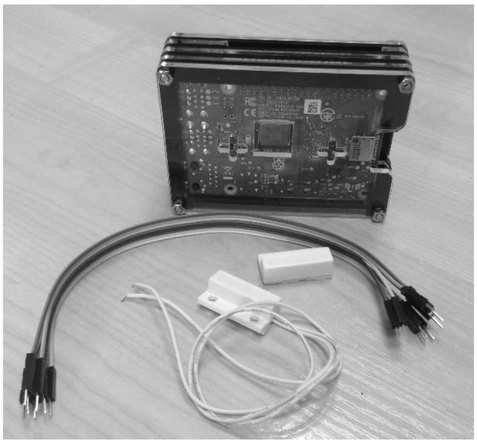


Fig. 2. Components used in the experiment: a Raspberry Pi, door sensors and cables.

B. Participants

Our design included two groups in our experiment. On one hand, the ADG, including participants diagnosed with Alzheimer's disease. On the other hand, we included a second group to take advantage from a second measurement using healthy people performing the same task (HG). By doing so, we wanted to check the ability of the test to differentiate between healthy people, and people with MCI, respectively.

A total of 13 older adults (all women) were recruited from the Teruel Center for Dementia and Alzheimer's disease. Inclusion criteria were: (1) AD diagnosis; and (2) ability to understand and follow verbal instructions. Exclusion criteria were: (1) secondary chronic disease that may affect cognitive functioning; (2) auditory and visual problems that may affect communication; and (3) physical limitations to access a one

TABLE I
PARTICIPANT DEMOGRAPHICS AND CLINICAL DATA (ADG)

Part. #	Age	Educational level	Months since diagnosis	MEC-35	Co-morbidity
1	87	11	24	22	No
2	75	8	48	19	Yes
3	89	7	48	28	Yes
4	77	8	136	21	Yes
5	87	8	27	22	Yes
6	87	8	114	25	Yes
7	62	11	42	27	No
8	81	8	152	26	Yes
9	85	10	30	21	No
10	87	7	84	17	Yes
11	87	8	36	28	Yes
12	77	9	48	29	Yes

TABLE II
PARTICIPANT DEMOGRAPHICS AND CLINICAL DATA (HG)

Part. #	Age	Gender	Educational level	MEC-35	Co-morbidity
1	78	M	6	35	Yes
2	70	F	6	35	No
3	88	F	6	35	Yes
4	73	F	6	35	No
5	80	M	6	35	No
6	82	F	6	35	No
7	65	M	13	35	No
8	77	F	10	35	No
9	78	F	6	35	No
10	83	M	6	35	No
11	84	F	6	35	Yes
12	74	M	6	35	No

meter-height cupboard and open the compartments. Based on the inclusion and exclusion criteria, only one subject was excluded due to her inability to reach the cupboard in a suitable way. All the participants had been diagnosed with AD.

The HG consisted of 12 participants with a maximum MEC-35 score as an inclusion criterium and we tried to get an age matched as close as possible.

C. Measurement

Demographic data of the participants were collected, including gender, age, educational level (years), time since diagnosis (months), cognitive function assessment by using the Cognitive mini-test (MEC-35) [21] which is the Spanish adaptation and validation of the MMSE [22] in its 35-item version. Comorbidity was also collected, including in this item the presence of visual difficulty, lack of inhibition, anxiety, processing speed, pulmonary fibrosis and use of cane, respectively. Participants in the ADG were aged between 62 and 89 years, (81.75 ± 7.8), with and educational level ranged between 7 and 11 (8.58 ± 1.38) years. The months since the disease was diagnosed ranged from 24 to 152. Table I shows the demographic and clinical data of the participants belonging to the ADG. Regarding the HG, participants were aged between 65 and 88 years, (77.7 ± 6.4), with and educational level ranged between 6 and 13 (6.92 ± 2.23) years. 41.66 % were male. Table II shows the data related to the HG.

D. Procedure

The task consisted of administering 4 subtasks of 8 items each (32 items in the global task). It was accomplished on four consecutive days, each day dedicated to a subtask. In the first subtask, 8 objects that can be found in a kitchen were placed inside the cupboard, while in the second subtask the items were related to personal hygiene items. The third was dedicated to sewing items while in the last subtask the participants had to memorize items found in the classroom where they work every day. Each of the subtasks consists of two phases. In the first phase (coding phase), the user was placed in front of the cupboard and was asked to memorize the elements of each of the compartments during 10 seconds [23], (40 seconds for the total of the cupboard). In the second phase (recovery phase), the participant had to locate the object required by the therapist by selecting a door. For example, they were asked questions like: Where is the milk? For any of the subtasks, the user has a time limit to choose the corresponding door which was fixed to 10 seconds. If this time was exceeded, then a failure was written down and the evaluation continued. Items were randomly placed in the compartments and shelves and doors could be opened individually. Accuracy responses and reaction times were recorded in plain text files to be saved in the local database and sent to a remote server (SFTP) for a subsequent analysis. The test was conducted in the room where the AD patients attend their daily therapy. The test was repeated after an interval of three weeks in order to perform a test-retest reliability analysis. Figure 3 shows an AD patient performing the task (the person depicted agreed to the use of her image).

Fig. 3. AD patient performing the task.

E. Statistical Analysis

Statistical analysis was carried out using SPSS 16. Shapiro-Wilk's test was performed to check for data normality (the sample size less than 30 participants). The variables age, months from diagnosis and level of education do not follow a normal distribution (Shapiro-Wilk's test no significant, $p > 0.05$), so Spearman's rho correlation was performed when checking for any association between accuracy response and age, years of education, time since diagnosis, as well as in the case of any association between reaction time and age. A Spearman's correlation analysis was also used to check any association between the MCE-35 test results and our task results. A repeated measures ANOVA was performed to check for differences in accuracy response among the different subtasks, whereas a paired t-test was performed to check for differences between the test-retest measures. The t student was used to check for differences between groups (HG vs ADG) as well as one-way ANOVA with repeated measures. We also performed a reliability analysis by reckoning the intraclass coefficient (ICC) with a two-way mixed effects model and absolute agreement, aimed at assessing the concordance of the test-retest measures.

III. Results

In this section we present the results obtained in terms of test performance (accuracy response), task completion times (reaction times), reliability analysis using the test-retest method, and the degree of association between the MEC-35 test scores (only for the ADG) and our task results, respectively. As secondary results, we try to analyze the relationships or degree of association between the different independent variables with the accuracy response (AR) and the reaction times (RT), respectively. Table III shows the obtained results.

TABLE III
Statistical Results for Both the ADG and HG

Measure	ADG	HG
accuracy vs age	rho=0.182, p=0.572	rho=-0.736, p=0.006.
accuracy vs years o. education	rho=-0.035, p=0.913	rho=0.410, p=0.185
accuracy vs time s. diagnosis	rho=0.094, p=0.772	-
Accuracy vs MEC-35	rho=0.710, p=0.01	-
accuracy vs gender	-	t=0.394, p=0.702
Co-morb vs no-co-morb. (accuracy)	t(10) = -6.41, p=0.535	t(10) = 1.051, p=0.318
Repeated measures ANOVA different subtasks (accuracy)	F=0.819, p=0.385	F=35.203, p<0.001
RT vs age	rho=0.472, p=0.121	rho=0.340, p=0.280
RT vs. time s. diagnosis	rho=-0.212, p=0.508,	-
Co-morb vs no-co-morb (total task time)	t(10) = -2.419, p=0.036	t(10) = -0.169, p=869
ICC	0.757	0.821
Paired t-test	t(11) = 1.52, p=0.156	t(11)=1.125, p=0.272

A. Accuracy Response (AR)

With respect to the ADG, we found that age is not related to the accuracy response either in any of the subtasks or in the total task (adding all the subtasks scores). Performance in the task does not depend either on the level of training of the participants or the time since diagnosis of the disease. The participants did not show significant differences in the accuracy response regarding whether or not they had any type of morbidity ($t\ (10) = -6.41$, $p = 0.536$). The analysis of repeated measures to see if there were differences in the accuracy response of each of the subtasks revealed that there were no significant differences between them ($F = 0.819$, $p = 0.385$). Figure 4 depicts the accuracy response results in percentage terms versus the different subtasks for the ADG at baseline and after 3 weeks. Finally, the Spearman's correlation coefficient showed a significant (large and positive) association between the results of the MEC-35 scale and the results obtained with our task ($p = 0.01$, $\rho = 0.710$), respectively. This coefficient is large, according to Cohen [24].

With respect to the HG, we found that age was related to the accuracy response in the whole task (rho=−0.736, p=0.006. Therefore, the older the participant, the worse performance. Performance in the task did not depend either on the level of training of the participants or gender. The participants did not show significant differences in the accuracy response regarding whether or not they had any type of morbidity ($t\ (10) = 1.051$, $p = 0.318$). Unlike the ADG, the analysis of repeated measures revealed significant differences in the accuracy response among the subtasks ($F = 35.203$, $p < 0.001$). Finally, we present the accuracy response results versus subtasks and group in figure 5. Figure 6 depicts the accuracy results for the whole sample (24 participants).

B. Reaction Time (RT)

Regarding the possible associations with the independent variables and the completion times of the respective tasks, we can highlight the following. As far as the ADG is concerned, we did not find any association between the age of the participants and the completion times of the different tasks and the total task. There was also no association between the months since diagnosis and such RT. Regarding co-morbidity and RT, we found significant differences between participants with some type of morbidity in the classroom subtask ($t\ (10) = -2.62$, $p = 0.026$) as well as in the time spent in the whole task ($t\ (10) = -2.419$, $p = 0.036$). In cases of co-morbidity, execution times have been longer in comparison with the no co-morbidity condition.

Regarding the HG, we did not find any association between the age of the participants and the completion times of the different tasks and the total task. Co-morbidity was not either associated to the total completion time of the task (RT). In cases of co-morbidity, execution times have been longer in comparison with the no co-morbidity condition, but non-significant.

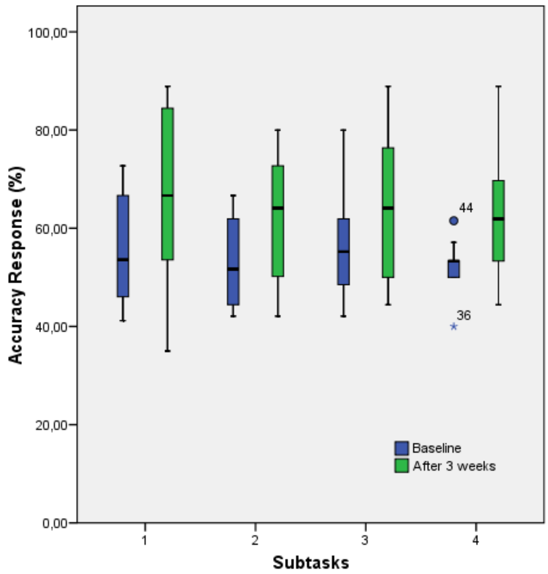


Fig. 4. Accuracy response results (%) vs. subtasks for the ADG at baseline and after 3 weeks. Subtask 1: kitchen, subtask 2: personal hygiene, subtask 3: sewing elements, subtask 4: classroom elements.

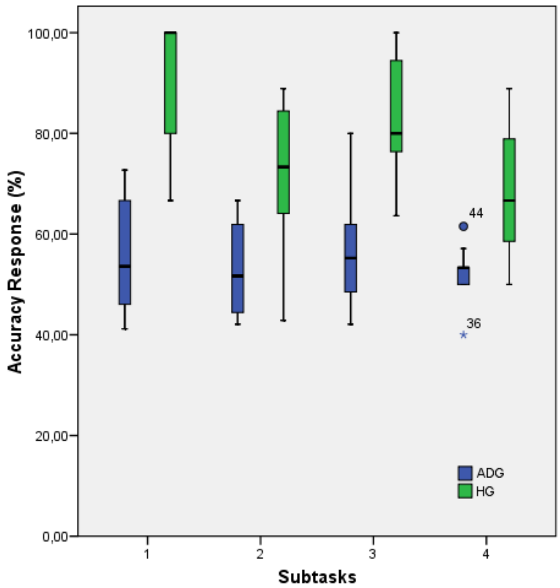


Fig. 5. Accuracy response results (%) versus subtasks for both the ADG and the HG, respectively. Subtask 1: kitchen, subtask 2: personal hygiene, subtask 3: sewing elements, subtask 4: classroom elements.

C. Test Retest Analysis

In order to evaluate the degree of reliability of our task, we performed a test-retest method, applying the same test three weeks after doing it for the first time. This is an adequate analysis since both memory and cognitive impairment

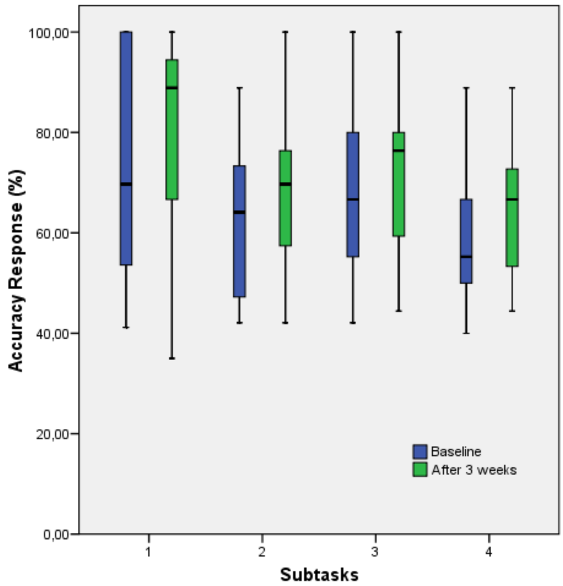


Fig. 6. Accuracy response results (%) for the 24 participants at baseline and after 3 weeks. Subtask 1: kitchen, subtask 2: personal hygiene, subtask 3: sewing elements, subtask 4: classroom elements.

are stable attributes. The degree of agreement between the measures reflected an Intraclass Correlation Coefficient (ICC) of 0.757 for the ADG, which corresponds to an excellent level of clinical significance according to Cicchetti [25]. No significant differences were found between the means of the scores of the task in the two moments in which it was applied ($t(11) = 1.52$; $p = 0.156$). With respect to the HG, we obtained an ICC equals to 0.821, also considered as excellent. In the same way, no significant differences were found between the means of the scores of the task in the two moments in which it was applied ($t(11)=1.125, p=0.272$). The ICC for the whole group was 0.904, an excellent level of clinical significance, too.

D. Pairwise Comparison

We found significant differences between groups in accuracy response in the whole task ($t=5.969$, $p<0.001$). The HG accuracy response mean in the whole task was 78.35 % whereas the ADG accuracy response mean was 54.10 %, respectively. Consequently, the resulting effect size ($d=2.42$) was very large according to Sawilowsky [26]. In the same way the repeated measures one-way ANOVA revealed between subject differences ($F=45.02$, $p<0.001$). We also found statistically significant differences within subjects ($F=27.6$, $p<0.001$) in the different subtasks. The interaction subtask*group was also significant ($F=27.608$, $p<0.001$). Figure 7 shows the estimated marginal means in accuracy response versus subtasks and group. Regarding completion times, we found statistically significant differences between groups ($t=-4.064$, $p=0.001$), with a large effect size ($d=1.66$) according to Cohen [24].

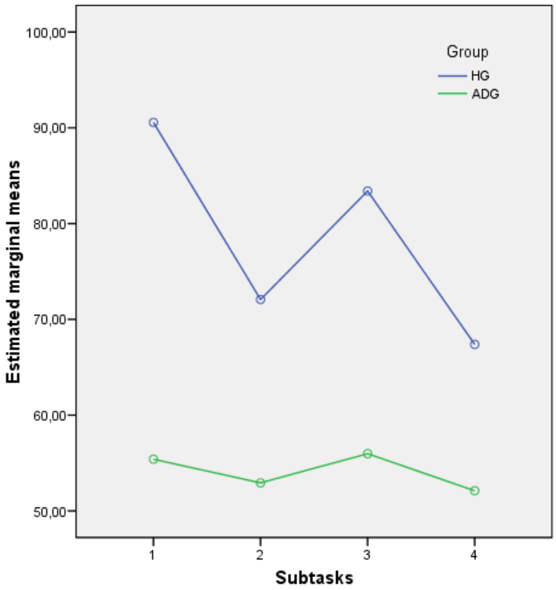


Fig. 7. Accuracy response estimated marginal means vs subtasks and group: ADG and HG. Subtask 1: kitchen, subtask 2: personal hygiene, subtask 3: sewing elements, subtask 4: classroom elements.

IV. Discussion

The main objective of our study was to evaluate the usefulness of a task based on an ADL for the detection of cognitive impairment. The results highlighted a strong positive and significant association with respect to the MEC-35 scale (Spearman rho=0.71) according to Cohen [24]. This results aligns with other works, like the study of Pitteri *et al.* [14], who also found significant correlations between the SDMT and the accuracy response of their task, thus verifying its validity as a diagnostic tool. Similarly, Kalafatis *et al.* [16] demonstrated a convergent validity with the MOCA test (Pearson $r = 0.58$) and the ACE test (Pearson $r = 0.62$), respectively. In both cases they found a slightly lower association than that achieved in our study. In the same way, the reliability values (calculated through the ICC) obtained in the test-retest analysis for both separate groups and considered as a whole sample, reflect an excellent level of clinical significance and therefore give robustness to our proposal.

Although a high correlation is not necessarily synonymous with agreement between methods, this task could hint signs of a cognitive impairment. As mentioned by Nakhla *et al.* [10], people with dementia tend to show lower performance in applications that involve ADLs, particularly in activities that involve memory and verbal fluency. Furthermore, some studies have already shown their ability to detect executive dysfunctions in daily live conditions that were underestimated by these classical tests [27].

The second measurement, using healthy participants performing the same task, has highlighted the usefulness of the test to differentiate between healthy people and people with MCI. The results obtained with the HG have been congruent with those obtained with the ADG, which indicates the consistency of the developed task. Nevertheless, we found some ceiling effects in accuracy performance for the HG only in the kitchen subtask. That is, more than 20% of participants scored 100% [28]. In particular, 7 out of 12 participants got a 100 %, but no one exceeded a 90% accuracy response in the total task (sum of the 4 subtasks), so there was no ceiling effect in the whole task. We find a plausible reason in the fact that participants may be more familiar with the objects in the kitchen and of course they do not have any kind of cognitive impairment. Similarly, Holmes and Shea [28] also found an important ceiling effect when using the instrument for cognitive abilities screening (CASI) to assess global cognitive function in people with dementia. Specifically, 4 cognitive domains were affected by this effect (4 out of 7). However, as in our case, the total score did not show any ceiling effect.

The ceiling effect is quite common when the tests are applied to nonclinical populations, such as the notable ceiling effects found in the RAVLT test [29], which limits its use in populations without evident memory impairments. Therefore, it is often necessary to introduce modifications to such tests or memory tasks. Hale *et al.* had to introduce modifications in their study in order to avoid these effects [30]. Something similar was done by Ivanoiu *et al.* [31] with the free delayed recall test, one of the tests with the highest sensitivity for early diagnosis of dementia. The authors designed a new memory test based on cued recall to avoid ceiling effects in early diagnosis of AD. Wester *et al.* found a reduction in the problem of ceiling and floor effects in the revised Rivermead Behavioral Memory Test (RBMT-3) versus the traditional RBMT [32].

A conclusion that we can obtain from our task is that it is suitable that the objects are known but they must be varied. To reduce the ceiling effect, we could add a little more difficulty, especially in cases of mild cognitive impairment. However, in general we can say that the tool has shown an acceptable discriminative validity when we administer it jointly (as a whole task). Nevertheless, we also agree with many authors that claim the necessity of more research to improve the ecological validity of this kind of memory tasks [32].

Regarding reaction times, the large effect size found between the groups precisely reflects the good cognitive status of the HG participants with respect to the ADG, in addition to the already reflected effect of comorbidity, which affects much more (and in a significant way) to the second group. In addition, the mean age of the ADG was slightly higher than the HG. We found studies in which similar memory tasks were validated (although in virtual environments), such as the one performed by Ouellet *et al.* [33], in which older adults spent more time than young adults in the completion of an everyday memory assessment task. Similarly, Moffat *et al.* [34] showed that the youngest age group performed a spatial memory task much faster than two other older groups of participants.

With respect to the already known age-related differences effect observed on episodic memory tasks, in our task, age was not independently associated with the accuracy response, either in any of the subtasks or in the total task, but only in the ADG. Nevertheless, the HG exhibited a strong (and negative) association between both variables. In the ADG, the low variability of age and the cognitive decline may explain this lack of association. By contrast, similar studies involving healthy participants have corroborated an age-related decrease in performance when dealing with spatial memory [35], [34] or episodic memory [36], [37]. In these cases, there was also a lot of variability in the age of the participants. This fact may lead us to think that certain tasks may be sensitive between age groups with very little variation within the same age group. Therefore, this detail should be taken into account in the design of these tasks, since both age and gender (including cultural background) could have a relevant influence on the results obtained, as described by Coutrot *et al.* [35].

Regarding the level of education of the subjects and the accuracy response, in both cases (individual subtasks and global task) and both groups there was no significant association between both variables. This result is in line with the study of García-Magariño *et al.* [38] despite the fact that the average level of training of the participants in their study (15.09 ± 4.83) was much higher than ours (8.58 ± 1.38), which makes our task very robust in this regard. This contrasts with other studies such as that of Chua *et al.* [11], who found that the range in the educational level of participants was so extraordinarily wide that it became a limitation of their study. To try to tackle the problem, they proposed in the future to stratify their participants by their level of education.

A. Clinical Implications

The introduction of this task as an exercise to be carried out within the daily activity of the AD patient can be very beneficial. On one hand, it would allow the therapist to better monitor the progress of the disease in an automatic way. On the other hand, it could also warn of a possible cognitive deterioration without resorting to the performance of traditional cognitive tests, since the deficiencies in the development of these activities can represent an important and consistent predictor of cognitive deterioration. Early detection of possible cognitive impairment is especially critical in the early stages of the disease and when certain symptoms are not so noticeable, because the pre-dementia stage is quite extensive [39]. For these reasons, such a task could be used when the patient is still relatively young, where the disease evolves more quickly and immediate treatment would have better results [15].

B. Limitations of the Study

The present study has obvious limitations. On one hand, the small size of the sample means that the results, although they are very promising, have to be confirmed in RTC studies with larger samples, in order to offer better evidence. In fact, there are few studies with sufficient evidence that present validated proposals for the diagnosis of cognitive problems. In the same way, cognitive training requires greater support so that it can be considered an effective strategy to promote the recovery of these functions [40], [41].

One of the problems we have found when developing the experience, is that people with some type of co-morbidity (especially cane carriers) have presented higher response times. This directly affects the performance of people when developing ADLs as mentioned by De Vriendt *et al.* [39], since the literature shows that reaction time can be an important variable to be considered [11], [34], [36].

C. Future Work

To overcome the abovementioned problems due to the comorbidity of some patients, we propose in the future the use of virtual reality (VR), either on its non-immersive mode (Tablet or desktop computer) or through an immersive virtual environment (via Head-mounted displays), to overcome these disadvantages. In this case, the subject would be sitting in a chair with total comfort and could be completely concentrated on the task to be carried out. In both cases, the aim is to automate this process in such a way that the therapist has the data through a mobile application and can carry out a more detailed follow-up of each of the patients, with the establishment of alert mechanisms. Thus, the implementation of advanced ADLs is also proposed as future work, since as mentioned by Fieo *et al.* [42], they produce better results than basic ones. We also want to bring this first experience to other groups such as stroke patients, due to their evident needs to promote cognitive functions and prevent dementia. Finally, we see a clear potential of our task to train people with some cognitive impairment in ADLs, as carried out by Foloppe *et al.* in his study [9].

V. Conclusion

With this work, we have demonstrated the usefulness of a memory task based on an ADL for the detection of cognitive impairments. Despite having a small sample of participants, the inclusion of a group of healthy older adults has shown the ability of the task to differentiate between healthy people and people with cognitive impairments. Consequently, the study could be used for early detection of the disease, when certain symptoms that are normally overlooked can be detected, and with this, treatment can be administered in time. The excellent level of clinical significance obtained through the test-retest reliability test give robustness to our proposal.

Acknowledgment

The authors want to thank all the participants for their effort and commitment, the area of Social Services, Family, Equality of the Teruel Town Council as well as SOCIALCORE Ltd. for their support.

References

[1] C. A. Lane, J. Hardy, and J. M. Schott, "Alzheimer's disease," *Eur. J. Neurol.*, vol. 25, pp. 59–70, Jan. 2018, doi: 10.1111/ene.13439.

[2] R. C. Petersen, "Mild cognitive impairment as a diagnostic entity," *J. Internal Med.*, vol. 256, no. 3, pp. 183–194, 2004, doi: 10.1111/j.1365-2796.2004.01388.x.

[3] Y. Liu, W. Tan, C. Chen, C. Liu, J. Yang, and Y. Zhang, "A review of the application of virtual reality technology in the diagnosis and treatment of cognitive impairment," *Frontiers Aging Neurosci.*, vol. 11, p. 280, Oct. 2019, doi: 10.3389/fnagi.2019.00280.

[4] B. Dubois, A. Padovani, P. Scheltens, A. Rossi, and G. Dell'Agnello, "Timely diagnosis for Alzheimer's disease: A literature review on benefits and challenges," *J. Alzheimer's Disease*, vol. 49, no. 3, pp. 617–631, Oct. 2015, doi: 10.3233/JAD-150692.

[5] J. M. F. Montenegro and V. Argyriou, "Cognitive evaluation for the diagnosis of Alzheimer's disease based on Turing test and virtual environments," *Physiol. Behav.*, vol. 173, pp. 42–51, May 2017, doi: 10.1016/j.physbeh.2017.01.034.

[6] G. D. Stanciu *et al.*, "Alzheimer's disease pharmacotherapy in relation to cholinergic system involvement," *Biomolecules*, vol. 10, no. 1, p. 40, Dec. 2019, doi: 10.3390/biom10010040.

[7] E. E. De Roeck, P. P. De Deyn, E. Dierckx, and S. Engelborghs, "Brief cognitive screening instruments for early detection of Alzheimer's disease: A systematic review," *Alzheimer's Res. Therapy*, vol. 11, no. 1, pp. 1–14, Feb. 2019, doi: 10.1186/s13195-019-0474-3.

[8] M. Senda *et al.*, "Diagnostic utility of the Addenbrooke's cognitive examination—III (ACE-III), mini-ACE, mini-mental state examination, Montreal cognitive assessment, and Hasegawa dementia scale-revised for detecting mild cognitive impairment and dementia," *Psychogeriatrics*, vol. 20, no. 2, pp. 156–162, Mar. 2020, doi: 10.1111/psyg.12480.

[9] D. A. Foloppe, P. Richard, T. Yamaguchi, F. Etcharry-Bouyx, and P. Allain, "The potential of virtual reality-based training to enhance the functional autonomy of Alzheimer's disease patients in cooking activities: A single case study," *Neuropsychol. Rehabil.*, vol. 28, no. 5, pp. 709–733, Jul. 2018, doi: 10.1080/09602011.2015.1094394.

[10] M. Z. Nakhla, D. Banuelos, C. Pagán, A. G. Olvera, and J. Razani, "Differences between episodic and semantic memory in predicting observation-based activities of daily living in mild cognitive impairment and Alzheimer's disease," *Appl. Neuropsychol., Adult*, pp. 1–12, Mar. 2021. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/23279095.2021.1893172, doi: 10.1080/23279095.2021.1893172.

[11] S. I. L. Chua *et al.*, "Virtual reality for screening of cognitive function in older persons: Comparative study," *J. Med. Internet Res.*, vol. 21, no. 8, Aug. 2019, Art. no. e14821, doi: 10.2196/14821.

[12] B. Thordardottir, A. M. Fänge, C. Lethin, D. R. Gatta, and C. Chiatti, "Acceptance and use of innovative assistive technologies among people with cognitive impairment and their caregivers: A systematic review," *BioMed Res. Int.*, vol. 2019, pp. 1–18, Mar. 2019, doi: 10.1155/2019/9196729.

[13] J. D. O'Leary, O. F. O'Leary, J. F. Cryan, and Y. M. Nolan, "A low-cost touchscreen operant chamber using a raspberry Pi," *Behav. Res. Methods*, vol. 50, no. 6, pp. 2523–2530, Dec. 2018, doi: 10.3758/s13428-018-1030-y.

[14] M. Pitteri, C. Dapor, S. Ziccardi, M. Guandalini, R. Meggiato, and M. Calabrese, "Visual-attentional load unveils slowed processing speed in multiple sclerosis patients: A pilot study with a tablet-based videogame," *Brain Sci.*, vol. 10, no. 11, p. 871, Nov. 2020, doi: 10.3390/brainsci10110871.

[15] S.-M. Khaligh-Razavi *et al.*, "Integrated cognitive assessment: Speed and accuracy of visual processing as a reliable proxy to cognitive performance," *Sci. Rep.*, vol. 9, no. 1, pp. 1–11, Jan. 2019, doi: 10.1038/s41598-018-37709-x.

[16] C. Kalafatis *et al.*, "Validity and cultural generalisability of a 5-minute AI-based, computerised cognitive assessment in mild cognitive impairment and Alzheimer's dementia," *Frontiers Psychiatry*, vol. 12, p. 1155, Jul. 2021, doi: 10.3389/fpsyt.2021.706695.

[17] F. Marson, S. Lasaponara, and M. Cavallo, "A scoping review of neuromodulation techniques in neurodegenerative diseases: A useful tool for clinical practice?" *Medicina*, vol. 57, no. 3, p. 215, Mar. 2021, doi: 10.3390/medicina57030215.

[18] A. Ruet and B. Brochet, "Cognitive assessment in patients with multiple sclerosis: From neuropsychological batteries to ecological tools," *Ann. Phys. Rehabil. Med.*, vol. 63, no. 2, pp. 154–158, Mar. 2020, doi: 10.1016/j.rehab.2018.01.006.

[19] T. D. Parsons and T. Mcmahan, "An initial validation of the virtual environment grocery store," *J. Neurosci. Methods*, vol. 291, pp. 13–19, Nov. 2017.

[20] M. P. Lawton and E. M. Brody, "Assessment of older people: Self-maintaining and instrumental activities of daily living," *Gerontologist*, vol. 9, pp. 179–186, Oct. 1969.

[21] A. Lobo, J. Ezquerra, F. G. Burgada, J. M. Sala, and A. S. Díaz, "El miniexamen, cognoscitivo (un test sencillo, práctico, para detectar alteraciones intelectuales en pacientes médicos)," *Actas Luso-Espanolas de Neurologia Psiquiatria y Ciencias Afines*, vol. 7, no. 3, pp. 189–202, 1979.

[22] M. F. Folstein, S. E. Folstein, and P. R. McHugh, "'Mini-mental state'. A practical method for grading the cognitive state of patients for the clinician," *J. Psychiatric Res.*, vol. 12, no. 3, pp. 189–198, Nov. 1975, doi: 10.1016/0022-3956(75)90026-6.

[23] F. González-Landero, I. García-Magariño, R. Amariglio, and R. Lacuesta, "Smart cupboard for assessing memory in home environment," *Sensors*, vol. 19, no. 11, p. 2552, Jun. 2019, doi: 10.3390/s19112552.

[24] J. Cohen, *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed. Hillsdale, NJ, USA: Erlbaum Associates, 1988.

[25] D. V. Cicchetti, "Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology," *Psychol. Assessment*, vol. 6, no. 4, pp. 284–290, 1994.

[26] S. S. Sawilowsky, "New effect size rules of thumb," *J. Modern Appl. Stat. Methods*, vol. 8, no. 2, pp. 597–599, Nov. 2009, doi: 10.22237/jmasm/1257035100.

[27] O. Rouaud *et al.*, "Contribution of ecological evaluation of executive disorders in multiple sclerosis," *Revue Neurologique*, vol. 162, no. 10, pp. 964–969, Oct. 2006, doi: 10.1016/s0035-3787(06)75106-2.

[28] W. C. Holmes and J. A. Shea, "Performance of a new, HIV/AIDS-targeted quality of life (HAT-QoL) instrument in asymptomatic seropositive individuals," *Qual. Life Res.*, vol. 6, no. 6, pp. 561–571, 1997.

[29] V. Drolet *et al.*, "A comparison of the performances between healthy older adults and persons with Alzheimer's disease on the rey auditory verbal learning test and the test de rappel libre/rappel indicé 16 items," *Gériatrie et Psychologie Neuropsychiatrie du Vieillissement*, vol. 12, no. 2, pp. 218–226, Jun. 2014, doi: 10.1684/pnv.2014.0469.

[30] C. Hale *et al.*, "The ModRey: An episodic memory test for nonclinical and preclinical populations," *Assessment*, vol. 26, no. 6, pp. 1154–1161, Sep. 2019, doi: 10.1177/1073191117723113.

[31] A. Ivanoiu *et al.*, "Memory evaluation with a new cued recall test in patients with mild cognitive impairment and Alzheimer's disease," *J. Neurol.*, vol. 252, no. 1, pp. 47–55, Jan. 2005, doi: 10.1007/s00415-005-0597-2.

[32] A. J. Wester, P. Leenders, J. I. M. Egger, and R. P. C. Kessels, "Ceiling and floor effects on the rivermead behavioural memory test in patients with alcohol-related memory disorders and healthy participants," *Int. J. Psychiatry Clin. Pract.*, vol. 17, no. 4, pp. 286–291, Oct. 2013, doi: 10.3109/13651501.2013.813553.

[33] É. Ouellet, B. Boller, N. Corriveau-Lecavalier, S. Cloutier, and S. Belleville, "The virtual shop: A new immersive virtual reality environment and scenario for the assessment of everyday memory," *J. Neurosci. Methods*, vol. 303, pp. 126–135, Jun. 2018, doi: 10.1016/j.jneumeth.2018.03.010.

[34] S. D. Moffat, A. B. Zonderman, and S. M. Resnick, "Age differences in spatial memory in a virtual environment navigation task," *Neurobiol. Aging*, vol. 22, no. 5, pp. 787–796, Sep. 2001, doi: 10.1016/S0197-4580(01)00251-2.

[35] A. Coutrot *et al.*, "Global determinants of navigation ability," *Current Biol.*, vol. 28, no. 17, pp. 2861–2866, Sep. 2018, doi: 10.1016/j.cub.2018.06.009.

[36] N. C. Lecavalier, É. Ouellet, B. Boller, and S. Belleville, "Use of immersive virtual reality to assess episodic memory: A validation study in older adults," *Neuropsychol. Rehabil.*, vol. 30, no. 3, pp. 462–480, Mar. 2020, doi: 10.1080/09602011.2018.1477684.

[37] M. O. Pflueger, R.-D. Stieglitz, P. Lemoine, and T. Leyhe, "Ecologically relevant episodic memory assessment indicates an attenuated age-related memory loss—A virtual reality study," *Neuropsychology*, vol. 32, no. 6, pp. 680–689, Sep. 2018, doi: 10.1037/neu0000454.

[38] I. García-Magariño, J. T. Fox-Fuller, G. Palacios-Navarro, A. Baena, and Y. T. Quiroz, "Visual working memory for semantically related objects in healthy adults," *Rev Neurol*, vol. 71, no. 8, pp. 277–284, 2020.

[39] P. De Vriendt, E. Cornelis, W. Cools, and E. Gorus, "The usefulness of evaluating performance of activities in daily living in the diagnosis of mild cognitive disorders," *Int. J. Environ. Res. Public Health*, vol. 18, no. 21, p. 11623, Nov. 2021, doi: 10.3390/ijerph182111623.

[40] T. B. Cumming, K. Tyedin, L. Churilov, M. E. Morris, and J. Bernhardt, "The effect of physical activity on cognitive function after stroke: A systematic review," *Int. Psychogeriatrics*, vol. 24, no. 4, pp. 557–567, 2012, doi: 10.1017/S1041610211001980.

[41] M. N. McDonnell, A. E. Smith, and S. F. Mackintosh, "Aerobic exercise to improve cognitive function in adults with neurological disorders: A systematic review," *Arch. Phys. Med. Rehabil.*, vol. 92, no. 7, pp. 1044–1052, Jul. 2011, doi: 10.1016/j.apmr.2011.01.021.

[42] R. Fieo, L. Zahodne, M. X. Tang, J. J. Manly, R. Cohen, and Y. Stern, "The historical progression from ADL scrutiny to IADL to advanced ADL: Assessing functional status in the earliest stages of dementia," *J. Gerontol., Ser. A*, vol. 73, no. 12, pp. 1695–1700, Nov. 2018, doi: 10.1093/gerona/glx235.

2.2. Artículo: The Cupboard Task: An immersive virtual reality-based system for everyday memory assessment

Int. J. Human–Computer Studies 167 (2022) 102885

Contents lists available at ScienceDirect

International Journal of Human - Computer Studies

journal homepage: www.elsevier.com/locate/ijhcs

The cupboard task: An immersive virtual reality-based system for everyday memory assessment

José Varela-Aldás [a,b], Jorge Buele [a,b], Rebecca Amariglio [c,d], Iván García-Magariño [e], Guillermo Palacios-Navarro [a,*]

[a] Department of Electronic Engineering and Communications, University of Zaragoza, Teruel Politechnic School of Engineering, C/ Atarazana, 2, Teruel 44003, Spain
[b] SISAu Research Group, Facultad de Ingeniería y Tecnologías de la Información y la Comunicación, Universidad Tecnológica Indoamérica, Ambato 180103, Ecuador
[c] Medical School, Harvard University, Boston, MA 02115, USA
[d] Massachusetts General Hospital, Boston, MA 02114, USA
[e] Department of Software Engineering and Artificial Intelligence, Complutense University of Madrid, Madrid 28040, Spain

ARTICLE INFO

Keywords:
Cognitive rehabilitation
Head-mounted display
Immersive virtual reality
Memory assessment
Loci method

ABSTRACT

Background and objective: Virtual Reality (VR) has the capacity to be used in cognitive rehabilitation interventions for diagnostic and training purposes. This technology allows the development of proposals that traditionally have been only implemented using physical elements that imply greater resources and a lesser degree of automation. This work presents an immersive virtual reality (IVR) application (the Cupboard task) for the evaluation of memory in a more ecological way and based on an activity of daily living (ADL).
Methods: To appraise its construct validity, we have carried out a comparative study with a traditional method of memory assessment (method of loci). To check for any association between performance and age, performance with years of education, and reaction time with age, the Pearson's correlation was used. One-way ANOVA was used to check for differences in performance by gender. We also performed a reliability analysis with a two way mixed effects model where people effects are random and measures effects are fixed. Therefore, intra-class correlation coefficient with absolute agreement was reckoned to assess the consistency or concordance of the measures made by both the method of loci and the cupboard IVR task.
Results: Both tasks were evaluated on a sample of 22 healthy participants who voluntarily took part in the experiment. The results obtained showed a high degree of concordance between both memory performance measures, which assumes good clinical relevance. In addition, other age-related effects were found, common to memory assessment tasks.
Conclusions: This work showed that it is possible to use an IVR application to successfully assess everyday memory. We have also demonstrated the potential of IVR to develop valid tests that assess memory functions reliably and efficiently and within ecologically valid contexts. The results obtained open the door to its use in clinical settings for cognitive training (and promoting cognitive health) of patients with mild cognitive impairment (MCI), severe cognitive impairment (SCI) such as Alzheimer or Dementia, etc., with full guarantees of application, although it must first be validated through a randomized control trial (RCT). The degree of usability of the Cupboard task was very high according to the test carried out by the participants.

1. Introduction

The use of VR is widely accepted in clinical settings that allow neuropsychology to treat various cognitive problems (Varela-Aldás et al., 2021). It can also be used to treat cognitive impairment caused by Traumatic brain injury (TBI) (Alashram et al., 2019). Likewise, there are other age-related diseases, such as MCI, which have also been treated through VR. Some of the positive effects that this technology has introduced have been shown in (Gamito et al., 2019; Liao et al., 2020). In the case of major cognitive impairment, like dementia, VR environments have been also developed (D'Cunha et al., 2019; Thapa et al., 2020).

Tests, tools and procedures that have been traditionally performed in a manual way can now be automated with the use of new technologies.

* Corresponding author.
E-mail address: guillermo.palacios@unizar.es (G. Palacios-Navarro).

https://doi.org/10.1016/j.ijhcs.2022.102885
Received 4 September 2021; Received in revised form 21 June 2022; Accepted 30 June 2022
Available online 14 July 2022

VR represents an affordable approach to recovering cognitive functions (Fernandez Montenegro and Argyriou, 2017). There are also other methods for memory training using VR, such as the method of loci (or memory palace method). It is a memorization technique whose origin dates back to classical Greece and Rome and which basically consists of assigning the different parts of the text that you want to memorize to different physical places (real or imaginary). Several studies (Peeters and Segundo-Ortin, 2019; Reggente et al., 2020; Krokos, Plaisant, and Varshney, 2019) have presented different immersive proposals based on this technique that seek to give it greater dynamism and therefore better results.

Another aspect of human cognition that can be affected deals with the visuospatial functions, which allow the representation, analysis and manipulation of objects mentally. In particular, although these functions allow the individual to interact with three-dimensional objects, a great deal of research has been carried out only in two dimensions (Korečko et al., 2019). Thus, it is relevant to determine whether the degree of immersion and the differences between the two and three dimensional designs have an influence on the rehabilitation processes. Ventura et al. (2019) evaluated memory performance through two exercises, the first one within an immersive environment and the second one within a non-immersive environment. The results showed that the group that began with the immersive exercise obtained a better performance when evaluating cognitive function, compared to the other group.

We find different studies in literature that have used ecological EVs for cognitive training and memory evaluation to detect memory dysfunctions (Ruet and Brochet, 2020). For example, Ouellet et al. (2018) focused on the evaluation of everyday memory, whereas Pflueger et al. (2018) and Moffat et al. (2001) evaluated spatial memory. Jebara's study did the same with episodic memory (Jebara et al., 2014) and attention and executive functioning were addressed in the study of Armstrong et al. (2013). We also found examples that have focused on patients with multiple sclerosis with cognitive deficiencies (Goverover et al., 2010; Lamargue-Hamel et al., 2015) or executive disorders (Rouaud et al., 2006). Most of the studies have concluded that these tools are perfectly valid not only for cognitive training in older adults (Corriveau Lecavalier et al., 2020), but for improving memory functions in brain-damaged adults (Caglio et al., 2012) or even for the assessment of episodic memory in Alzheimer's patients (Lecouvey et al., 2019), among others. Furthermore, they have the advantages (with respect to traditional test batteries) of providing an objective measure of individual memory components in ADL simulations (Parsons and McMahan, 2017). To see the importance of the design of this tools compared to the classical evaluation through batteries of neuropsychological tests, some authors have demonstrated their ability to detect executive dysfunctions in daily live conditions that were underestimated by these classical tests in a group of patients with multiple sclerosis (Rouaud et al., 2006). This can be partly understandable since the classic test batteries are performed under very simple and artificial conditions with few or no distractors (Ruet and Brochet, 2020).

In this context, some of the abovementioned studies have included tasks that are based on activities that users can perform in their daily life. The activities of daily living (ADLs) are often called basic ADLs, and they include the fundamental skills typically needed to manage basic physical need, belonging to areas such as personal hygiene, dressing, toileting, ambulating, and eating (Mlinac and Feng, 2016). On the other hand, we can make the distinction with the instrumental ADLs (IADLs), which include activities of a higher level and related to independent living in community. According to Lawton and Brody (1969), these IADLs include activities such as ability to use the telephone, shopping, food preparation, housekeeping, laundry, mode of transportation, responsibility for own medications and the ability to handle finances. However, the concept of IADL should be extended to social participation, since it is closely linked to it. In fact, in the study of Tomioka et al. (2016), a strong association was found between participation in social groups and performing IADLs independently among the community-dwelling elderly, regardless of gender.

The analysis of the literature has shown us the usefulness of VR systems in cognitive training and assessment processes. However, the analyzed works have been more focused on usability and reliability (Krokos et al., 2019; Ventura et al., 2019,; Jebara et al., 2014; Corriveau Lecavalier et al., 2020) without validating the performance with traditional and clinically validated tools. Other works have focused on the evaluation of the performance of everyday life activities (Goverover et al., 2010; Lamargue-Hamel et al., 2015) not being memory tasks per se, for example, purchasing an airline ticket online using the Internet (Goverover et al., 2010; Lamargue-Hamel et al., 2015), or a driving simulator task (Goverover et al., 2010; Lamargue-Hamel et al., 2015). Some works (Ouellet et al., 2018; Moffat et al., 2001; Armstrong et al., 2013; Rouaud et al., 2006; Parsons and McMahan, 2017) have validated performance results with paper-and-pencil test measures by means of correlation coefficient, without using more reliable validation measures such as the intraclass correlation coefficient. Therefore, we consider that there is still a gap that we intend to fill with this work: the use of immersive environments to develop IADL-based memory tasks that can be validated with reliable clinical instruments.

In this work, a system for everyday memory assessment is proposed, using an immersive virtual reality (IVR) environment. Thus, the user exercises sensory-visual memory, working memory, spatial orientation and executive function at the same time. The work is based on an experiment carried out by González-Landero et al. (2019), who proposed a prototype of an automated three-door cupboard with Internet of Things (IoT) technology. The system now proposed fully virtualizes this prototype and increases the cupboard with one more door (4 in total), making data collection (response times and accuracy response) in a more automated and simple way. We hypothesized that our IVR application is an ecological task that can be effective for the assessment of everyday memory. Our hypothesis will be validated with a traditional method such as the method of loci. At the same time, we will check if the task is sensitive to the typical age-related differences effect observed on episodic memory tasks.

2. Materials and methods

2.1. Design of the virtual environment

In this work, we intend to bring to VR an instrumental ADL such as the opening of a series of cupboards to take different objects that can be found in them so that it constitutes a memory assessment tool. We have chosen an IADL task because the associated functions are normally lost before basic ADLs, and therefore the assessment of IADLs may identify early decline (Ward et al., 1998). Fig. 1 shows the general scheme of the IVR-based system. Immersion is achieved using a Head-mounted display (HMD) device (Oculus Go) and a handheld controller that allows interaction with the system. The results generated are stored in the local database and sent to a remote server on the network, for a subsequent analysis. Unity has been used as a game engine.

The virtual environment consists of a task (cupboard task) that is based on an activity of daily life (ADL) for the assessment of everyday memory. Fig. 2 illustrates the two stages of the game. In the training stage (study phase) the user visualizes the elements inside the cupboards. The elements are placed automatically and randomly within the shelves and the doors can be opened individually, with a waiting time for learning that has been set at 10 s (González-Landero et al., 2019). In the evaluation stage (recall phase), the user must locate the elements requested by the application, by selecting both the door and the desired element. The user has a time limit to choose a door and an element (10 s), otherwise an error is recorded and the evaluation continues. Accuracy responses and response times were recorded in plain text files to be saved in the local database and sent to the remote server (SFTP). The data is first stored in a local database to protect us against eventual drops in the WIFI signal in the place where the experiment is carried out. In the

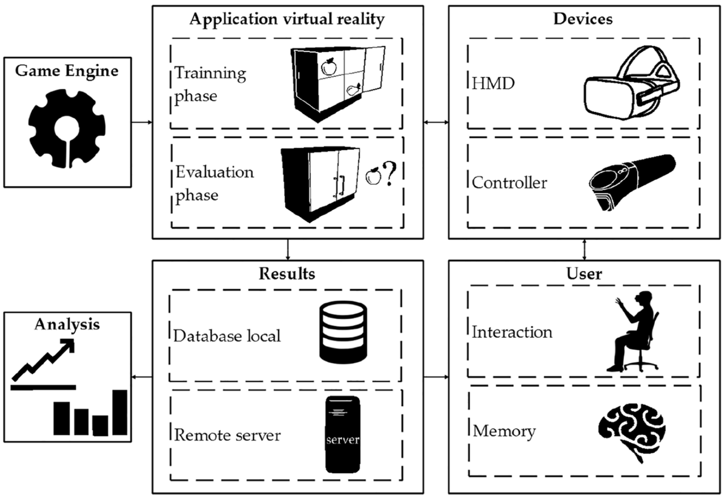


Fig. 1. General description of the IVR-based system.

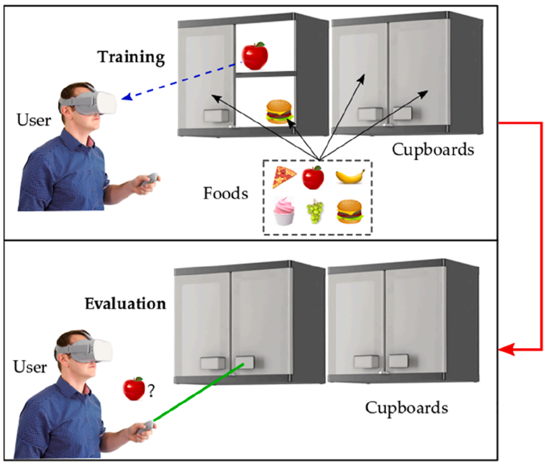


Fig. 2. Activities to be implemented in the VR application.

event of such drops or a poor signal, the data will be stored first in the local database and the next time a proper connection is provided, the data will immediately be sent to the remote server.

2.2. Tasks

To evaluate our IVR-based proposal, we implemented a task based on the method of loci. To apply the technique, each participant had to imagine a house with four rooms to act as the Memory Palace, where different objects were placed in each room. The participant was asked for the places where the elements were placed. The Memory Palace task was implemented through a non-immersive approach (by means of a desktop computer application and a mouse-based interaction). On the other hand, the Cupboard task was implemented via an immersive approach through HMD.

The participants were asked to answer the questions in the shortest time possible. Both tasks were designed according to two levels of difficulty, by configuring 7 elements for the first level and 9 elements for the second level. This means that tthe number of elements to memorize was doubled (14 and 18, respectively). The main reason for selecting such number of objects is twofold. On one hand, it has to do with the experience of other studies dealing with memory tasks. Similar studies such as the one conducted by Plechatá et al., 2021 used four different levels of difficulty with 3, 5, 7 and 9 items to memorize, respectively. Other authors decided to work with a set of 21 faces to remember (Krokos et al., 2019). Reggente et al. (2020) used a sequence of 15 3D objects whereas Corriveau Lecavalier et al. (2020) used 12 articles in his virtual store task and later recovered them in the recall phase from among 24 objects. Although it was not a virtual task, González-Landero et al. (2019) used 15 objects to memorize in a 3-compartment physical cupboard. On the other hand, since we worked in a virtual environment the objects had to be placed in the different compartments with a reasonable level of resolution according to the cupboard dimensions. Finally, the design of interventions with different levels of difficulty has previously been used in numerous cognitive training studies (Gamito et al., 2019; Aarnoudse-Moens et al., 2018; Gamito et al., 2020).

2.3. Intervention

The experiment took place during the covid-19 pandemic, where the mobility conditions for the dates of the experiments were severely restricted. This resulted in a very hard recruiting process. Although an RCT may provide more evidence, we opted for a quasi-experimental one-group design, in order to seek greater efficiency of the statistical contrast by reducing variability and so increasing statistical power.

The experiment was performed in two different days. The first day was devoted to the Loci task, whereas the second day the cupboard task was performed. Before carrying out the Loci task, each participant worked on concentration exercises for 15 min to prepare them for the task. In the VR task, users were familiarized with the virtual environment prior to the start of the tests for 15 min approximately (handling of the laser pointer to open doors, selection of objects, etc.). Therefore, the intervention time for every participant was about 30 min each day (60 min for the whole experiment). Fig. 3 shows a participant performing the Cupboard task with the Oculus Go.

2.4. Statistical analysis

Statistical analysis was carried out using SPSS 16. Shapiro-Wilk test was performed to check for data normality (the sample is less than 30 participants). Pearson's Chi-squared test was used to verify the

Fig. 3. Participant performing the Cupboard task with the Oculus Go.

homogeneity regarding to gender. To check for any association between performance and age, performance with years of education, and reaction time with age, the Pearson's correlation was used. One-way ANOVA was used to check for differences in performance by gender. We also performed a reliability analysis with a two way mixed effects model where people effects are random and measures effects are fixed. Therefore, intra-class correlation coefficient with absolute agreement was reckoned to assess the consistency or concordance of the measures made by both the Memory Palace method and the cupboard IVR task. Finally, a usability test was completed by the sample to measure feasibility of the developed IVR task. The statistical significance level was set to 0.05.

2.5. Participants

Initially we wanted to detect a large correlation according to Cohen (1988) ($\geq$ 0.5), between both methods. Therefore, for a significance level equal to 0.05 and a power of 80% (the usual value in research), GPower software (G Power, 2020) gave us a sample of 21 subjects. A total of 22 healthy subjects were recruited. The Mini Mental State Examination (MMSE) test was used as a screening measure in the enrollment phase. The inclusion criteria were: (a) ages between 18 and 65 years old; (b) MMSE score greater or equal to 26 as suggested by Kukull et al. (1994); and (c) no physical limitations, especially in the hand they use most frequently. Initial training was given to the participants prior to the experiment to give them the opportunity to get familiar with the VR setup (understanding of controls and basic actions). The study was carried out according to the Declaration of Helsinki and was approved by the Institutional Review Board of Universidad Tecnológica Indoamerica (protocol code UTI-IIDI-054-2021, approval date 18 March 2021). All the participants were volunteers and signed an informed consent previous to their participation in the research. The demographics of the participants is depicted in Table 1. No significant differences were found in the sample with respect to gender (p = .394).

3. Results

We present the results obtained after the experiments for both tasks, as well as a comparison in terms of accuracy response. Table 2 shows the accuracy response results as a percentage for both tasks (memory palace and VR Cupboard).

Table 1
Participant demographics.

Demographics	Value	%	Demographics	Value
Gender:			Age	
Male	9	40.91	Mean	36.64
Female	13	59.09	SD	12.91
Experience VR			Education years	
Yes	7	31.82	Mean	13.59
No	15	68.18	SD	4.24
Cognitive exercise				
Yes	17	77.27		
No	5	22.73		

3.1. Memory palace

The results obtained after applying the memory palace method collected the precision and reaction times of the 22 participants in 2 levels of difficulty (with 2 rounds per level). Although a positive and high significant association (r = 0.477) was observed in the accuracy response in the two levels, the paired-samples t test did not reveal significant differences between levels (t (21), p = 0.219). No association was found between performance and age (Pearson's correlation not statistically significant) either. Regarding reaction times, we only found a significant positive correlation with age only in the case of 9 elements (r = 0.551, p = 0.008).

3.2. Cupboard task

The procedure to be carried out in the Cupboard task was similar to the previous one. With regard to the relationship between performance and age, a very high and negative Pearson correlation (- 0.751) significant at the 0.01 level was found. On the contrary, we did not find any association between performance and years of formal education (p > 0.05). There were no differences by sex in terms of performance at this level either (F (1.20) = 0.379, p = 0.545)). Regarding reaction times, three were recorded: the cupboard time (CT) or time to select the cupboard, the object time (OT) or time it takes to select the object, and the total time (TT), or sum of the previous times.

On the other hand, and for level 1, we found a high and positive association (Pearson's coefficient = 0.814) significant at the 0.01 level between the cupboard reaction time and the age of the participants. We repeated the calculation for the total reaction time of the task, and we find a very similar situation (Pearson's coefficient high (0.831) and significant at the 0.01 level). We also had a negative and high association between total reaction time and performance (Pearson's coefficient = -0.928, p < 0.001), which indicates that the longer the reaction time, the worse the results. Regarding the relationship between performance and age, no significant Pearson correlation was found. Similarly, no association was found between performance and years of formal education (p > 0.05). Therefore, the performance in the execution of the task (in the two levels of difficulty) does not depend on the educational level of the participants. We did not find differences by sex in terms of performance at this level (F (1,20) = 2.413, p = 0.136)) either. The paired-samples t test did not reveal significant differences between the accuracy response at the two levels (t (21), p = 0.795).

In relation to reaction times (cupboard time) and age, we found a moderate and positive association (Pearson's coefficient = 0.457) significant. Although in the case of 9 objects the correlation is lower than in the case of 7, in both cases it is observed that the older the subject, the longer the response time is. We found a very similar situation (Pearson's coefficient =0.504 and significant p = 0.017) after repeating the calculation for the total time. We also had a negative and high association between total reaction time and performance (Pearson's coefficient = -0.690, p < 0.001), which indicated that the longer the reaction time, the worse the results.

Table 2
Accuracy response results (%) for both tasks (Memory Palace and VR Cupboard).

	Measure	Memory Palace [%] Round 1	Round 2	All	VR Cupboard task [%] Round 1	Round 2	All
Level 1	Mean	62.5	71.99	67.24	71.38	70.86	71.12
	SD	25.61	27.81	26.85	20.91	17.47	19.04
Level 2	Mean	69.7	76.26	72.98	70.48	70.66	70.57
	SD	24.77	20.94	22.91	16.32	14.99	15.49

3.3. Accuracy response. Comparisons between methods

In this section we compare the two methods for memory assessment. To assess the consistency of the measures made by both the Memory Palace method and the cupboard task and thereby validate the latter, we have reckoned the intra-class correlation coefficient with absolute agreement. This measure is much more robust than Pearson's correlation coefficient, since the latter does not assess agreement since it is not sensitive to differences of constant type or proportional type, respectively.

For the first level (7 objects) an intra-class correlation coefficient of .614 was obtained, while for the second level (9 objects) an intra-class correlation coefficient of, 0.662 was obtained, which according to Cicchetti (1994), correspond to a good level of clinical significance (reliability coefficient between .60 and .74). In addition, in both cases the result of the ANOVA analysis reflects the absence of bias because the means obtained with these two tools do not present significant differences ($F = 0.507$; $p = 0.484$) for the case of 7 items and ($F = 0.917$; $p = 0.349$) for the case of 9 items, respectively.

To complement the validity analysis of our method, and since the differences in measurements between the two methods followed a normal distribution (Shapiro-Wilk test non-significant), we were able to apply the Bland-Atman graphical test (Bland-Atman plot), whose result is depicted in Figs. 4 and 5, respectively. We see that the mean difference is close to zero, -3.32 at the first level (see Fig. 4) and 3.2 at the second level (see Fig. 5), respectively, which indicates that both methods obtain similar means. For the first level (7 objects), the VR Cupboard method overestimates the results with respect to the Loci method (negative mean), since it measures 3.32 more units on average. On the other hand, in the second level (9 objects), the VR Cupboard method underestimates the results (positive mean), since it measures 3.2 units less (on average). Anyway, such value (systematic bias) is limited to ±3%, approximately, with respect to the maximum of the scale, which implies a good approximation of the methods. It is observed that 95% of the differences between both methods are located between the limits of agreement.

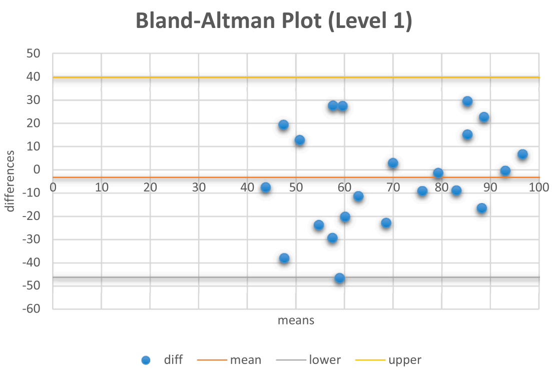


Fig. 4. Bland-Altman plot for both Memory Palace and VR Cupboard task in the first level of difficulty (7 objects). Horizontal axis: mean of both methods. Vertical axis: differences between methods (paired values). Lower and upper limits of agreement mean 95% CI for differences between methods.

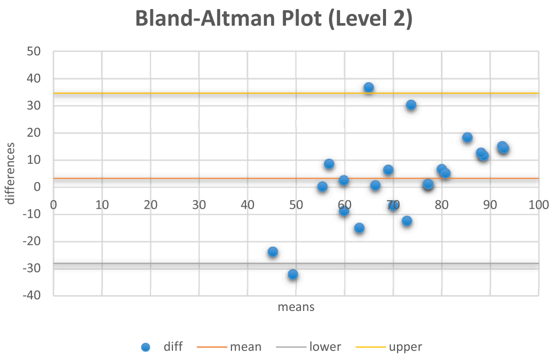


Fig. 5. Bland-Altman plot for both Memory Palace and VR Cupboard task in the second level of difficulty (9 objects). Horizontal axis: mean of both methods. Vertical axis: differences between methods (paired values). Lower and upper limits of agreement mean 95% CI for differences between methods.

Only a couple of outliers appear at level 2 (9 items), which may be due to the increased difficulty. These limits establish the range in which the differences will be found in the data of both methods (approximately 95% of the time). Finally, it is important to mention that the variability is consistent throughout the range of values and around the bias line (mean difference line).

3.4. Usability analysis

To assess the feasibility of the application from the participants' point of view, the USEQ (User Satisfaction Evaluation Questionnaire) (Gil-Gómez et al., 2017) satisfaction test was applied. The results showed us a high degree of participant satisfaction (see Table 3). In general, the participants approved the characteristics of the system and considered that the proposal may be helpful in cognitive rehabilitation. An additional question about their task preference (Memory Palace vs Cupboard Task) was asked to the participants, and 86.36% of them showed preference for the Cupboard Task.

Table 3
USEQ test results for the VR Cupboard task.

Question	Mean	SD
Q1. Did you enjoy your experience with the system?	4.82	0.49
Q2. Were you successful using the system?	4.43	0.53
Q3. Were you able to control the system?	4.91	0.29
Q4. Is the information provided by the system clear?	4.95	0.21
Q5. Did you feel discomfort during your experience with the system?	4.82	0.49
Q6. Do you think that this system will be helpful for rehabilitation?	4.95	0.21
Total:	28.89/ 30	0.37

4. Discussion

4.1. Construct validity

Our hypothesis regarding the construct validity of the VR-based designed task was that the memory performance in the Cupboard task would have a great deal of concordance to that obtained via a traditional assessment method, such as the method of loci. The results obtained (accuracy response) after comparison of the developed system with a conventional memory measurement system (method of memory palace or loci), attest to this. The measure of consistency or concordance (with absolute agreement) of both methods, performed through the intra-class correlation coefficient, has revealed a good level of clinical significance, according to Cicchetti (1994). This was true for the two levels of difficulty implemented in the task. Moreover, no bias was observed between the means obtained by both methods and both levels of difficulty. The choice of this measure of concordance, through ICC (instead of Pearson's correlation), together with the verification through the Bland-Atman diagram, provide us with a high degree of validity in the confirmation of our hypothesis. Although our results align with previous studies pointing out that VR can measure similar constructs as those measured by clinical or experimental measures, we find some differences with them.

Taking into account similar studies identified in the literature, some of them do not make any comparison between the performance of both methods (VR task versus traditional cognitive tests) to validate the experimental method (Goverover et al., 2010; Lamargue-Hamel et al., 2015; Plechatá et al., 2021). Other studies use the Pearson's correlation to see the degree of association between the cognitive performance achieved with the virtual tool and some traditional cognitive tests (Ouellet et al., 2018; Moffat et al., 2001; Parsons and McMahan, 2017). For example, Moffat et al. (2001) found moderate to low correlations between navigation performance in the virtual task and traditional psychometric measures of cognitive aging. Parsons and McMahan (2017) only found moderate correlations with the traditional neuropsychological memory scores in her Virtual Environment Grocery Store task for both conditions imposed in their study (low distraction and high distraction on the virtual task). Ouellet et al. (2018) only found moderate correlations in the scores for correct recall in the Virtual Shop task compared to traditional neuropsychological measure of episodic memory (r=0.35). However, they found no association between performance on the measure of episodic memory and the Multifactorial Memory Questionnaire (Troyer et al., 2006). Therefore, the degrees of association found by the aforementioned studies were moderate to low, whereas our study found a good clinical validity in our comparison through an ICC greater than 0.6.

We also think that the good results obtained by our task could have come from the fact that the task, as occurs with the loci method, reinforces an object-location binding behavior during encoding (Reggente et al., 2020). This is one of the strengths that we have tried to exploit in the VR Cupboard task, which reinforces theoretical memory models that emphasize spatial context in encoding as the core of mnemonic function (Reggente et al., 2020) and adds evidence to the fact that spatial context has influence on event memory (Robin et al., 2018). Some authors such as Wallet et al. (2011) have suggested that spatial knowledge from virtual environments could be transferable to the real world.

Another aspect that has been widely discussed in the literature and that has been able to contribute to obtaining good results in our study lies in the fact that the assessment task is based on an instrumental activity of daily living (IADL). Our results may have been influenced (positively) by the inclusion of a more meaningful environment as evidence suggests that memory for real-life objects is more efficient when the objects are in a context (Pflueger et al., 2018). This makes this type of memory assessment tasks closer to the functioning of everyday memory and therefore can better predict problems related to memory than clinical tests, as pointed out by Pflueger et al. (2018). Also the elicitation of a strong sense of "being physically present", as well as the induction in the observer of virtual embodiment that these immersive systems provide, has also been able to contribute to the good results of our task.

4.2. Age-related differences

In addition to the above, we wanted to demonstrate that the task would be sensitive to typical age-related differences effect observed on episodic memory tasks. In fact, our task was sensitive to age, as younger adults performed better than older adults as far as the accuracy response was concerned. This means that the VR task thus designed is sensitive to typical memory impairment (Craik, 1986). These results align with other recent and related studies on VR tasks for memory assessment (Corriveau Lecavalier et al., 2020; Pflueger et al., 2018). The study of Plechatá et al. (2021) implemented the same task (shopping task) in two systems (immersive and non-immersive) and found age-related differences in terms of both assessed performance and user experience, respectively, when dealing with episodic memory. Other studies have corroborated this same age-related decrease in performance when dealing with spatial memory (Moffat, Zonderman, and Resnick, 2001; Maidenbaum et al., 2019; Coutrot et al., 2018). Regarding reaction times, the observed correlation between age and reaction times on our task aligns with other visual working memory tasks (García-Magariño et al., 2020). In the work of Armstrong et al. (2013) there was also a positive correlation of age with the average response times for the two VR conditions in their experiment. Ouellet et al. (2018) also found longer completion times in older adults compared to younger ones.

4.3. Influence of the type of virtual environment

Another noteworthy issue that we have not addressed because it was not the subject of study, deals with the influence of the type of virtual environment used (immersive vs. non-immersive) on performance in memory tasks. Krokos et al. (2019) found that the participants in the immersive condition performed 8.8% higher compared to the non-immersive condition as far as the overall average recall performance was concerned. Similarly, Huttner et al. (2019) concluded that all the average scores in the immersive condition were approximately 5 to 7% higher than those in the non-immersive condition. However, Maidenbaum et al. (2019) found that humans display similar spatial memory performance in a spatial memory task both when performing it via a standard computer screen and via an HMD. In our case, we have not found significant differences in performance between the two methods (loci vs. VR Cupboard task) and conditions (immersive vs. non-immersive). We realize that the studies carried out to date are not conclusive in this matter and therefore the debate is still open and deserves due attention.

4.4. Usability

Finally, the usability analysis of the proposal yields satisfactory results meeting the expectations of the researchers (USEQ = 96.3%), because the application was designed with practical and easy-to-use features, including clear and reduced information, and limiting movements within the virtual environment to avoid discomfort in the user. These results are consistent with other proposals for immersive VR via HMD, such as that of Hassandra et al. (2021) focused on older people with MCI symptoms. Plechatá et al. (2021) also reported a very good user experience with the immersive tool, although they used an ad hoc developed usability questionnaire.

4.5. Limitations

The study carried out has numerous limitations that should be taken into account when interpreting the results. First, the experiment took place during the covid-19 pandemic, which resulted in a very hard recruiting process and it took a lot to get the final number of participants. Since all the participants were volunteers, this detail could introduce some selection bias. On the other hand, the dose used in each task might have not been sufficient to achieve a greater improvement in performance of participants. In addition, each task was performed only once by each participant. Participants could have repeated the task after an interval of 3 weeks, thereby making some assessment of reliability through test-retest analysis. Another limitation that could be addressed in further studies is that the recall process was tested immediately after the encoding period, so we do not have a measure of long-term memory durability. As far as technical aspects of the system are concerned, some of the participants experienced some difficulties in handling the small joystick that comes with the VR googles. Hence, the reaction times have been longer. To overcome this limitation, we are working in a new version of the system by using the Oculus Quest 2, a new generation of HMDs. that allow the user interact with the VR environment with his/her hands, yet they provide full hand tracking. On one hand, the participants would not be worried and focused on pressing the right button anymore, and at the same time kinematics parameters such us reaction times will improve as they would be lower.

4.6. *Applications and future work*

The low cost and simplicity of our solution, together with the automation of data collection immediately, open the doors to its use as a routine memory task for the early detection of cognitive decline, not only in home-based environments, but in clinical settings. In a very simple way, and with the designed task included in a rehabilitation program, a routine that sends data to the occupational therapist to know the cognitive status of each patient can be easily programmed. By contrast, we have found in literature virtual tasks that are not easy to perform in clinical practice, since they require specific facilities such as sleep laboratories facilities. We found an example of such tasks in the one designed by Lamargue-Hamel et al. (2015) (Driving Simulator Dual Task), in which, in addition, some participants experienced motion sickness and were not able to complete the task.

Future work deals with the design of proposals for both cognitive assessment and training using immersive VR systems, to elucidate the ability of these systems to improve the cognitive performance of population. We also want to investigate of the effects of active navigation in virtual environments on memory performance. The term active navigation (mainly in virtual environments) refers to the idea of navigating through an environment in an active, self-directed way, or by performing a free exploration. Research in this area suggests that VE exploration by means of an active navigation enables superior spatial learning compared with a more passive, or observational encounter of the same environment (von Stülpnagel and Steffens, 2012). According to Wilson et al. (1997), active navigation in VE can be divided into physical activity (motor control) and psychological activity (decision-making). The processes involved in active navigation constitutes a type of enactment that can lead to memory performance enhances both in spatial (Brooks, 1999) and episodic memory (Jebara et al., 2014). Finally, we plan to carry on a randomized control trial (RCT) including participants with some cognitive impairments such as people suffering from Alzheimer's disease. Such study could show us more evidence about the discriminant ability of our task in the cognitive aspect.

5. Conclusions

This work showed that it is possible to use an IVR application to successfully assess everyday memory. The results of our study have demonstrated a good level of clinical significance, in addition to the fact that the task maintains the characteristics of traditional memory tasks (e.g. age-related differences). We have also demonstrated the potential of IVR to establish a new methodology to develop valid tests that assess memory functions reliably and efficiently and within ecologically valid contexts. The results obtained open the door to its use in clinical settings for cognitive training (and promoting cognitive health) of patients with MDI, DCI, Alzheimer, etc. with full guarantees of application, although it must first be validated through a randomized control trial (RCT).

Institutional review board statement

The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of UNIVERSIDAD TECNOLÓGICA INDOAMÉRICA (protocol code UTI-IIDI-054-2021, approval date 18 March 2021).

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgments

The authors wish to thank the participants and the Universidad Tecnológica Indoámerica for the support provided in this research.

References

Aarnoudse-Moens, C.S.H., Twilhaar, E.S., Oosterlaan, J., van Veen, H.G., Prins, P.J.M., van Kaam, A.H.L.C., van Wassenaer-Leemhuis, A.G., 2018. Executive function computerized training in very preterm-born children: a pilot study. Games Health J. 7, 175–181. https://doi.org/10.1089/g4h.2017.0038.

Alashram, A.R., Annino, G., Padua, E., Romagnoli, C., Mercuri, N.B., 2019. Cognitive rehabilitation post traumatic brain injury: a systematic review for emerging use of virtual reality technology. J. Clin. Neurosci. 66, 209–219. https://doi.org/10.1016/j.jocn.2019.04.026.

Armstrong, C.M., Reger, G.M., Edwards, J., Rizzo, A.A., Courtney, C.G., Parsons, T.D., 2013. Validity of the Virtual Reality Stroop Task (VRST) in active duty military. J. Clin. Exp. Neuropsychol. 35, 113–123. https://doi.org/10.1080/13803395.2012.740002.

Brooks, B.M., 1999. The specificity of memory enhancement during interaction with a virtual environment. Memory 7, 65–78. https://doi.org/10.1080/741943713.

Caglio, M., Latini-Corazzini, L., D'Agata, F., Cauda, F., Sacco, K., Monteverdi, S., Zettin, M., Duca, S., Geminiani, G., 2012. Virtual navigation for memory rehabilitation in a traumatic brain injured patient. Neurocase 18, 123–131. https://doi.org/10.1080/13554794.2011.568499.

Cicchetti, D.V., 1994. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. Psychol. Assess. 6, 284–290.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences, 2nd ed. L. Erlbaum Associates, Hillsdale, N.J.

Corriveau Lecavalier, N., Ouellet, É., Boller, B., Belleville, S., 2020. Use of immersive virtual reality to assess episodic memory: a validation study in older adults. Neuropsychol. Rehabil. 30, 462–480. https://doi.org/10.1080/09602011.2018.1477684.

Coutrot, A., Silva, R., Manley, E., de Cothi, W., Sami, S., Bohbot, V.D., Wiener, J.M., Hölscher, C., Dalton, R.C., Hornberger, M., Spiers, H.J., 2018. Global determinants of navigation ability. Curr. Biol. 28, 2861–2866.e4. https://doi.org/10.1016/j.cub.2018.06.009.

Craik, F.I.M., 1986, "A functional account of age differences in memory," In: F. Klix and H. Hagendorf, Eds., Human Memory and Cognitive Capabilities: Mechanisms and Performances, Elsevier, Amsterdam, pp. 409-422.

D'Cunha, N.M., Nguyen, D., Naumovski, N., McKune, A.J., Kellett, J., Georgousopoulou, E.N., Frost, J., Isbel, S., 2019. A mini-review of virtual reality-based interventions to promote well-being for people living with dementia and mild cognitive impairment. Gerontology 65, 430–440. https://doi.org/10.1159/000500040.

Fernandez Montenegro, J.M., Argyriou, V., 2017. Cognitive evaluation for the diagnosis of Alzheimer's disease based on Turing Test and Virtual Environments. Physiol. Behav. 173, 42–51. https://doi.org/10.1016/j.physbeh.2017.01.034.
G Power, n.d. 2020 https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.
Gamito, P., Oliveira, J., Alves, C., Santos, N., Coelho, C., Brito, R., 2020. Virtual reality-based cognitive stimulation to improve cognitive functioning in community elderly: a controlled study. Cyberpsychol. Behav. Soc. Netw. 23, 150–156. https://doi.org/10.1089/cyber.2019.0271.
Gamito, P., Oliveira, J., Morais, D., Coelho, C., Santos, N., Alves, C., Galamba, A., Soeiro, M., Yerra, M., French, H., Talmers, L., Gomes, T., Brito, R., 2019. Cognitive stimulation of elderly individuals with instrumental virtual reality-based activities of daily life: pre-post treatment study. Cyberpsychol. Behav. Soc. Netw. https://doi.org/10.1089/cyber.2017.0679.
García-Magariño, I., Fox-Fuller, J.T., Palacios-Navarro, G., Baena, A., Quiroz, Y.T., 2020. Visual working memory for semantically related objects in healthy adults. Rev. Neurol 71, 277–284.
Gil-Gómez, J.A., Manzano-Hernández, P., Albiol-Pérez, S., Aula-Valero, C., Gil-Gómez, H., Lozano-Quilis, J.A., 2017. USEQ: a short questionnaire for satisfaction evaluation of virtual rehabilitation systems. Sensors 17, 1–12. https://doi.org/10.3390/s17071589.
González-Landero, F., García-Magariño, I., Amariglio, R., Lacuesta, R., 2019. Smart cupboard for assessing memory in home environment. Sensors 19, 2552. https://doi.org/10.3390/s19112552.
González-Landero, F., García-Magariño, I., Amariglio, R., Lacuesta, R., 2019. Smart cupboard for assessing memory in home environment. Sensors 19, 1–21. https://doi.org/10.3390/s19112552.
Goverover, Y., O'Brien, A.R., Moore, N.B., DeLuca, J., 2010. Actual reality: a new approach to functional assessment in persons with multiple sclerosis. Arch. Phys. Med. Rehabil. 91, 252–260. https://doi.org/10.1016/j.apmr.2009.09.022.
Hassandra, M., Galanis, E., Hatzigeorgiadis, A., Goudas, M., Mouzakidis, C., Karathanasi, E.M., Petridou, N., Tsolaki, M., Zikas, P., Evangelou, G., Papagiannakis, G., Bellis, G., Kokkotis, C., Panagiotopoulos, S.R., Giakas, G., Theodorakis, Y., 2021. A virtual reality app for physical and cognitive training of older people with mild cognitive impairment: mixed methods feasibility study. JMIR Serious Games 9, e24170. https://doi.org/10.2196/24170.
Huttner, J.-P., Qian, Z., Robra-Bissantz, S., 2019. A Virtual memory palace and the user's awareness of the method of Loci. In: Proceedings of the European Conference on Information Systems (ECIS2019. Stockholm-Uppsala, Sweden, pp. 1–14.
Jebara, N., Orriols, E., Zaoui, M., Berthoz, A., Piolino, P., 2014. Effects of enactment in episodic memory: a pilot virtual reality study with young and elderly adults. Front. Aging Neurosci 6. https://doi.org/10.3389/fnagi.2014.00338.
Korečko, Š., Hudák, M., Sobota, B., Marko, M., Cimrová, B., Farkaš, I., Rosipal, R., 2019. Assessment and training of visuospatial cognitive functions in virtual reality: proposal and perspective. In: Proceedings of the 9th IEEE International Conference on Cognitive Infocommunications, CogInfoCom 2018. Institute of Electrical and Electronics Engineers Inc., pp. 39–44
Krokos, E., Plaisant, C., Varshney, A., 2019. Virtual memory palaces: immersion aids recall. Virtual Real. 23, 1–15. https://doi.org/10.1007/s10055-018-0346-3.
Kukull, W.A., Larson, E.B., Teri, L., Bowen, J., McCormick, W., Pfanschmidt, M.L., 1994. The mini-mental state examination score and the clinical diagnosis of dementia. J. Clin. Epidemiol. 47, 1061–1067. https://doi.org/10.1016/0895-4356(94)90122-8.
Lamargue-Hamel, D., Deloire, M., Saubusse, A., Ruet, A., Taillard, J., Philip, P., Brochet, B., 2015. Cognitive evaluation by tasks in a virtual reality environment in multiple sclerosis. J. Neurol. Sci. 359, 94–99. https://doi.org/10.1016/j.jns.2015.10.039.
Lawton, M.P., Brody, E.M., 1969. Assessment of older people: self-maintaining and instrumental activities of daily living. Gerontologist 9, 179–186.
Lecouvey, G., Morand, A., Gonneaud, J., Piolino, P., Orriols, E., Pélerin, A., Da Silva, L.F., de La Sayette, V., Eustache, F., Desgranges, B., 2019. An impairment of prospective memory in mild Alzheimer's disease: a ride in a virtual town. Front. Psychol. 10, 1–12. https://doi.org/10.3389/fpsyg.2019.00241.
Liao, Y.Y., Tseng, H.Y., Lin, Y.J., Wang, C.J., Hsu, W.C., 2020. Using virtual reality-based training to improve cognitive function, instrumental activities of daily living and neural efficiency in older adults with mild cognitive impairment. Eur. J. Phys. Rehabil. Med. 56, 47–57. https://doi.org/10.23736/S1973-9087.19.05899-4.
Maidenbaum, S., Patel, A., Stein, E., Jacobs, J., 2019. Spatial memory rehabilitation in virtual reality - extending findings from epilepsy patients to the general population. In: Proceedings of the International Conference on Virtual Rehabilitation. ICVR, Institute of Electrical and Electronics Engineers Inc.
Mlinac, M.E., Feng, M.C., 2016. Assessment of activities of daily living, self-care, and independence. Arch. Clin. Neuropsychol. 31, 506–516. https://doi.org/10.1093/arclin/acw049.
Moffat, S.D., Zonderman, A.B., Resnick, S.M., 2001. Age differences in spatial memory in a virtual environment navigation task. Neurobiol. Aging 22, 787–796. https://doi.org/10.1016/S0197-4580(01)00251-2.
Ouellet, É., Boller, B., Corriveau-Lecavalier, N., Cloutier, S., Belleville, S., 2018. The virtual shop: a new immersive virtual reality environment and scenario for the assessment of everyday memory. J. Neurosci. Methods 303, 126–135. https://doi.org/10.1016/j.jneumeth.2018.03.010.
Parsons, T.D., McMahan, T., 2017. An initial validation of the virtual environment grocery store. J. Neurosci. Methods 291, 13–19. https://doi.org/10.1016/j.jneumeth.2017.07.027.
Peeters, A., Segundo-Ortin, M., 2019. Misplacing memories? An enactive approach to the virtual memory palace. Conscious. Cogn. 76, 102834 https://doi.org/10.1016/j.concog.2019.102834.
Pflueger, M.O., Stieglitz, R.D., Lemoine, P., Leyhe, T., 2018. Ecologically relevant episodic memory assessment indicates an attenuated age-related memory loss - a virtual reality study. Neuropsychology 36, 680–689.
Plechatá, A., Nekovářová, T., Fajnerová, I., 2021. What is the future for immersive virtual reality in memory rehabilitation? A systematic review. NeuroRehabilitation 1–24. https://doi.org/10.3233/nre-201534. Preprint.
Reggente, N., Essoe, J.K.Y., Baek, H.Y., Rissman, J., 2020. The method of loci in virtual reality: explicit binding of objects to spatial contexts enhances subsequent memory recall. J. Cogn. Enhanc. 4, 12–30. https://doi.org/10.1007/s41465-019-00141-8.
Reggente, N., Essoe, J.K.Y., Baek, H.Y., Rissman, J., 2020. The method of loci in virtual reality: explicit binding of objects to spatial contexts enhances subsequent memory recall. J. Cogn. Enhanc. 4, 12–30. https://doi.org/10.1007/s41465-019-00141-8.
Robin, J., Buchsbaum, B.R., Moscovitch, M., 2018. The primacy of spatial context in the neural representation of events. J. Neurosci. 38, 2755–2765. https://doi.org/10.1523/JNEUROSCI.1638-17.2018.
Rouaud, O., Graule-Petot, A., Couvreur, G., Contegal, F., Osseby, G.V., Benatru, I., Giroud, M., Moreau, T., 2006. Apport de l'évaluation écologique des troubles exécutifs dans la sclérose en plaques. Rev. Neurol. (Paris) 162, 964–969. https://doi.org/10.1016/S0035-3787(06)75106-2.
Ruet, A., Brochet, B., 2020. Cognitive assessment in patients with multiple sclerosis: from neuropsychological batteries to ecological tools. Ann. Phys. Rehabil. Med. 63, 154–158. https://doi.org/10.1016/j.rehab.2018.01.006.
Thapa, N., Park, H.J., Yang, J.-G., Son, H., Jang, M., Lee, J., Kang, S.W., Park, K.W., Park, H., 2020. The effect of a virtual reality-based intervention program on cognition in older adults with mild cognitive impairment: a randomized control trial. J. Clin. Med. 9, 1283. https://doi.org/10.3390/jcm9051283.
Tomioka, K., Kurumatani, N., Hosoi, H., 2016. Association between social participation and instrumental activities of daily living among community-dwelling older adults. J. Epidemiol. 26, 553–561. https://doi.org/10.2188/jea.JE20150253.
Troyer, A.K., Leach, L., Strauss, E., 2006. Aging and response inhibition: normative data for the victoria stroop test. Aging Neuropsychol. Cogn. 13, 20–35. https://doi.org/10.1080/138255890968187.
Varela-Aldás, J., Buele, J., Lorente, P.R., García-Magariño, I., Palacios-Navarro, G., 2021. A virtual reality-based cognitive telerehabilitation system for use in the covid-19 pandemic. Sustainability 13, 1–24. https://doi.org/10.3390/su13042183.
Ventura, S., Brivio, E., Riva, G., Baños, R.M., 2019. Immersive versus non-immersive experience: exploring the feasibility of memory assessment through 360° technology. Front. Psychol. https://doi.org/10.3389/fpsyg.2019.02509.
von Stülpnagel, R., Steffens, M.C., 2012. Can active navigation be as good as driving? A comparison of spatial memory in drivers and backseat drivers. J. Exp. Psychol. 18, 162–177. https://doi.org/10.1037/a0027133.
Wallet, G., Sauzéon, H., Pala, P.A., Larrue, F., Zheng, X., N'Kaoua, B., 2011. Virtual/real transfer of spatial knowledge: benefit from visual fidelity provided in a virtual environment and impact of active navigation. Cyberpsychol. Behav. Soc. Netw. 14, 417–423. https://doi.org/10.1089/cyber.2009.0187.
Ward, G., Jagger, C., Harper, W., 1998. A review of instrumental ADL assessments for use with elderly people. Rev. Clin. Gerontol. 8, 65–71. https://doi.org/10.1017/S0959259898008089.
Wilson, P.N., Foreman, N., Gillett, R., Stanton, D., 1997. Active versus passive processing of spatial information in a computer-simulated environment. Ecol. Psychol. 9, 207–222. https://doi.org/10.1207/s15326969eco0903_3.

2.3. Artículo: Influence of Hand Tracking in Immersive Virtual Reality for Memory Assessment

International Journal of
Environmental Research and Public Health

MDPI

Article

Influence of Hand Tracking in Immersive Virtual Reality for Memory Assessment

José Varela-Aldás [1,2,*], Jorge Buele [2,3], Irene López [2] and Guillermo Palacios-Navarro [3]

[1] Centro de Investigaciones de Ciencias Humanas y de la Educación—CICHE, Universidad Indoamérica, Ambato 180103, Ecuador
[2] SISAu Research Group, Facultad de Ingeniería, Industria y Producción FAINPRO, Universidad Indoamérica, Ambato 180103, Ecuador
[3] Department of Electronic Engineering and Communications, University of Zaragoza, 44003 Teruel, Spain
* Correspondence: josevarela@uti.edu.ec

Abstract: Few works analyze the parameters inherent to immersive virtual reality (IVR) in applications for memory evaluation. Specifically, hand tracking adds to the immersion of the system, placing the user in the first person with full awareness of the position of their hands. Thus, this work addresses the influence of hand tracking in memory assessment with IVR systems. For this, an application based on activities of daily living was developed, where the user must remember the location of the elements. The data collected by the application are the accuracy of the answers and the response time; the participants are 20 healthy subjects who pass the MoCA test with an age range between 18 to 60 years of age; the application was evaluated with classic controllers and with the hand tracking of the Oculus Quest 2. After the experimentation, the participants carried out presence (PQ), usability (UMUX), and satisfaction (USEQ) tests. The results indicate no difference with statistical significance between both experiments; controller experiments have 7.08% higher accuracy and 0.27 ys. faster response time. Contrary to expectations, presence was 1.3% lower for hand tracking, and usability (0.18%) and satisfaction (1.43%) had similar results. The findings indicate no evidence to determine better conditions in the evaluation of memory in this case of IVR with hand tracking.

Keywords: immersive virtual reality; hand tracking; memory assessment; presence; usability; satisfaction

check for updates

Citation: Varela-Aldás, J.; Buele, J.; López, I.; Palacios-Navarro, G. Influence of Hand Tracking in Immersive Virtual Reality for Memory Assessment. *Int. J. Environ. Res. Public Health* **2023**, *20*, 4609. https://doi.org/10.3390/ijerph20054609

Academic Editors: Luis Rizo-Dominguez and Carolina Del Valle Soto

Received: 14 January 2023
Revised: 26 February 2023
Accepted: 3 March 2023
Published: 5 March 2023

1. Introduction

Virtual reality (VR) can be presented differently depending on the degree of immersion: non-immersive, semi-immersive, and fully immersive. Non-immersive VR offers virtual environments from a conventional computer where users control their movements through a joystick or other control device [1]. Desktop applications have been used in psychological research for decades, although this term is not applied uniformly across studies [2]. On the other hand, to provide the user with a series of experiences similar to real ones, VR has evolved by implementing immersive virtual reality (IVR) environments, offering the perspective of living in a simulated reality [3]. This type of VR promises a wealth of experiences, combining sensations for training tasks and learning new skills, even helping healthy people redesign themselves for a more meaningful and exciting life [4].

An immersive system can consist of concrete surrounding projection surfaces, or even VR glasses, which virtually place the user within the virtual environment for a high level of immersion [5]. A system that uses VR glasses known as a Head-Mounted Display (HMD) is considered immersive since the user sees only the computer-generated image, and the rest of the physical world is blocked from view [6,7]. A total immersion system can incorporate a wide field of view, high resolution, HMD, and auditory, tactile, or force feedback [6,8].

VR systems contain parameters, such as immersion and presence, which are two terms to consider in the user's performance when executing virtual tasks [7,9]. Immersion is related to technology, while presence is a cognitive, perceptual, and psychological consequence of immersion. On the other hand, presence can be understood as the psychological perception of "existing in" the virtual world [10]. The use of HMD devices could affect the sense of presence and immersion, directly impacting participant performance and motivation. On the other hand, hand tracking is a component that has not been studied in the field of cognitive evaluation and rehabilitation, promising benefits in users' learning processes [11]. VR-based tools represent an alternative for the diagnosis and cognitive rehabilitation, which can be comparable to conventional procedures [12]. Different studies have endorsed an improvement in cognitive abilities in people suffering from trauma, Alzheimer's disease, Parkinson's disease, after suffering a stroke, among others [13,14], also demonstrating benefits for neurocognitive assessment and significant ecological validity [15,16]. VR in treating cognitive processes is a thematic axis that has been booming in recent years. Technological progress, reduced hardware costs, and software support allow new applications to be developed that improve the quality of life of human beings. Cognitive problems can affect all audiences, including young people [17] and people who have suffered previous illnesses [18–20]. However, older adults tend to present the greatest affectations, which is why it is necessary to take preventive measures to anticipate this reality [21–23].

This work compares two interaction methods with a VR application for memory assessment; specifically, hand tracking is compared versus standard controls; both methods are used throughout training and evaluation. This research's objectives include analyzing different variables to determine the interaction method that favors the VR experience in memory assessment. This analysis addresses the variables of interest of accuracy in the responses, response time, presence, usability, and satisfaction. The study expects better results for the interaction with hand tracking since this element complements the first-person experience, involving the user more actively. In addition, the naturalness of the movements when selecting an object can facilitate the interaction and, therefore, the memorization of the objects.

2. Related Works

Related works are presented in the following order: VR applications for cognitive activities, IVR applications in cognitive activities, IVR studies involving participants without a diagnosis of neurodegenerative diseases, and applications with hand tracking as an interaction method.

VR applications for cognitive activities—The found bibliography shows many applications of VR in cognitive evaluation and rehabilitation. In [24], a virtual environment is presented that allows the person to train sensory memory and space orientation with excellent results. Something similar is described in [25], where a museum is shown, in [26] an airport is shown, and in [27] a virtualized city is shown. Likewise, spatial orientation can be merged with working memory, as in [28], which allows the user to navigate the environment and remember images. Similarly, in [29] a virtual store is presented, and in [30], a town where patients must remember objects. In this application, the working memory, sensory-visual memory, spatial orientation, and executive function are being trained in an integral way.

There are experimental studies that have used VR to assess various cognitive functions. The authors in [31] used a VR application with six daily activities to evaluate 18 patients with Alzheimer's disease. The cognitive functions examined were episodic memory, prospective memory, visuospatial orientation, executive functions, attention, and general processing speed, finding significantly worse results in the participants with diagnosis compared to a control group concerning the percentages of achievement and the times required to complete the game. The research was also applied a usability questionnaire, where participants found the game easy to use, enjoyed playing it, and had no problems interacting. Another recent study used a virtual supermarket VR application installed on a tablet to assess the cognitive performance of patients with mild cognitive impairment, in addition to measuring brain activity using a portable electroencephalogram and comparing the results with a traditional test [32]. The authors concluded that the experimental tool is helpful for the detection of mild cognitive impairment and cognitive evaluation in an accessible and pleasant way for older adults.

More and more VR-based studies are introducing simulations of ADLs in cognitive deficits. Using these virtual environments has shown significant improvements in general cognitive functioning concerning traditional methods [33]. In [34], the authors found a case in which training in a virtual kitchen allowed a subject with Alzheimer's disease to relearn cooking activities, and said learning remained stable over time. For its part, the study by [35] found that the cognitive functions of adults with mild cognitive impairment showed greater neuronal efficiency. All this background invites us to think about the need for a methodological framework for designing VR tasks involving ADL with different cognitive impairment levels.

IVR applications in cognitive activities—For several years there has been a growing motivation to develop IVR applications oriented to human cognition to achieve a higher level of immersion [36]. The degree of immersion is important when developing VR applications since it has even been considered a dimension in clinical neuropsychology when evaluating spatial cognition and executive functions. The degree to which participants feel present in the virtual environment has implications for task performance, positively benefiting users' cognitive performance when recalling facts or memorizing elements [37,38]. A systematic review of studies addressing the efficacy of VR-based rehabilitation reviews the relevant literature on the role of immersion in memory assessment and rehabilitation [39]. This review concludes that there are some theoretical advantages of IVR over non-immersive technology, but there needs to be more evidence to draw definitive conclusions.

IVR studies involving participants without a diagnosis of neurodegenerative diseases—Virtual environments have different immersion levels, so there are divided criteria for the effects produced in the evaluation and cognitive rehabilitation processes. On the one hand, the results obtained by [40] mention that greater immersion offers better performance, while [41,42] describe that there is no significant relationship. Therefore, there is a need to develop more investigations that allow the analysis of the elements that contribute to the immersion of the system. In this sense, hand tracking contributes to the immersion of the system; in this way, it seeks to generate an authentic experience for the user, who, while performing an evaluation, can interact with the environment and feel comfortable. More visual stimuli are offered, emphasizing the emphasis on establishing objects as similar to a real environment. The elements used in the activity are found in a conventional kitchen, contributing to the familiarity of the user while carrying out the diagnosis process.

Regarding the influence of immersion in VR applications for memory training, the question is whether the accuracy of memory retrieval is better in systems with hand tracking compared to the application with controllers. Some works, such as [43,44], have shown significant improvements when the exercises have been carried out in immersive environments. However, changes within this level of immersion still need to be analyzed. In the first case, significant differences were found in the performance of a memory test by the experimental group using IVR. In contrast, in the second study, the results showed an improvement in episodic memory performance in the group that performed the memory exercise in the desktop application condition. Thus, there is still a long way to go to determine whether the degree of immersion guarantees better performance in the different memory tasks.

On the other hand, few studies analyze active navigation in a virtual environment and its effect on memory performance. This includes the user's physical and psychological activity, that is, motor control and decision-making. In this way, we have the effect of virtual enactment, defined as the influence provided by active navigation or another component on memory retrieval, compared to passive virtual observation [45]. An association or analogy is produced here between the representation effect [46] and active virtual navigation, since both selectively impact specific object processing, such as recognition, but not relational processing. Some studies have shown that this effect can improve spatial memory performance [47] and episodic memory [48]. However, more recent studies did not find significant differences in spatial learning when comparing both navigation methods [49].

Memory-oriented IVR applications have been tested primarily on healthy people and patients with mild cognitive impairment. Another work used an immersive virtual store using the HMD Nvisor ST50 device to assess episodic memory in healthy patients who had to memorize 12 items [30]. The results indicate high levels of presence and motivation, and memory performance on the IVR task is positively correlated with performance on the traditional memory task for both age groups. In addition, the system in this proposal is sensitive to notable age-related differences because older adults omit more items than younger ones. Other authors presented an immersive system using the HMD nVisor ST50 device, with a virtual environment made from a virtual store to assess everyday memory [50]. The participants were 20 healthy young people, 19 healthy older adults, and 35 older people with subjective cognitive impairment who performed the virtual store task. The results obtained with the healthy group allowed researchers to know if the proposal showed adequate levels of difficulty, as well as the effects of the task on age, while the results of the group with cognitive impairment allowed the researchers to relate the performance in the immersive task with the performance of memory in two traditional activities. The conclusions indicate that the accuracy of the responses in the experimental activity was sensitive to age due to obtaining better performance in young people. Furthermore, this performance was correlated with the assessment obtained in the traditional tool, specifically with episodic memory functions and processing speed. On the other hand, in [25], the authors developed a highly immersive application for a virtual museum with two rooms. This was validated with young participants who had to walk through the virtual environment while memorizing the details of each room. The results showed that the participants more easily remembered the objects that had a shorter spatiotemporal distance from each other.

Applications with hand tracking as an interaction method—Regarding works that use hand tracking in cognitive activities, no studies were found in important sources that allow establishing a point of reference for this research. For example, in [51], the authors investigated the user performance in a memory puzzle task using VR. The experiment was carried out with 30 participants under three conditions: hand tracking, controller without haptics, and controller with haptics. The results of this study indicate better performance for hand tracking in solving the task with hand tracking but not better in the initial selection time. On the other hand, in [52], the authors used VR for endotracheal intubation training with the two interaction modalities (hand tracking and controllers) to analyze usability. The results measured in this study indicate that interactions with hand tracking or controllers were not significantly different. Therefore, in this research, an immersive system was used to assess memory and to analyze the influence of hand tracking. Our proposal is based on the application of [53], where four virtualized cabinets are proposed, with objects to be memorized inside. The user must memorize the elements and identify in which cabinet they are located. The parameters analyzed are accuracy, response time, presence, usability, and satisfaction, and better performance for control using hand tracking was established as a hypothesis compared to the traditional method of manual controllers.

3. Materials and Methods

There are many innovative proposals for the evaluation of memory, and as presented in the literature, experimental methods involving technology have been contrasted with traditional methods to guarantee their validity. Specifically, VR has raised expectations, promising better tools to diagnose neurodegenerative diseases on time. In this new context, the resources available for the screening process are multiple, including immersion technology such as hand tracking. Although access to these resources is still limited, further growth in VR technologies is expected.

The cost of HMD devices has been reduced in recent years, appearing as independent devices that do not require an additional computer for their operation. These options include sensors and cameras that allow scanning of the device's environment, including hand tracking. This has prompted the development of first-person view VR applications where users interact with their hands [54,55]. Specifically, Meta's Oculus Quest 2 is a low-cost HMD device that includes this technology as a second option to interact with the virtual world [56]. These features engage users more actively, dispensing additional controls to interact with applications. Although positive effects are expected in the evaluation of memory, no studies contrast this assumption. This work compares the results of a VR application to evaluate using hand tracking with respect to classic controllers. Figure 1 shows the general scheme of the methodology used.

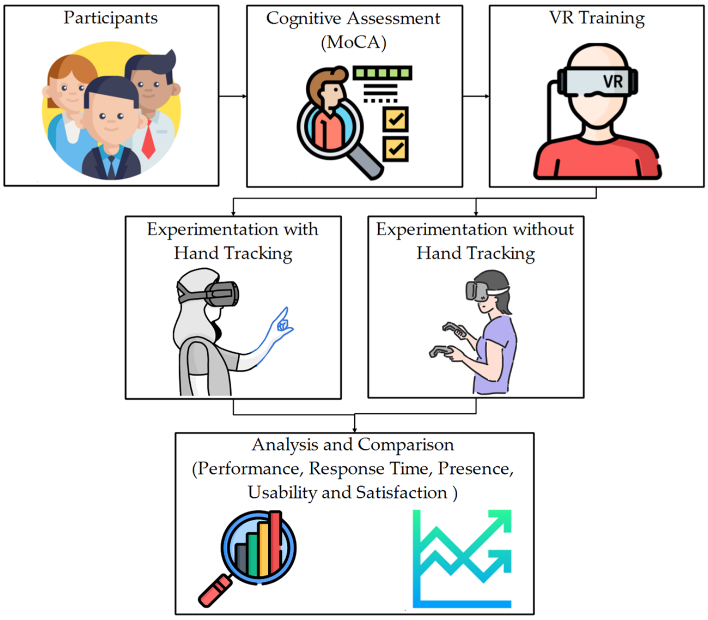


Figure 1. General outline of this research.

The method begins with selecting participants through a cognitive assessment exam; this allows for the discrimination of participants with low memory performance and for working only with healthy participants. The selected participants are trained in virtual reality to avoid biases related to the lack of experience with the technology used. Next, the memory training and evaluation phases were performed using a VR application with controllers and hand tracking. This application collects data automatically (Performance and response time), and other data were collected manually through instruments (Presence, usability, and satisfaction) for analysis and comparison.

3.1. Application

The application designs an activity of daily living (ADL) based on cabinets that have been previously evaluated [53,57]. The activity consists of cabinets and kitchen elements, where the user must remember the location of the elements within the cabinets. In training, the user visualizes the elements inside the cabinets, and the number of elements is configurable according to the required difficulty. The elements are located automatically and randomly inside the shelves, and the doors open for a specific time of waiting for learning. In the evaluation, the user must select the correct cabinet door; this is done with the controllers or the user's hands, as the case may be. The user has a time limit to choose a door and an element; otherwise, an error is recorded, and the evaluation continues.

Each door conceals a section of cabinet elements and is designed to contain a maximum of 4 elements. In total, four sections are proposed; that is, the capacity is 16 elements. The number of elements can be configured through a menu and corresponds to the required difficulty level. On the other hand, the elements to remember are commonly consumed foods. For this, a database was created with 20 foods: bananas, blueberries, carrots, cereal box, cheese, juice pack, watermelon, mushrooms, skinned chicken, soda can, tomato, yogurt, pizza, kiwi, ice cream, hamburger, ham, cherries, acorn, and cake. A kitchen's essential components are required for the virtual environment's design, such as table, chair, stove, glasses, dishes, refrigerator, broom, and clock.

At startup, all the elements of the virtual kitchen are loaded, including the menu that allows user data to be entered and the difficulty level to be set using a laser pointer. The difficulty of the task is limited from 1 to 10, because a larger number of elements is too complicated to remember. When starting the activity, the food is instantiated inside the cabinets, and the training stage begins opening each cabinet door to show the food with a 10 s pause; the doors open one after the other. In the evaluation stage, the question of each element to be remembered is shown. If the wrong door is selected or the waiting time expires (10 s), an error is recorded. On the contrary, if the selection is correct, a success is registered, and each door chosen opens and shows the elements it contains so that the user selects the element in the established time. In the selection of the elements, errors and successes are also required. Depending on the experiment, the user selects the door and the cabinet element using the controllers or the hands.

The training time is 40 s plus the animation time of the doors opening and closing; total, the training time is approximately 65 s. The average evaluation time is 26 s plus the animation time of the doors opening and closing; the average evaluation time is approximately 57 s.

The virtual environment is built in three development layers as shown in Figure 2—a first construction and configuration layer, then a layer that provides the interaction properties to the environment components, and finally a scripting layer that gives it functionality to GameObjects.

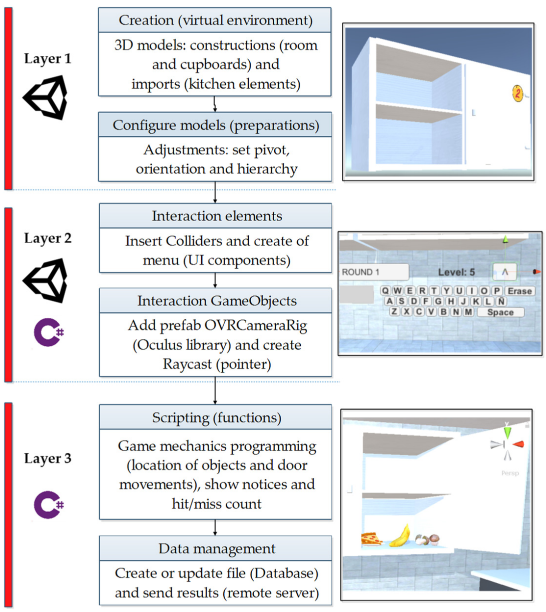


Figure 2. Development layers of the virtual environment.

Layer 1—In the creation of the 3d models, the basic construction components provided by Unity are used, using plans, cubes, lights, and others to assemble the room of the scene and the empty cabinets. On the other hand, the more complex elements such as table, chair, dishes, and other kitchen elements are imported from the As-sets of the Unity store, including the foods that are created as prefabs to be instantiated inside the As-sets. cabinets when required. Additionally, it is necessary to prepare these elements to incorporate the movements and other actions of the game; for this, the pivot to the doors is configured, the food is oriented with a view towards the user, and the hierarchies are established.

Layer 2—The interaction of the user with the system components is carried out using a laser pointer, requiring the insertion of a Box Collider component in the cabinet doors and foods, and in this way a collision with the object is detected, which allows the desired actions to be activated. The user menu is laid out within a Canvas with text labels and buttons for entering information, including an alphabetic keyboard for entering the user's name. To insert the GameObject that represents the tracking camera of the Oculus Quest 2, the OVRCameraRig prefab from the Oculus Integration library was used, which is linked directly to the hardware, and the laser aiming was implemented using a RayCast object that was synchronized with the movements of the controller and hands, as the case may be.

Layer 3—The game procedures are programmed using the rules of the previously described activities, and everything starts when the user presses the start button, destroying and instantiating the food according to the selected difficulty level, opening and closing the doors sequentially with fixed waiting time. Although the activities do not require the locomotion of the player, the automated translation of the main camera is programmed to focus the view towards the middle of each cabinet according to the training sequence. Below are the text labels of the game questions and prompts, and the counters record the successes and failures based on the user's decisions. Finally, the collected data were grouped into plain text files and sent to the remote server using the SSH:NET library.

3.2. Participants

Regarding the participants, healthy candidates with gender equality and with different ages between 18 and 60 years were sought, and all recruited candidates passed the cognitive assessment test. For cognitive assessment, the Montreal Cognitive Assessment (MoCA) test was used, since the group of participants has a high level of education, and only participants who obtain 26 points or more pass. In total, a group of 20 participants was obtained, whose demographics are described in Table 1. Overall, 50% of the participants declare the masculine gender, and another 50% declare the feminine gender. The mean age of the group is 36.05 years with a standard deviation (SD) of 9.69 years, the youngest is 20 years old, and the oldest 56 years old. The mean education time is 19.4 years with an SD of 2.85 years, the shortest time is 15 years, and the maximum is 25 years. In the MoCA test, there is a mean group score of 27.75 with an SD of 1.37, with values between 36 and 30 points.

Table 1. Participant demographics.

Demographics	Value	Demographics	Value
		Age	
Gender:		Mean	36.05
Male	10	SD	9.69
Female	10	Min	20
		Max	56
MoCA		Education years	
Mean	27.75	Mean	19.4
SD	1.37	SD	2.85
Min	26	Min	15
Max	30	Max	25

3.3. Procedures

All the procedures carried out in this study have the approval of the ethics committee of the Universidad Indoamérica of Ecuador. Figure 3 details the processes to be carried out in this research. To evaluate the proposal, two main activities were designed with a VR application, with the controller and with hand tracking, in that order. Participants must perform a cognitive assessment using the instrument called MoCA, which was done prior to the selection of suitable participants for the tests. On the other hand, the cabinet's application has a preliminary evaluation phase that allows errors to be corrected before the actual tests. Likewise, the group of participants has a training stage in the use of virtual reality with the Oculus Quest 2 to proceed with the application of the cabinets, at the end of each experimental period the participants complete the presence, usability, and satisfaction test of the application. At the end of the procedures, the results were analyzed and compared.

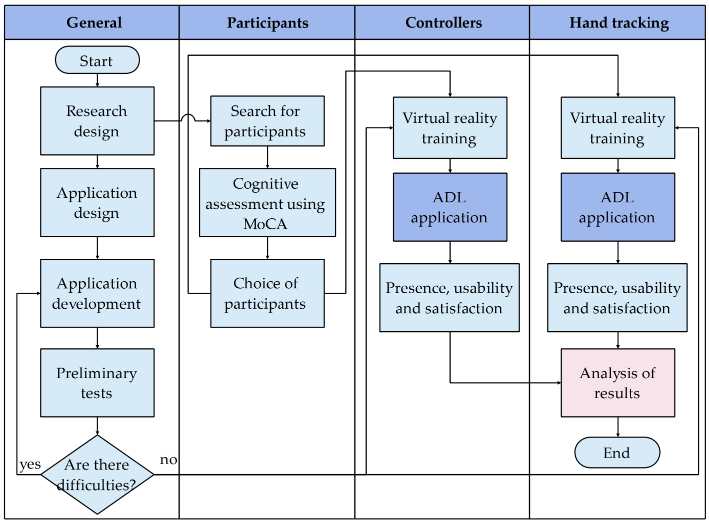


Figure 3. Process diagram of the activities carried out.

3.4. Instruments

The instruments used to collect data from the participants before and after the experiments with the VR application using the controllers and hand tracking independently are presented below:

MoCA—This simple test assesses multiple cognitive domains, including memory, language, executive functions, visuospatial abilities, calculation, abstraction, attention, concentration, and orientation. MoCA memory tests involve multiple words, some learning tests, a long delay in the recall, and demanding numerical tasks [58]. This instrument was developed in a clinical memory setting and standardized in a highly educated population. Results with 26 points or more are considered to indicate normal cognitive status, and participants with less than 12 years of education have an additional point [59]. In this work, the MoCA test was used as a discriminant to access the experiments as participants because they have a high level of education.

Presence questionnaire (PQ)—This test was used to assess the sense of presence in virtual environments and is made up of 32 questions with seven response levels [60]. The evaluation items consider the factors of control, sensation, distraction, and realism. Only 29 questions were considered in this investigation because the questions related to haptic and sound interaction (Q15–Q17) were discarded [61]. Scores for questions Q14, Q17, and Q18 were calculated by subtracting the value of 7, and scores for all remaining items were calculated by subtracting 1 from the value chosen by the user.

Usability Metric for User eXperience (UMUX)—It is a 4-question instrument used for the subjective evaluation of the usability of an application. The responses have 7 levels of selection, from strongly disagree to strongly agree. The results of this test have been validated with respect to the 10-question usability scale, and they were organized according to ISO 9241-11 [62]. The usability measures provided by this tool allow for a broad understanding of the user experience based on a compact instrument.

User Satisfaction Evaluation Questionnaire (USEQ)—It is a 6-question questionnaire to assess satisfaction with virtual rehabilitation systems. Question Q5 has a negative answer; it must be subtracted from the maximum value plus one to obtain its real score [63]. Although the original tool has a 5-level Likert scale, in this work, a 7-level scale was used to match the rest of the post-experimentation instruments, allowing for the expansion of the instrument's sensitivity level.

The data are processed through statistics; the significant statistical difference was analyzed using the Student's *t*-test for paired samples. Since both data come from the same group of individuals, a significance level of 5% (α = 0.05) was established.

4. Results

The experiments using the VR application based on an ADL were carried out in the following order. On the first session, the application was evaluated using the traditional Oculus Quest 2 controllers, and on the second session, hand tracking was used to assess the application. Our research is based on [64], where the participants used mouse, hand tracking, and controller in VR without altering the order of use of the technology. Although there is research using randomization [55,65], this has not been demonstrated to produce different results. Figure 4 shows photos of the participants using the Oculus Quest 2 with the controllers and hand tracking, respectively. The view of the virtual environment from the user's perspective was monitored from a phone screen to verify the correct development of the tests. The duration times of each session were approximately 25 min, including data entry, breaks, training, evaluation, and answering tests.

Figure 4. Participants using the application of Oculus Quest 2 with controllers and hand tracking.

In this research, the application was configured for a difficulty level of 7 elements because classical studies establish a range of 5 to 9 elements as the appropriate number to assess memory [66]. Figure 5 shows images of the virtual environment, observing the whole room setup and the cupboards from a first person view, where the user is in a central position of the room visualizing each element that provides realism to the scene. Users can move freely in the virtual environment; they use locomotion in both stages, in training to better visualize the objects and in the evaluation to get closer to the selected element. When using the controllers, the user only sees the control devices that are synchronized with the real movements, and in the case of hand tracking, the hands are presented according to the user's movements. In addition, the images show the cabinets, food, and information texts incorporated into the application.

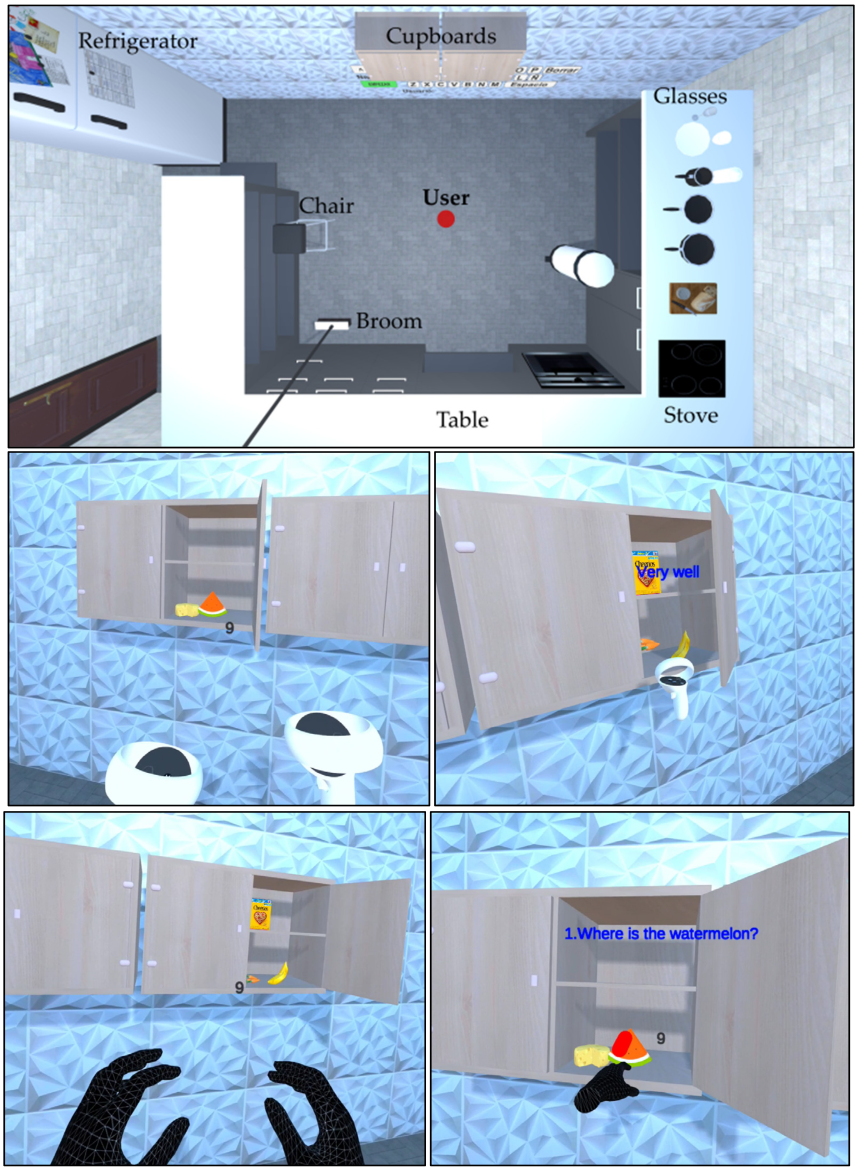


Figure 5. Virtual environment: full scene top view and user view images.

4.1. Accuracy

The performance of the participants in the virtual activity was determined from the accuracy of the answers (success/(success + errors)). Figure 6 shows the comparison of the accuracy between both use cases of the VR application (Controllers vs. Hand Tracking), where 11 participants had a better performance using the controllers and 9 participants improved their accuracy when using hand tracking. In addition, the mean accuracy with controllers (U = 79.55%) was higher than the mean with hand tracking (U = 72.47%), which is evidenced in the box and whisker plot of Figure 7. Regarding the dispersion, the accuracy with controllers has a lower SD (13.72%) with respect to the accuracy using hand tracking (SD = 17%). Furthermore, the statistical analysis determines a p-value = 0.085.

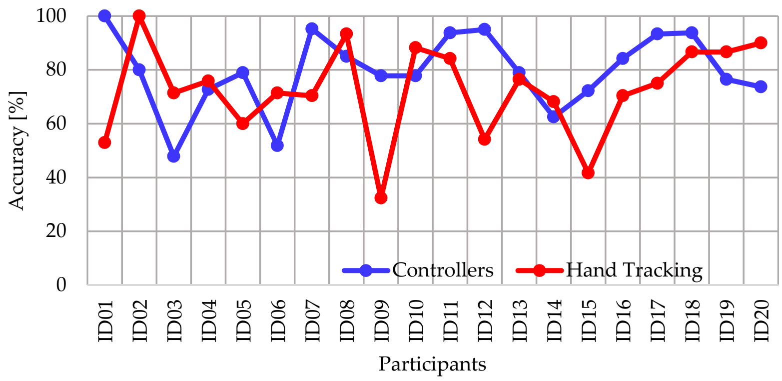


Figure 6. Comparison of VR app activity and the accuracy of the answers.

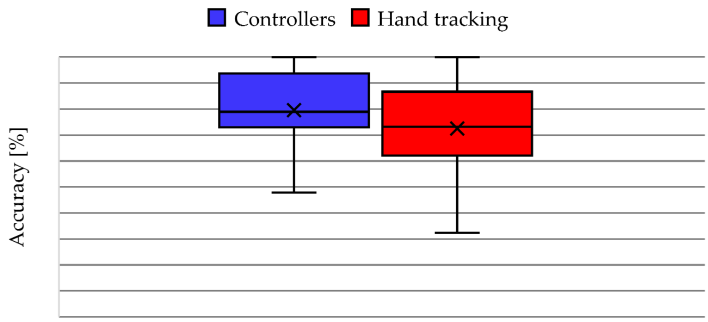


Figure 7. Box-and-whisker plot of accuracy of the answers in VR app activity.

4.2. Response Time

To analyze the response time of the participants, all the cumulative times of the door selection and the selection of food inside the cabinet were averaged in a complete experiment. Figure 8 shows the comparison of response times between both cases of the activity, where 13 participants had a faster response when using the controllers and 7 participants were faster when using hand tracking. In addition, the mean response time with controllers (U = 3.33 s) was faster than the mean with hand tracking (U = 3.6 s), which is evidenced in the box and whisker plot of Figure 9. Regarding the dispersion, the response time with controllers has a lower SD (1.3 s) compared to the accuracy using hand tracking (SD = 1.5 s). Furthermore, the statistical analysis determines a p-value = 0.29.

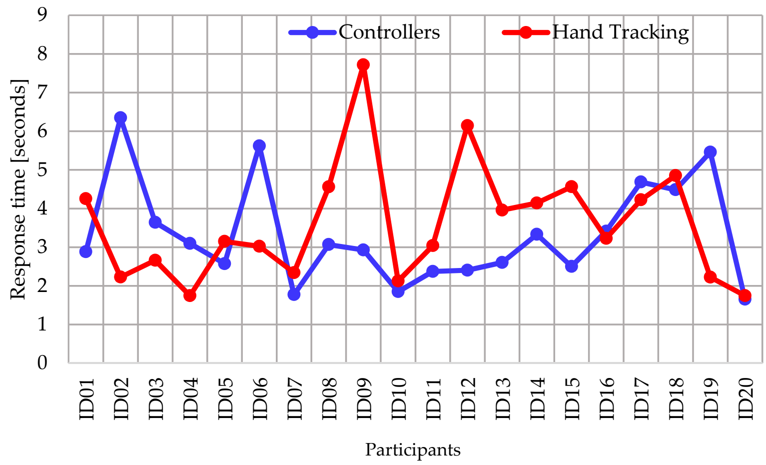


Figure 8. Comparison of response times in VR app activity.

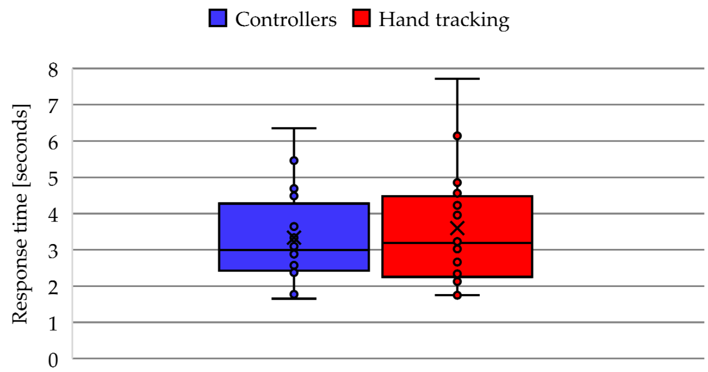
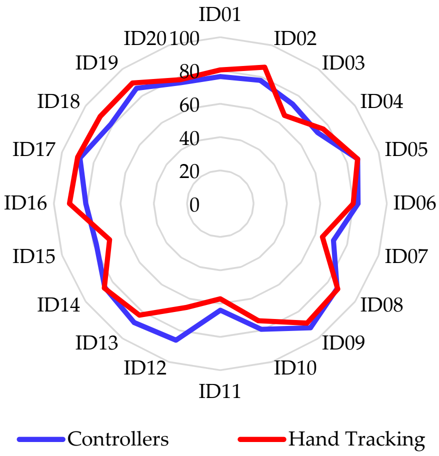


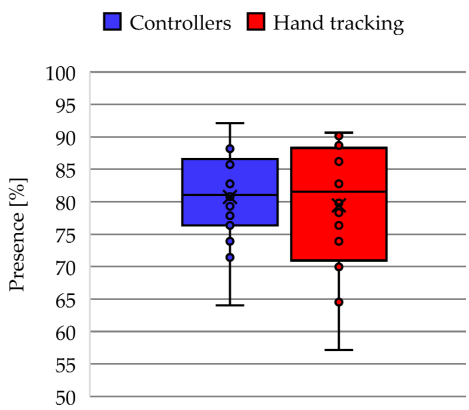
Figure 9. Box and whisker plot of response times in VR app activity.

4.3. Presence

The results obtained from the PQ instrument were scaled by being converting to percentages to analyze the perception of presence of the participants when using the application with both interaction methods. Figure 10a shows the comparison of the presence score assigned by the participants, where 10 participants indicate a higher score for hand tracking, 9 participants indicate a higher score for controllers and 1 participant has exactly the same score for both methods. In addition, the mean presence score with controllers (U = 80.74%) is slightly higher than the mean with hand tracking (U = 79.43%), which can be seen in the box-and-whisker plot of Figure 10b. Regarding dispersion, the presence score with controllers has a lower SD (6.85%) compared to presence using hand tracking (SD = 9.95%). Furthermore, the statistical analysis determines a *p*-value = 0.21.



(**a**)



(**b**)

Figure 10. Results of the participants in the PQ instrument: (**a**) Radial diagram of the comparison between the scores of presences in the activity of the VR application; (**b**) Box-and-whisker plot of presence scores in VR app activity.

In relation to the items evaluated in the PQ instrument, Figure 11 shows the comparison of the presence scores organized by questions obtained with the mean of the answers of all the participants.

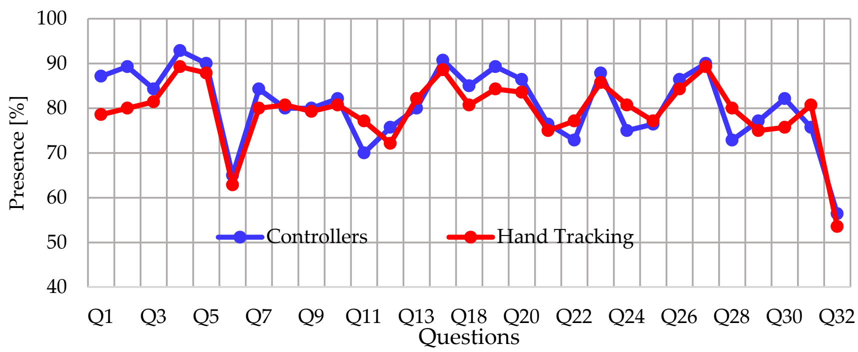
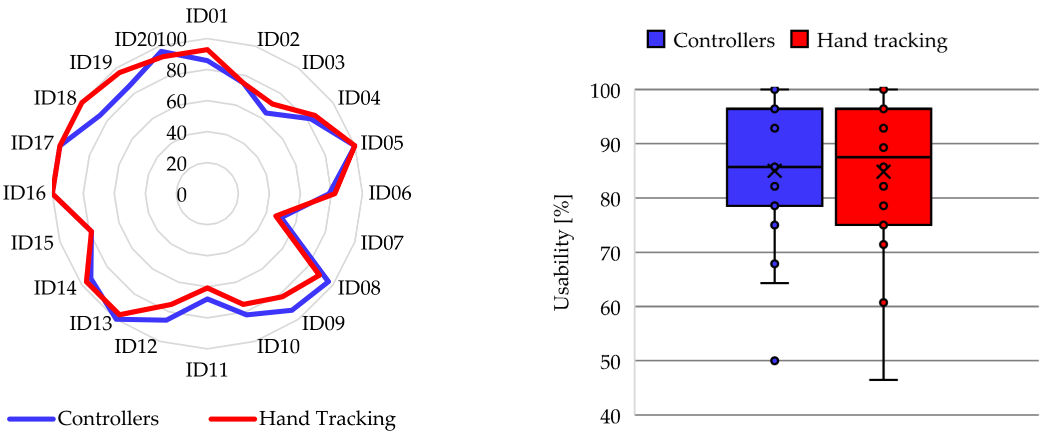


Figure 11. Comparison of the mean scores assigned by the participants in the questions of the PQ instrument when using the application with different interaction methods.

4.4. Usability

The results obtained from the UMUX instrument were scaled by being convertedto percentages to analyze the perception of usability of the participants when using the application with both interaction methods. Figure 12a shows the comparison of the UMUX score assigned by the participants, where 8 participants indicate a higher score for controllers, 7 participants indicate a higher score for hand tracking, and 5 participants have exactly the same score for both methods. In addition, the mean presence score with controllers (U = 85%) was almost the same as the mean with hand tracking (U = 84.82%), which can be seen in the box-and-whisker plot of Figure 12b. Regarding the dispersion, the usability score with controllers has a lower SD (13.1%) compared to the presence using hand tracking (SD = 14.24%), although the former has an atypical value. Furthermore, the statistical analysis determines a p-value = 0.45.



(**a**) (**b**)

Figure 12. Results of the participants in the UMUX instrument: (**a**) Radial diagram of the comparison between the usability scores in the activity of the VR application; (**b**) Box-and-whisker plot of usability scores in the VR app activity.

In relation to the items evaluated in the UMUX instrument, Figure 13 compares the usability scores organized by questions obtained with the mean of the answers of all the participants.

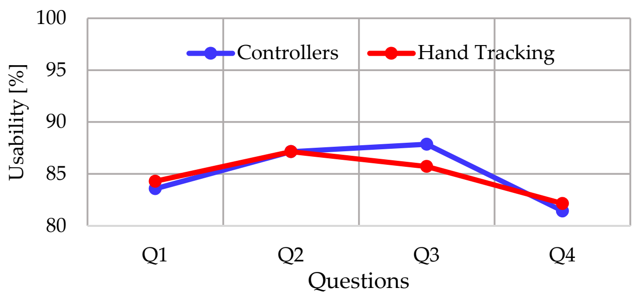


Figure 13. Comparison of the mean scores assigned by the participants in the questions of the UMUX instrument when using the application with different interaction methods.

4.5. Satisfaction

The results from the USEQ instrument were scaled by being converted to percentages to analyze the participants' satisfaction when using the application with both interaction methods. Figure 14a shows the comparison of the satisfaction score assigned by the participants, where 10 participants indicate a higher score for controllers, 9 participants indicate a higher score for hand tracking, and 1 participant has the same score for both methods. In addition, the mean USEQ score with controllers (U = 89.64%) is slightly higher than the mean with hand tracking (U = 88.21%); this can be seen in the box-and-whisker plot of Figure 14b. Regarding the dispersion, the SD of the satisfaction scores with controllers and hand tracking have similar values (11.6% and 11.36%, respectively), although there are outliers for both cases. Furthermore, the statistical analysis determines a p-value = 0.15.

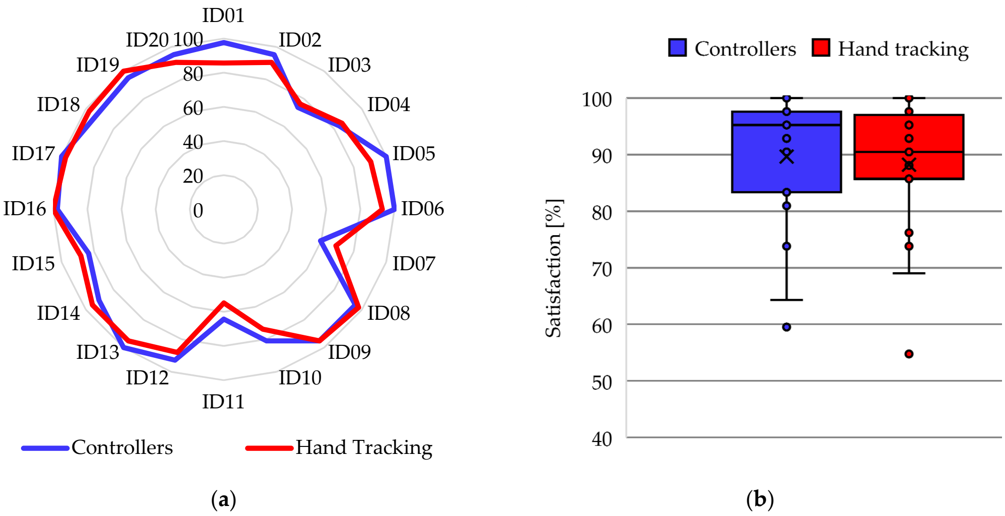


Figure 14. Results of the participants in the USEQ instrument: (**a**) Radial diagram of the comparison between the satisfaction scores in the activity of the VR application; (**b**) Box-and-whisker plot of VR app activity satisfaction scores.

In relation to the items evaluated in the USEQ instrument, Figure 15 compares the satisfaction scores for each question obtained with the mean of the answers of all the participants.

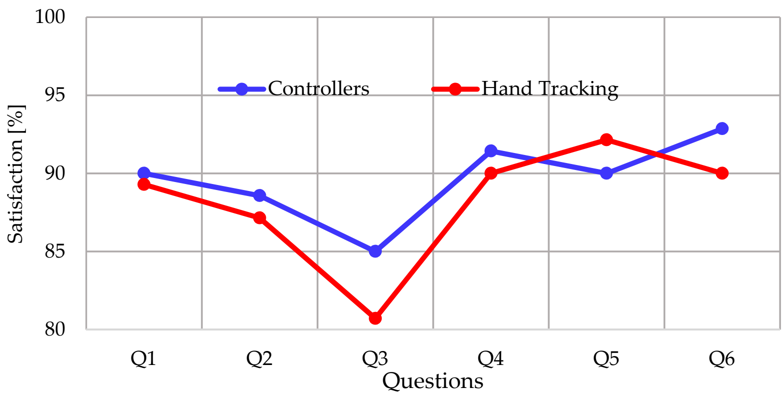


Figure 15. Comparison of the mean scores assigned by the participants in the questions of the USEQ instrument when using the application with different interaction methods.

5. Discussion

Our research uses two interaction methods for active navigation without finding a big difference in response precision and response time. Although there is a certain advantage in the mean accuracy of the answers using controllers, similar to [55,64,65], in [67] the users described greater physical and cognitive effort when performing tasks with their hands in the virtual environment. In [51] the results indicate the opposite, obtaining a better performance when using hand tracking in a cognitive task, requiring more studies analyzing user performance with different interaction methods. In our case, a difference of 7.08% was not decisive to establish which was better, and the statistical value indicates no statistically significant difference. On the other hand, in response times, the participants were faster using the controllers, similar to [51]. However, a difference of 0.27 s is not decisive to establish which is better, considering that 35% of the participants were faster when using hand tracking. Furthermore, the statistical value confirms that there is no statistically significant difference. It is evident that studies are lacking clarification on these uncertainties, so future work should incorporate tests with multiple levels of active navigation and evaluate the types of memory to show more explicit evidence about such effects of virtual recreation.

A term closely related to and inherent to the immersion of VR systems is presence. In [68], the authors developed a VR application with two variants for different levels of presence. The group that used the application with the highest level of presence remembered 28% more objects than the other variant of the application, which could imply a positive relationship between the degree of presence and cognitive performance on the test. Other findings raise the question of whether this benefit only occurs in cases where immersion manipulation affects elements of the environment that are directly relevant to the subsequent assessment of memory [69]. Therefore, it is interesting to investigate this question, especially when no clear methodology allows for evaluating the levels of presence in the different VR systems. So far, questionnaires have been designed to obtain these levels [70–72]. In our work, the difference in the mean value between interaction methods is minimal (1.3%), which does not allow for determining the best presence experience. Moreover, the statistical value indicates that there is no statistically significant difference. The questions with the greatest difference between interaction methods in the presence rating are Q1, Q2, Q11, and Q30. In Q1, the use of the application with controllers is higher by 8.57%. This question is related to the level of control that the user had with the system, indicating that the participants had less control with hand tracking. In Q2 the controllers are higher by 9.29%, and this question is related to the level of sensitivity of the virtual environment, indicating that the participants perceive the interaction method with hand tracking as less sensitive. In Q11, hand tracking is higher by 7.14%, and this question is related to the consistency coming from the senses, indicating that the participants prefer the sensory perception produced by this method of interaction. In Q11 the controllers are 6.43% higher, and this question is related to how well the user can concentrate on the activities instead of the control mechanisms, indicating that the participants concentrate better using the controllers than with hand tracking. The latter is important because the activity requires concentration to improve the accuracy in the answers, although the difference is minimal, and a certain preference for traditional controls is evident. In general, we found no evidence of a better sense of presence by varying the method of interaction, which should be considered in future work to clarify related hypotheses.

Regarding usability and satisfaction, these works have contributed to the universe of research that has proven the benefits of VR in cognitive assessment [29]. The results were favorable both in the use of controllers and the use of hand tracing for the interaction with the application of this research, since high scores were obtained for the UMUX and the USEQ. In usability, the difference in the mean value between interaction methods was negligible (0.18%), which does not allow us to determine the best usability experience, similar to [52]. Moreover, the statistical value indicates that there is no statistically significant difference. In the analysis of the questions, Q3 has the most considerable difference between interaction methods in usability rating. This question is related to the ease of use of the application; in this case, the application with controllers was 2.14% easier to use than the application with hand tracking. In the literature there is a related work that determined a similar result [73]. In this case, the improvement was 7%.

In satisfaction, the difference in the mean value of the USEQ between interaction methods is minimal (1.43%), which does not allow for determining the best alternative regarding satisfaction. Moreover, the statistical value confirms that there is no statistically significant difference. In the analysis of the questions, Q3 and Q6 have the largest difference between interaction methods in the satisfaction rating. Question Q3 of the USEQ is related to application control, confirming that the user has better control when using the controllers. Something similar occurs in question Q6 of the USEQ; this item is related to the use of this application in memory evaluation; in this case, the application with controllers is

2.86% more preferred for this purpose than the application with hand tracking. Although it is a minimal difference, this implies that the participants prefer to use the controllers to assess memory when performing this cognitive activity. In most cases, the indicators are not conclusive, but there is a slight trend toward using controllers to interact with the application from this research. These findings are supported by [73], where there was greater satisfaction with VR controllers, but its conclusions also indicate that the differences are not significant.

The limitations of this study are the interference effect caused by a possible repetition of objects, the lack of randomization in the experiments, and the absence of a control group. Future work could consider these limitations in their studies. The participants limit this work; future research should address the validation of this tool with larger groups of participants who are older or diagnosed with a neurodegenerative disease. In this way, we will have more evidence to elucidate if the tasks developed can be sensitive in the accuracy of the answers or in the execution times, with the purpose of early diagnosis of neurodegenerative diseases [74] reinforcing the validity of the results obtained. These tools have demonstrated their importance in detecting cognitive dysfunctions that traditional tests have been unable to detect [75].

6. Conclusions

This research analyzes the influence of hand tracking in an IVR application developed to assess the memory of 20 healthy participants with homogeneous characteristics. The hardware used was the Oculus Quest 2 standalone HMD device, which has two controllers and the hand tracking function. The application is based on an ADL that has been previously evaluated with respect to traditional methods. The factors analyzed are the accuracy of the answers, the response time, the presence, the usability, and the satisfaction of the participants. Contrary to expectations, in all these factors, there is a certain tendency for worse results using hand tracking as a method of interaction with the application. Still, these results are inconclusive because the differences are minor, and none were found to have a statistically significant difference that supports this assumption. On the other hand, the indicators had high scores that guaranteed the acceptance of this type of proposal as a memory evaluation tool, especially in the satisfaction (USEQ) of the participants, which denotes values close to 90%.

In practice, these results imply that using hand tracking technology in immersive VR applications for memory evaluation does not favor or impair performance, reaction speed, perception of presence, usability, and user satisfaction, although these results should be interpreted with caution. On the other hand, in the literature, only some investigations support and refute the findings of this work, which prevents establishing definitive conclusions with the results obtained in this study. Finally, this work is limited by the number or type of participants, which is why new studies are required with a larger population or participants with a diagnosis of a neurodegenerative disease that complements the results of this research.

Author Contributions: Conceptualization, J.V.-A., J.B. and G.P.-N.; methodology, J.V.-A. and G.P.-N.; software, J.V.-A.; validation, J.V.-A. and J.B.; formal analysis, J.V.-A. and G.P.-N.; investigation, J.V.-A. and J.B.; resources, J.V.-A. and I.L.; data curation, J.B. and I.L.; writing—original draft preparation, J.V.-A.; writing—review and editing, J.V.-A. and G.P.-N.; visualization, J.V.-A. and I.L.; supervision, G.P.-N. and I.L.; project administration, G.P.-N. and I.L.; funding acquisition, J.V.-A. and I.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of Universidad Indoamérica (protocol code UTI-IIDI-001-2023, approval date 1 September 2022).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank CICHE Research Center and SISAu Research Group for the support in this work. The results of this work are part of the project "Rehabilitación cognitiva de la memoria explícita usando realidad virtual inmersiva" developed by Universidad Indoamérica. This work was supported in part by collaboration with REDTPI4.0 CYTED program.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lange, B.; Koenig, S.; Chang, C.Y.; McConnell, E.; Suma, E.; Bolas, M.; Rizzo, A. Designing Informed Game-Based Rehabilitation Tasks Leveraging Advances in Virtual Reality. *Disabil. Rehabil.* **2012**, *34*, 1863–1870. [CrossRef]
2. Furht, B. Desktop Virtual Reality. In *Encyclopedia of Multimedia*; Springer: Boston, MA, USA, 2008; pp. 150–151. [CrossRef]
3. Alcañiz, M.; Bigné, E.; Guixeres, J. Virtual Reality in Marketing: A Framework, Review, and Research Agenda. *Front. Psychol.* **2019**, *10*, 1530. [CrossRef] [PubMed]
4. Georgiev, D.D.; Georgieva, I.; Gong, Z.; Nanjappan, V.; Georgiev, G.V. Virtual Reality for Neurorehabilitation and Cognitive Enhancement. *Brain Sci.* **2021**, *11*, 221. [CrossRef] [PubMed]
5. Garcia-Betances, R.I.; Jiménez-Mixco, V.; Arredondo, M.T.; Cabrera-Umpiérrez, M.F. Using Virtual Reality for Cognitive Training of the Elderly. *Am. J. Alzheimer's Dis. Other Dement.* **2015**, *30*, 49–54. [CrossRef] [PubMed]
6. Sherman, W.R.; Craig, A.B. Understanding Virtual Reality: Interface, Application, and Design. *Presence* **2003**, *12*, 441–442. [CrossRef]
7. Crosbie, J.; McDonough, S.; Lennon, S.; McNeill, M. Development of a Virtual Reality System for the Rehabilitation of the Upper Limb after Stroke. In *Personalised Health Management Systems*; Nugent, C.D., McCullagh, P.J., McAdams, E.T., Eds.; IOS Press: Amsterdam, The Netherlands, 2005; Volume 117, pp. 218–222. ISBN 1586035657.
8. Slater, M. Immersion and the Illusion of Presence in Virtual Reality. *Br. J. Psychol.* **2018**, *109*, 431–433. [CrossRef]
9. Rizzo, A.A.; Schultheis, M.; Kerns, K.A.; Mateer, C. Analysis of Assets for Virtual Reality Applications in Neuropsychology. *Neuropsychol. Rehabil.* **2004**, *14*, 207–239. [CrossRef]
10. Heeter, C. Being There: The Subjective Experience of Presence. *Presence Teleoperators Virtual Environ.* **1992**, *1*, 262–271. [CrossRef]
11. González-Ortega, D.; Díaz-Pernas, F.J.; Martínez-Zarzuela, M.; Antón-Rodríguez, M.; Díez-Higuera, J.F.; Boto-Giralda, D. Real-Time Hands, Face and Facial Features Detection and Tracking: Application to Cognitive Rehabilitation Tests Monitoring. *J. Netw. Comput. Appl.* **2010**, *33*, 447–466. [CrossRef]
12. Sayma, M.; Tuijt, R.; Cooper, C.; Walters, K.; Heyn, P.C. Are We There Yet? Immersive Virtual Reality to Improve Cognitive Function in Dementia and Mild Cognitive Impairment. *Gerontologist* **2020**, *60*, E502–E512. [CrossRef]
13. Mantovani, E.; Zucchella, C.; Bottiroli, S.; Federico, A.; Giugno, R.; Sandrini, G.; Chiamulera, C.; Tamburin, S. Telemedicine and Virtual Reality for Cognitive Rehabilitation: A Roadmap for the COVID-19 Pandemic. *Front. Neurol.* **2020**, *11*, 926. [CrossRef] [PubMed]
14. Isernia, S.; Di Tella, S.; Pagliari, C.; Jonsdottir, J.; Castiglioni, C.; Gindri, P.; Salza, M.; Gramigna, C.; Palumbo, G.; Molteni, F.; et al. Effects of an Innovative Telerehabilitation Intervention for People with Parkinson's Disease on Quality of Life, Motor, and Non-Motor Abilities. *Front. Neurol.* **2020**, *11*, 846. [CrossRef]
15. Parsons, T.D.; Courtney, C.G.; Arizmendi, B.; Dawson, M. Virtual Reality Stroop Task for Neurocognitive Assessment. In *Medicine Meets Virtual Reality 18*; IOS Press: Amsterdam, The Netherlands, 2011; Volume 163, pp. 433–439. ISBN 9781607507055.
16. Parsons, T.D.; Courtney, C.G. Neurocognitive and Psychophysiological Interfaces for Adaptive Virtual Environments. In *Human-Centered Design of E-Health Technologies: Concepts, Methods and Applications*; IGI Global: Hershey, PA, USA, 2011; pp. 208–233.
17. Coleman, B.; Marion, S.; Rizzo, A.; Turnbull, J.; Nolty, A. Virtual Reality Assessment of Classroom—Related Attention: An Ecologically Relevant Approach to Evaluating the Effectiveness of Working Memory Training. *Front. Psychol.* **2019**, *10*, 1851. [CrossRef]
18. Faria, A.L.; Cameirão, M.S.; Couras, J.F.; Aguiar, J.R.O.; Costa, G.M.; Bermúdez i Badia, S. Combined Cognitive-Motor Rehabilitation in Virtual Reality Improves Motor Outcomes in Chronic Stroke—A Pilot Study. *Front. Psychol.* **2018**, *9*, 854. [CrossRef] [PubMed]
19. Maggio, M.G.; Maresca, G.; De Luca, R.; Stagnitti, M.C.; Porcari, B.; Ferrera, M.C.; Galletti, F.; Casella, C.; Manuli, A.; Calabrò, R.S. The Growing Use of Virtual Reality in Cognitive Rehabilitation: Fact, Fake or Vision? A Scoping Review. *J. Natl. Med. Assoc.* **2019**, *111*, 457–463. [CrossRef]
20. Alashram, A.R.; Annino, G.; Padua, E.; Romagnoli, C.; Mercuri, N.B. Cognitive Rehabilitation Post Traumatic Brain Injury: A Systematic Review for Emerging Use of Virtual Reality Technology. *J. Clin. Neurosci.* **2019**, *66*, 209–219. [CrossRef]
21. Gamito, P.; Oliveira, J.; Morais, D.; Coelho, C.; Santos, N.; Alves, C.; Galamba, A.; Soeiro, M.; Yerra, M.; French, H.; et al. Cognitive Stimulation of Elderly Individuals with Instrumental Virtual Reality-Based Activities of Daily Life: Pre-Post Treatment Study. *Cyberpsychology, Behav. Soc. Netw.* **2019**, *22*, 69–75. [CrossRef] [PubMed]
22. Varela-Aldás, J.; Palacios-Navarro, G.; Amariglio, R.; García-Magariño, I. Head-Mounted Display-Based Application for Cognitive Training. *Sensors* **2020**, *20*, 6552. [CrossRef] [PubMed]
23. Thapa, N.; Park, H.J.; Yang, J.-G.; Son, H.; Jang, M.; Lee, J.; Kang, S.W.; Park, K.W.; Park, H. The Effect of a Virtual Reality-Based Intervention Program on Cognition in Older Adults with Mild Cognitive Impairment: A Randomized Control Trial. *J. Clin. Med.* **2020**, *9*, 1283. [CrossRef] [PubMed]

24. Caglio, M.; Latini-Corazzini, L.; D'Agata, F.; Cauda, F.; Sacco, K.; Monteverdi, S.; Zettin, M.; Duca, S.; Geminiani, G. Virtual Navigation for Memory Rehabilitation in a Traumatic Brain Injured Patient. *Neurocase* **2012**, *18*, 123–131. [CrossRef]
25. van Helvoort, D.; Stobbe, E.; Benning, R.; Otgaar, H.; van de Ven, V. Physical Exploration of a Virtual Reality Environment: Effects on Spatiotemporal Associative Recognition of Episodic Memory. *Mem. Cogn.* **2020**, *48*, 691–703. [CrossRef]
26. Tummon, H.M.; Allen, J.; Bindemann, M. Facial Identification at a Virtual Reality Airport. *Iperception.* **2019**, *10*. [CrossRef]
27. Plancher, G.; Gyselinck, V.; Piolino, P. The Integration of Realistic Episodic Memories Relies on Different Working Memory Processes: Evidence from Virtual Navigation. *Front. Psychol.* **2018**, *9*, 47. [CrossRef] [PubMed]
28. Tascón, L.; García-Moreno, L.M.; Cimadevilla, J.M. Almeria Spatial Memory Recognition Test (ASMRT): Gender Differences Emerged in a New Passive Spatial Task. *Neurosci. Lett.* **2017**, *651*, 188–191. [CrossRef]
29. Corriveau Lecavalier, N.; Ouellet, É.; Boller, B.; Belleville, S. Use of Immersive Virtual Reality to Assess Episodic Memory: A Validation Study in Older Adults. *Neuropsychol. Rehabil.* **2020**, *30*, 462–480. [CrossRef]
30. Lecouvey, G.; Morand, A.; Gonneaud, J.; Piolino, P.; Orriols, E.; Pélerin, A.; Da Silva, L.F.; de La Sayette, V.; Eustache, F.; Desgranges, B. An Impairment of Prospective Memory in Mild Alzheimer's Disease: A Ride in a Virtual Town. *Front. Psychol.* **2019**, *10*, 241. [CrossRef]
31. Vallejo, V.; Wyss, P.; Rampa, L.; Mitache, A.V.; Müri, R.M.; Mosimann, U.P.; Nef, T. Evaluation of a Novel Serious Game Based Assessment Tool for Patients with Alzheimer's Disease. *PLoS ONE* **2017**, *12*, e0175999. [CrossRef]
32. Iliadou, P.; Paliokas, I.; Zygouris, S.; Lazarou, E.; Votis, K.; Tzovaras, D.; Tsolaki, M. A Comparison of Traditional and Serious Game-Based Digital Markers of Cognition in Older Adults with Mild Cognitive Impairment and Healthy Controls. *J. Alzheimer's Dis.* **2021**, *79*, 1747. [CrossRef]
33. Faria, A.L.; Andrade, A.; Soares, L.; Bermúdez I Badia, S. Benefits of Virtual Reality Based Cognitive Rehabilitation through Simulated Activities of Daily Living: A Randomized Controlled Trial with Stroke Patients. *J. Neuroeng. Rehabil.* **2016**, *13*, 96. [CrossRef] [PubMed]
34. Foloppe, D.A.; Richard, P.; Yamaguchi, T.; Etcharry-Bouyx, F.; Allain, P. The Potential of Virtual Reality-Based Training to Enhance the Functional Autonomy of Alzheimer's Disease Patients in Cooking Activities: A Single Case Study. *Neuropsychol. Rehabil.* **2018**, *28*, 709–733. [CrossRef] [PubMed]
35. Liao, Y.-Y.; Tseng, H.-Y.; Lin, Y.-J.; Wang, C.-J.; Hsu, W.-C. Using Virtual Reality-Based Training to Improve Cognitive Function, Instrumental Activities of Daily Living and Neural Efficiency in Older Adults with Mild Cognitive Impairment. *Eur. J. Phys. Rehabil. Med.* **2020**, *56*, 47–57. [CrossRef] [PubMed]
36. García-Betances, R.I.; Arredondo Waldmeyer, M.T.; Fico, G.; Cabrera-Umpiérrez, M.F. A Succinct Overview of Virtual Reality Technology Use in Alzheimer's Disease. *Front. Aging Neurosci.* **2015**, *7*, 80. [CrossRef]
37. Krohn, S.; Tromp, J.; Quinque, E.M.; Belger, J.; Klotzsche, F.; Rekers, S.; Chojecki, P.; Mooij, J.d.; Akbal, M.; McCall, C.; et al. Multidimensional Evaluation of Virtual Reality Paradigms in Clinical Neuropsychology: Application of the VR-Check Framework. *J. Med. Internet Res.* **2020**, *22*, e16724. [CrossRef]
38. Brade, J.; Lorenz, M.; Busch, M.; Hammer, N.; Tscheligi, M.; Klimant, P. Being There Again—Presence in Real and Virtual Environments and Its Relation to Usability and User Experience Using a Mobile Navigation Task. *Int. J. Hum. Comput. Stud.* **2017**, *101*, 76–87. [CrossRef]
39. Plechatá, A.; Nekovářová, T.; Fajnerová, I. What Is the Future for Immersive Virtual Reality in Memory Rehabilitation? A Systematic Review. *NeuroRehabilitation* **2021**, *48*, 389–412. [CrossRef] [PubMed]
40. Ventura, S.; Brivio, E.; Riva, G.; Baños, R.M. Immersive Versus Non-Immersive Experience: Exploring the Feasibility of Memory Assessment Through 360° Technology. *Front. Psychol.* **2019**, *10*, 2509. [CrossRef]
41. Voinescu, A.; David, D. The Effect of Learning in a Virtual Environment on Explicit and Implicit Memory by Applying a Process Dissociation Procedure. *Int. J. Hum. Comput. Interact.* **2019**, *35*, 27–37. [CrossRef]
42. Pollard, K.A.; Oiknine, A.H.; Files, B.T.; Sinatra, A.M.; Patton, D.; Ericson, M.; Thomas, J.; Khooshabeh, P. Level of Immersion Affects Spatial Learning in Virtual Environments: Results of a Three-Condition within-Subjects Study with Long Intersession Intervals. *Virtual Real.* **2020**, *24*, 783–796. [CrossRef]
43. Krokos, E.; Plaisant, C.; Varshney, A. Virtual Memory Palaces: Immersion Aids Recall. *Virtual Real.* **2019**, *23*, 1–15. [CrossRef]
44. Plechatá, A.; Sahula, V.; Fayette, D.; Fajnerová, I. Age-Related Differences with Immersive and Non-Immersive Virtual Reality in Memory Assessment. *Front. Psychol.* **2019**, *10*, 1330. [CrossRef]
45. Tuena, C.; Serino, S.; Dutriaux, L.; Riva, G.; Piolino, P. Virtual Enactment Effect on Memory in Young and Aged Populations: A Systematic Review. *J. Clin. Med.* **2019**, *8*, 620. [CrossRef] [PubMed]
46. Engelkamp, J.; Zimmer, H.D.; Mohr, G.; Sellen, O. Memory of Self-Performed Tasks: Self-Performing during Recognition. *Mem. Cogn.* **1994**, *22*, 34–39. [CrossRef]
47. Brooks, B.; Attree, E.; Rose, F.; Clifford, B.; Leadbetter, A. The Specificity of Memory Enhancement during Interaction with a Virtual Environment. *Memory* **1999**, *7*, 65–78. [CrossRef] [PubMed]
48. Jebara, N.; Orriols, E.; Zaoui, M.; Berthoz, A.; Piolino, P. Effects of Enactment in Episodic Memory: A Pilot Virtual Reality Study with Young and Elderly Adults. *Front. Aging Neurosci.* **2014**, *6*, 338. [CrossRef]
49. Barhorst-Cates, E.M.; Rand, K.M.; Creem-Regehr, S.H. Does Active Learning Benefit Spatial Memory during Navigation with Restricted Peripheral Field? *Attention Perception Psychophys.* **2020**, *82*, 3033–3047. [CrossRef] [PubMed]

50. Ouellet, É.; Boller, B.; Corriveau-Lecavalier, N.; Cloutier, S.; Belleville, S. The Virtual Shop: A New Immersive Virtual Reality Environment and Scenario for the Assessment of Everyday Memory. *J. Neurosci. Methods* **2018**, *303*, 126–135. [CrossRef] [PubMed]
51. Jamalian, N.; Gillies, M.; Leymarie, F.F.; Pan, X. The Effects of Hand Tracking on User Performance: An Experimental Study of an Object Selection Based Memory Game. In Proceedings of the 2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Singapore, Singapore, 17–21 October 2022; IEEE: New York, NY, USA; pp. 768–776.
52. Khundam, C.; Sukkriang, N.; Noël, F. No Difference in Learning Outcomes and Usability between Using Controllers and Hand Tracking during a Virtual Reality Endotracheal Intubation Training for Medical Students in Thailand. *J. Educ. Eval. Health Prof.* **2021**, *18*, 22. [CrossRef]
53. Varela-Aldás, J.; Buele, J.; Amariglio, R.; García-Magariño, I.; Palacios-Navarro, G. The Cupboard Task: An Immersive Virtual Reality-Based System for Everyday Memory Assessment. *Int. J. Hum. Comput. Stud.* **2022**, *167*, 102885. [CrossRef]
54. Han, S.; Liu, B.; Cabezas, R.; Twigg, C.D.; Zhang, P.; Petkau, J.; Yu, T.-H.; Tai, C.-J.; Akbay, M.; Wang, Z.; et al. MEgATrack. *ACM Trans. Graph.* **2020**, *39*, 87. [CrossRef]
55. Masurovsky, A.; Chojecki, P.; Runde, D.; Lafci, M.; Przewozny, D.; Gaebler, M. Controller-Free Hand Tracking for Grab-and-Place Tasks in Immersive Virtual Reality: Design Elements and Their Empirical Study. *Multimodal Technol. Interact.* **2020**, *4*, 91. [CrossRef]
56. Facebook Technologies, LLC. First Steps with Hand Tracking. Available online: https://sidequestvr.com/app/3358/first-steps-with-hand-tracking (accessed on 1 December 2022).
57. González-Landero, F.; García-Magariño, I.; Amariglio, R.; Lacuesta, R. Smart Cupboard for Assessing Memory in Home Environment. *Sensors* **2019**, *19*, 2552. [CrossRef] [PubMed]
58. Julayanont, P.; Nasreddine, Z.S. Montreal Cognitive Assessment (MoCA): Concept and Clinical Review. In *Cognitive Screening Instruments*; Springer: Cham, Switzerland, 2017; pp. 139–195. [CrossRef]
59. MoCA Test Inc. In *MoCA Test*; MoCA Test Inc.: Quebec, QC, Canada.
60. Witmer, B.G.; Singer, M.J. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence Teleoperators Virtual Environ.* **1998**, *7*, 225–240. [CrossRef]
61. De Paolis, L.T.; De Luca, V. The Effects of Touchless Interaction on Usability and Sense of Presence in a Virtual Environment. *Virtual Real.* **2022**, *26*, 1551–1571. [CrossRef]
62. Finstad, K. The Usability Metric for User Experience. *Interact. Comput.* **2010**, *22*, 323–327. [CrossRef]
63. Gil-Gómez, J.A.; Manzano-Hernández, P.; Albiol-Pérez, S.; Aula-Valero, C.; Gil-Gómez, H.; Lozano-Quilis, J.A. USEQ: A Short Questionnaire for Satisfaction Evaluation of Virtual Rehabilitation Systems. *Sensors* **2017**, *17*, 1589. [CrossRef]
64. Rantamaa, H.-R.; Kangas, J.; Kumar, S.K.; Mehtonen, H.; Järnstedt, J.; Raisamo, R. Comparison of a VR Stylus with a Controller, Hand Tracking, and a Mouse for Object Manipulation and Medical Marking Tasks in Virtual Reality. *Appl. Sci.* **2023**, *13*, 2251. [CrossRef]
65. Lin, L.; Normoyle, A.; Adkins, A.; Sun, Y.; Robb, A.; Ye, Y.; Di Luca, M.; Jorg, S. The Effect of Hand Size and Interaction Modality on the Virtual Hand Illusion. In Proceedings of the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Osaka, Japan, 23–27 March 2019; IEEE: New York, NY, USA; pp. 510–518.
66. Miller, G.A. The Magical Number Seven, plus or Minus Two: Some Limits on Our Capacity for Processing Information. *Psychol. Rev.* **1956**, *63*, 81. [CrossRef]
67. Johnson, C.I.; Whitmer, D.E.; Entinger, J.; Peterson, E.K.; Sobel, B.M. Interacting with Virtual Reality with a Controller Instead of the Body Benefits Performance and Perceptions. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2022**, *66*, 1294–1298. [CrossRef]
68. Reggente, N.; Essoe, J.K.Y.; Baek, H.Y.; Rissman, J. The Method of Loci in Virtual Reality: Explicit Binding of Objects to Spatial Contexts Enhances Subsequent Memory Recall. *J. Cogn. Enhanc.* **2020**, *4*, 12–30. [CrossRef]
69. Smith, S.A. Virtual Reality in Episodic Memory Research: A Review. *Psychon. Bull. Rev.* **2019**, *26*, 1213–1237. [CrossRef]
70. Slater, M. Measuring Presence: A Response to the Witmer and Singer Presence Questionnaire. *Presence Teleoperators Virtual Environ.* **1999**, *8*, 560–565. [CrossRef]
71. Usoh, M.; Catena, E.; Arman, S.; Slater, M. Using Presence Questionnaires in Reality. *Presence Teleoperators Virtual Environ.* **2000**, *9*, 497–503. [CrossRef]
72. Lessiter, J.; Freeman, J.; Keogh, E.; Davidoff, J. A Cross-Media Presence Questionnaire: The ITC-Sense of Presence Inventory. *Presence Teleoperators Virtual Environ.* **2001**, *10*, 282–297. [CrossRef]
73. Khundam, C.; Vorachart, V.; Preeyawongsakul, P.; Hosap, W.; Noël, F. A Comparative Study of Interaction Time and Usability of Using Controllers and Hand Tracking in Virtual Reality Training. *Informatics* **2021**, *8*, 60. [CrossRef]
74. Cavedoni, S.; Chirico, A.; Pedroli, E.; Cipresso, P.; Riva, G. Digital Biomarkers for the Early Detection of Mild Cognitive Impairment: Artificial Intelligence Meets Virtual Reality. *Front. Hum. Neurosci.* **2020**, *14*, 245. [CrossRef] [PubMed]
75. Ruet, A.; Brochet, B. Cognitive Assessment in Patients with Multiple Sclerosis: From Neuropsychological Batteries to Ecological Tools. *Ann. Phys. Rehabil. Med.* **2020**, *63*, 154–158. [CrossRef]

2.4. Artículo: Virtual reality applications based on instrumental activities of daily living (iADLs) for cognitive intervention in older adults: a systematic review

Buele *et al.*
Journal of NeuroEngineering and Rehabilitation (2023) 20:168
https://doi.org/10.1186/s12984-023-01292-8

Journal of NeuroEngineering and Rehabilitation

REVIEW **Open Access**

Virtual reality applications based on instrumental activities of daily living (iADLs) for cognitive intervention in older adults: a systematic review

Jorge Buele[1,3], José Luis Varela-Aldás[2] and Guillermo Palacios-Navarro[3*]

Abstract

Background In recent years, the use of virtual reality (VR) as a complementary intervention in treating cognitive impairment has significantly increased. VR applications based on instrumental activities of daily living (iADL-VR) could offer a promising approach with greater ecological validity for intervention in groups with cognitive impairments. However, the effectiveness of this approach is still debated.

Objective This systematic review aims to synthesize the effects of iADL-VR interventions to rehabilitate, train, or stimulate cognitive functions in healthy adults and people with mild cognitive impairment (MCI) and different types of dementia.

Methods A systematic search was performed in the Scopus, PubMed, IEEE Xplore, Web of Science, and APA PsycNet databases until September 2022 and repeated in April 2023. The selected studies met the search terms, were peer-reviewed, included an iADL-VR intervention, and were written in English. Descriptive, qualitative studies, reviews, cognitive assessment, non-intervention studies, those unrelated to VR or iADL, those focused on motor aspects, and non-degenerative disorders were excluded. The PEDro scale was used to assess the methodological quality of the controlled studies. To present and synthesize the results, we organized the extracted data into three tables, including PEDro scores, participant characteristics, and study characteristics.

Results Nineteen studies that met the inclusion and exclusion criteria were included. The total sample reached 590 participants, mostly women (72.67%). Approximately 30% were diagnosed with Alzheimer's disease or dementia, and 20% had mild cognitive impairment. Variables such as authors and year of publication, study design, type of intervention and VR applied, duration of the intervention, main findings, and conclusions were extracted. Regarding demographic characteristics, the sample size, age, sex, years of education, neurological diagnosis, dropouts, and the city and country where the intervention took place were recorded. Almost all studies showed improvements in some or all the outcomes after the intervention, generally greater in the iADL-VR group than in the control group.

Conclusion iADL-VR interventions could be beneficial in improving the performance of cognitive functions in older adults and people with MCI and different types of dementia. The ecological component of these tasks makes them very suitable for transferring what has been learned to the real world. However, such transfer needs to be confirmed

*Correspondence:
Guillermo Palacios-Navarro
guillermo.palacios@unizar.es
Full list of author information is available at the end of the article

by further studies with larger and more homogeneous samples and longer follow-up periods. This review had no primary funding source and was registered with PROSPERO under registration ID: 375166.

Keywords iADL, Mild cognitive impairment, Cognitive rehabilitation, Cognitive functions, Older adults, Virtual reality

Introduction

Cognition encompasses various intellectual functions and processes, including perception, attention, consciousness, language, memory, emotions, and executive functions [1, 2]. These cognitive functions work in conjunction with visuospatial abilities, which make it possible to identify stimuli necessary for movement, depth perception, and environmental navigation [3]. These cognitive abilities are essential for individuals to carry out their routine tasks and maintain normal functioning in their environment. Everyday life tasks and routines are called activities of daily living (ADLs) and are essential for self-care and independence [4]. They can be classified into two subgroups: basic activities of daily living (bADL) and instrumental activities (iADL) [5]. Personal care activities such as bathing, dressing, toileting, and functional mobility (the ability to move from one place to another) are in the bADL group [6]. Instrumental activities are based on more complex skills that require multiple cognitive processes, such as food preparation, medication management, and financial management.

According to the American Occupational Therapy Association (AOTA), there are 11 iADLs that are more complex and, as such, may present a challenge for some older adults [7]. These include tasks such as (i) care of others; (ii) care of pets and animals; (iii) child rearing; (iv) communication management; (v) driving and community mobility; (vi) financial management; (vii) home establishment and management; (viii) meal preparation and cleanup; (ix) religious and spiritual expression; (x) safety and emergency maintenance; and (xi) shopping [7]. A decrease in the ability to perform iADLs is linked to the initiation of cognitive decline, which can be a component of the natural aging process. The decline in iADL performance becomes increasingly noticeable as MCI emerges and becomes even more pronounced in cases of dementia [8–10]. As the world's population ages, the incidence of dementia increases, a term that encompasses a variety of clinical diagnoses, including Alzheimer's disease (AD), Parkinson's disease, vascular dementia (VaD), frontotemporal dementia (FTD), Huntington's disease and Lewy Body Dementia (LBD), each with their own causes and specific risk factors. As pointed out by Iribarnea et al., [11] AD is the most common cause of dementia, accounting for 80% of cases in people over 65 years of age, followed by VaD, FTD and LBD. Zhang et al. [12] pointed out in their review that Mild AD is the leading cause of dementia, accounting for 50–70% of cases. In another study, Iadecola et al. [13] highlighted that although AD prevails as the leading cause of clinically diagnosed dementia in Western countries, VaD might be more prevalent in East Asia. Furthermore, several vascular factors emerge as important factors in the pathogenesis and clinical manifestation of AD [14].

Alzheimer's disease is believed to be linked to an abnormal buildup of proteins in the brain, such as beta-amyloid and tau protein, which leads to degeneration of brain cells [15]. This disease progresses in stages, beginning with the impairment of episodic memory, followed by deficits in areas such as semantics and attention, and later, with deficits in visuospatial and auditory-verbal memory [16]. The increase in the prevalence of neurodegenerative diseases, such as Alzheimer's disease, has become a global phenomenon. In 2019, more than 50 million people worldwide were estimated to be living with dementia, and this number is expected to increase to 150 million by 2050, posing a significant burden on healthcare systems and society in general [17].

Given the increasing prevalence of neurocognitive disorders, interventions to improve cognitive functions and iADL are of great importance [18]. These interventions include cognitive training (CTR), which focuses on the systematic practice of specific tasks to improve cognitive performance [19]; cognitive rehabilitation (CRE), which addresses specific cognitive difficulties through compensatory and adaptive strategies [20]; and cognitive stimulation (CST), which involves participation in a variety of cognitive and social activities to maintain and improve overall cognitive functioning [21]. Paper-and-pencil therapies represent traditional cognitive treatments that have been used for several decades to address cognitive deficits in older adults. Although they are beneficial and clinically validated, they present difficulties in maintaining patient motivation and adherence to these processes [22]. In addition, the lack of ecological proposals in clinical neuropsychology interventions has been criticized because they do not always reflect the actual functional performance of the individual [23]. Ecological validity is used in this context to express generalizability (the level to which the findings of an evaluation relate to and/or predict behaviors beyond the testing environment) and representativeness (the plausibility or degree to which the evaluations resemble situations of daily life in which such behaviors will be necessary) [24].

VR has emerged as a potentially valuable tool in the field of cognitive intervention, offering real and ecologically valid demands to stimulate neuroplasticity and enhance regenerative processes, as established by Maggio et al. [25]. In this sense, neuroplasticity refers to the brain's ability to change and adapt in response to environmental experiences and stimuli [26]. Stimulation of these areas can strengthen neural connections and improve information processing capacity, which can lead to improvements in cognitive performance and the ability to perform iADLs. Therefore, understanding neuroplasticity is essential to explain how behavioral interventions and VR can improve cognitive functions in older adults with cognitive impairment. Shah et al. [27] mention that cognitive training can stimulate neuroplasticity, thus increasing cognitive reserve.

The existing literature suggests that VR could be beneficial in the evaluation and intervention of dementia and MCI [28]. Skurla et al. [29] investigated the relationship between VR and mental health in older adults and mentioned that it can be used as a training tool, although there are still areas for potential improvement. Coyle et al. [30] presented a systematic review showing that computerized and VR training had consistent improvements in attention, executive function, memory (visual and verbal), and memory strategy. There were also favorable psychological effects, including a reduction in depressive symptoms and anxiety. Papaioannou et al. [31] reviewed the efficacy and moderators of VR for cognitive training in people with dementia and mild cognitive impairment, suggesting that VR is an effective treatment in this population. Maggio et al. [28] presented a scoping review that highlighted the opportunities and challenges in the implementation of VR technology. They emphasized the possibility of increasing motivation and participation, which could improve the effects of conventional therapies. Likewise, Yu et al. [32] investigated the use of virtual and augmented reality technologies in neuropsychological rehabilitation and underlined the potential of these technologies to improve quality of life and cognitive performance in older adults.

It is important to mention that VR can come in different degrees of immersion, such as non-immersive, semi-immersive, and fully immersive. At the non-immersive level, virtual environments are presented from a conventional computer, and users control their interaction through devices such as joysticks or other controllers [33]. There is an intermediate category of VR known as semi-immersive VR, where users interact with the virtual environment, but are still aware of their surrounding physical environment. Although perception of the real world is not completely blocked, semi-immersive systems can offer an immersive experience with interactive features [34]. This type of VR can come with more sophisticated graphics and larger flat screens or a large screen projector [35], although we can also find the use of the IREX system, which combines a monitor, video camera, virtual objects, and data gloves to recognize the movement of patients [36]. On the other hand, fully immersive VR allows users to experience a simulated reality in an immersive way, giving them the feeling of living inside the virtual world [37]. Fully immersive VR systems can include projections on surrounding physical surfaces or even head-mounted displays (HMDs) that completely immerse the user in the virtual environment, achieving a high degree of immersion [38].

However, excessive use of HMD can lead to unwanted effects, including visual disturbances, disorientation, postural instability, nausea, headache, and postural discomfort, among others [39]. These effects are explained by conflicts in sensory and spatial integration. In the way virtual environments are designed, there is often a mismatch between the visual system, the vestibular system, and the individual's movement or posture system. The user receives visual signals of movement, while their vestibular system indicates that there is no change in posture or actual movement. When the individual cannot quickly integrate this information, which differs from his or her experience in the real world (even if it is simulated), discomfort and physiological problems may arise. Furthermore, the lack of synchronization between virtual images, motion detection through the helmet and integration with corresponding visual feedback can lead to orientation problems and dizziness [40]. Importantly, when users have health problems, such as a history of epileptic seizures, the risk of adverse effects increases significantly. Therefore, it is essential to evaluate the health history of participants before including them in an intervention that involves the use of VR.

The review carried out by Corregidor-Sánchez et al. [41] analyzed the effectiveness of virtual systems (not specifically ADL-based interventions) in improving the performance of older people in carrying out their daily activities. They analyzed 23 studies and found a slight improvement effect on iADL, although not significant. It is also mentioned that the quality of the evidence from these studies is very low, and therefore, their true contribution is uncertain, motivating the development of studies with higher quality and methodological rigor. Kurz did something similar, dividing VR applications into three categories: stimulation, training, and cognitive rehabilitation [42]. He concluded that further randomized controlled trials (RCTs) are needed to validate delayed cognitive decline and its positive influence on ADLs and quality of life. On the other hand, in the review carried out by Romero-Ayuso et al. [43], VR applications based on iADL were used in cognitive screening and assessment. The authors highlighted several key advantages of VR, including its cost-effectiveness, safety features, ability to authentically replicate real-world scenarios (ecological validity), versatility in addressing diverse conditions, and the convenience it offers in terms of seamless data collection and scoring [44].

Although there are challenges and limitations associated with VR, its use in interventions could significantly improve the quality of life for affected individuals and their caregivers. The literature search did not identify any previous reviews that specifically focused on the analysis of VR applications that simulate activities of daily living in interventions for older adults with degenerative cognitive disorders. Given the importance of iADL for older adults and the need to find effective interventions to maintain and improve their cognitive functions, it is relevant to address this research topic. The purpose of this systematic review is to synthesize existing evidence regarding the effectiveness of cognitive intervention strategies that use VR to simulate iADL for intervention in healthy older adults, those with MCI, or those with dementia. We hypothesize that continuous training with iADL-based VR applications will have a satisfactory effect on improving comprehensive cognitive function. As secondary objectives and considering the knowledge acquired in this review, we will seek to provide guidelines or instructions for clinical practice and the implications that this review may have in future research, indicating where future research on iADL based on VR should be directed.

Methods

Search strategy

One of the authors (JB) conducted a systematic computerized search in the electronic databases: Scopus, PubMed, IEEE Xplore, Web of Science, and APA PsycNet. The keywords and search syntax were adapted to the characteristics of each database. The exact search terms are included in Additional file 1: Annex 1. A comprehensive search of the English-language literature was performed, and the range of years was considered from inception to April 20, 2023. This review was registered in PROSPERO (Registration ID: 375166).

Inclusion criteria

Studies were included if they a) were original peer-reviewed articles, including controlled studies or single-group studies; b) involved an iADL-VR intervention for training, rehabilitation, and/or stimulation of cognitive functions; c) had at least one outcome measure related to the clinical effects obtained after the intervention; and d) were published in English.

Regarding VR systems, all types were admitted; however, immersive, semi-immersive, and non-immersive systems were differentiated. According to the literature, applications based on immersive VR systems could have greater ecological validity [45, 46]. There were no restrictions on the age, sex, years of formal education, dropouts, or nationality of the selected study participants. There were no limitations regarding the program's administration, frequency, duration, intensity or sessions. For interventions that included an experimental group (EG) using VR and a control group (CG), both active (ACG) (other interventions) and passive (PCG) (no procedure) controls were included.

Exclusion criteria

We established the following exclusion criteria for study selection: a) studies solely focused on theoretical, descriptive, or qualitative research without providing any type of intervention; b) studies focused solely on motor rehabilitation or if they aimed at cognitive-motor rehabilitation; c) studies that considered cognitive disorders that are not degenerative in nature, such as stroke or traumatic brain injury (TBI); d) studies involving cognitive screening or diagnosis; e) interventions not aimed at cognitive training and rehabilitation; f) studies not involving the use of VR or not including ADLs in the intervention; and g) any type of review, including both systematic and narrative reviews, as well as meta-analyses.

Data extraction

Data from the included articles were extracted by two reviewers (JB and JV-A) who worked independently. The general characteristics and results of the studies were recorded, including the author's name, the year of publication, the study design, the type of intervention and VR applied, the task or place simulated virtually, the duration of the intervention, main results, and conclusions. Regarding the demographic characteristics of the participants in the different studies, the following variables were recorded: sample size, mean age and standard deviation, sex, years of formal education, neurological diagnosis, number of dropouts, and the city and country where the intervention took place.

Methodological quality assessment

Authors JB and JV-A assessed the methodological quality of the controlled studies using the Physiotherapy Evidence Database (PEDro) rating scale [47]. Any disagreement between the two reviewers about the methodological quality of the studies was resolved by consensus with the help of a third reviewer (GP-N). The PEDro scale consists of 11 items for evaluating the methodological quality of a study, although one of them (eligibility criteria item) does not contribute to the total score [47]. A score of 1 is obtained if the criterion is satisfied. Therefore, the PEDro total score ranges from 0 to 10, and the higher the score is, the better the methodological quality of the clinical trial. The PEDro scale was chosen based on its reliability, validity, and ease of use for evaluating randomized clinical trials and other controlled study designs in cognition-related interventions [48]. A PEDro score of 9–10 is considered "excellent," 6–8 as "good", and 4–5 as "fair", whereas any score below 4 indicates a "poor" quality study [49].

Results

Data synthesis

The initial search yielded a total of 5568 articles from five databases. After removing 1779 duplicates, 3782 abstracts were further examined, and 3830 articles were excluded. Three hundred twenty-one articles were selected for full-text reading. After excluding 301 that met the eligibility criteria, 19 articles were included in the final review. The study selection process was conducted taking into account the PRISMA guidelines [50], and its results are summarized in Fig. 1.

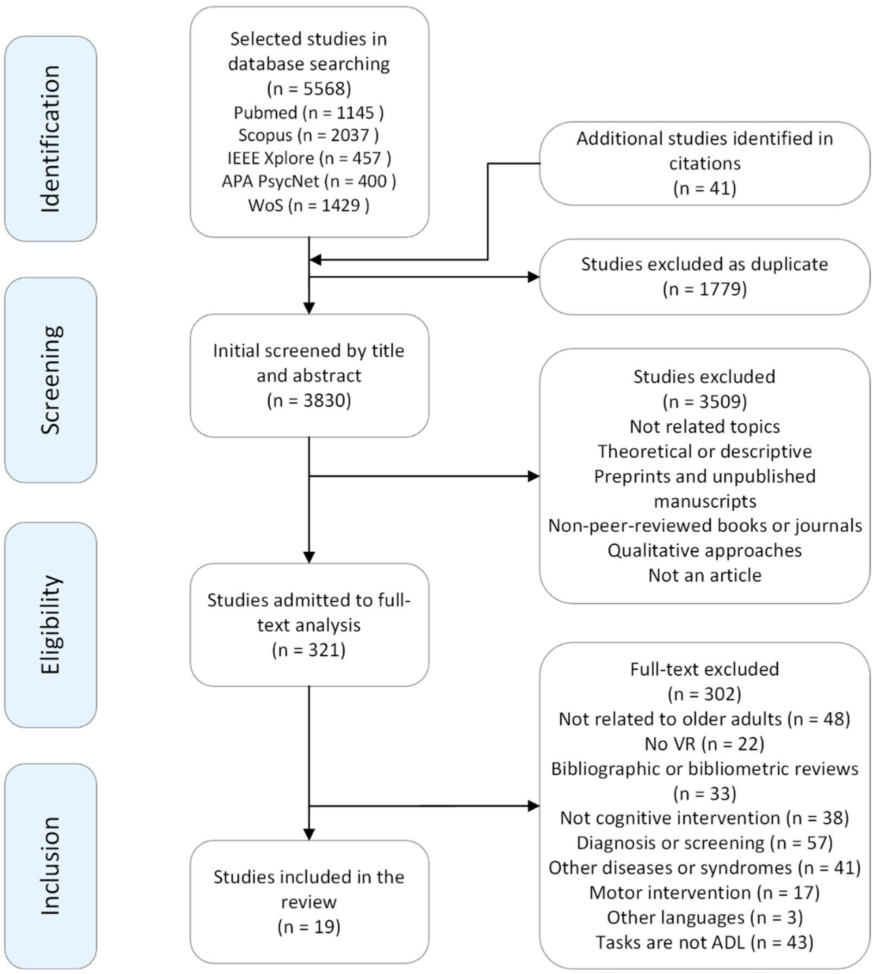


Fig. 1 Consort diagram of study selection

Methodological quality assessment

The PEDro scores for all controlled trials studies are presented in Table 1. They are not yet available in the PEDro database [47], so we had to evaluate them. Their final score was obtained by consensus between the authors. The twelve assessed studies ranged from 4 to 8 (out of 10), with an average score of 6.16 ± 1.14, which suggests that the included studies were of “good” methodological quality. The eligibility criteria were satisfied in all of the studies except that of Yamaguchi et al. [51]. All the studies included in our review satisfied the baseline comparability criteria. However, it is worth noting that, due to the nature of VR-based interventions, it can be challenging to apply some items of the PEDro scale, such as subject blinding and therapist blinding, as well as concealed allocation. This last item was not fulfilled in any of the studies we reviewed. Therefore, we considered studies with PEDro scores of 4 or higher to be of reasonable quality in our review [52]. However, it is important to acknowledge that applying concealed allocation and other criteria of the PEDro scale in VR intervention studies can be inherently challenging, and this should be considered when interpreting the results of our review and planning future research in this field.

Overview of interventions

Participant characteristics

A total of 590 participants across nineteen studies were included in this review. The study of Foloppe et al. [53] considered only one person, whereas in Tarnanas et al.’s study [54], 105 people were included. The average number of participants per intervention was ≈ 31 (23). The age of the participants in all the studies was over 60 years, with an average age of 75.25 (5.55). A total of 165 men (28.01%) were included in the studies, on average ≈ 9 (9) per intervention and 424 women (71.99%), on average ≈ 24 (16) per intervention. Regarding the years of formal education, five studies did not report any information [54–58]. Man et al. [59] made a classification by years of study (0, 1–2, > 2) and Oliveira et al. [60] classified people according to their educational level. In the rest (n = 12), there was an average of 8.5 (2.05) years of formal education.

Concerning the cognitive diagnosis, patients with MCI (n = 4) were included [54, 61–63]; AD or dementia (n = 6) [51, 55, 57, 58, 60, 64]; healthy (n = 2) [56, 65]; MCI and healthy (n = 2) [66, 67]; MCI and mild dementia (MD) (n = 1) [68]; probable AD (pAD) (n = 2) [53, 59]; AD, depression and healthy (n = 1) [69] and MCI and memory deficit (n = 1) [70]. In (n = 8) [54, 57, 60, 61, 66–68, 70], dropouts were reported. Table 2 summarizes the demographic characteristics of the participants for each of the included studies. For each study, the following are shown: the authors and year of publication, the size of the sample and that of the experimental and/or control groups, the participant diagnosis, age, gender, years of formal education, number of dropouts, and the city and country where the intervention took place.

Characteristics of interventions

Of the 19 studies in our review, one case study, six pilots, six clinical trials, and 6 randomized controlled trials (RCTs) were identified. The case study provided a detailed view of a specific case [53], while the pilots offered preliminary information on the effectiveness and feasibility of VR interventions in iADL [51, 55, 57, 58, 63, 68]. Clinical trials (CTs) evaluated the effectiveness in larger groups of participants [56, 64–67, 69], and the RCTs provided methodological rigor by randomly assigning participants to intervention and control groups [54, 59–62, 70].

In one study [62], a passive control group (PCG) was used. Seven studies [56, 58–61, 63, 70] used an active control group (ACG). Tarnanas et al. [54] used both a PCG and an ACG. Ten studies [51, 53, 55, 57, 64–69] involved only virtual therapy.

a) *Intervention type.* Regarding the type of intervention, three groups were identified: cognitive training (CTR), cognitive rehabilitation (CRE), and cognitive stimulation (CST). Thirteen studies [57–59, 61–64, 66–70] presented a CTR intervention. Two studies [53, 55] described that their interventions are within the CRE. Four studies [54, 56, 60, 65] carried out a CST, and in [51], a relearning program was implemented. Eleven interventions [51, 53–55, 57, 58, 62, 66–68, 70] simulated a single task, while the others simulated multitasking.
b) *Cognitive domain.* A total of 32 different cognitive domains were identified across the 19 studies included in this review. Of these, 12 studies focused on executive functions [54–56, 60–63, 65–68, 70], 10 on attention [53–56, 62, 63, 65–68], and 8 on visuospatial processing [54, 57, 61, 62, 64, 67, 69, 70]. Other domains evaluated included memory (n = 6) [53, 54, 66–69], iADLs (n = 6) [53, 56, 60, 62, 64, 70], general or global cognition (n = 5) [56, 60, 64, 68, 70], verbal memory (n = 4) [61, 63, 64, 70], and working memory (n = 4) [55, 56, 63, 65].
c) *Simulated task.* VR applications that simulated iADLs were highly heterogeneous. Five studies [62, 66–69] simulated purchases in a store/supermarket. In two studies [58, 63], VR tasks were performed in an apartment. One study implemented kitchen tasks [51], and Foloppe et al. [53] alternated between a real

Table 1 PEDro scores of the controlled-trial studies

Study	Eligibility criteria	Random allocation	Concealed allocation	Baseline comparability	Subject blinding	Therapist blinding	Assessor blinding	< 15% drop-out	Intention-to-treat analysis	Between group difference reported	Point estimate and variability reported	Total Pedro Score
Man et al. (2012) [59]	1	1	0	1	0	0	0	1	1	1	1	6/10
Kang et al. (2021) [61]	1	1	0	1	0	0	1	1	0	1	1	6/10
Schreiber et al. (1999) [58]	1	1	0	1	0	0	1	1	1	1	1	7/10
Panerai et al. (2021) [64]	1	0	0	1	0	0	1	1	1	1	1	6/10
Hofmann et al. (2003) [69]	1	0	0	1	0	0	0	1	1	1	1	5/10
Yamaguchi et al. (2012) [51]	0	0	0	1	0	0	0	1	1	1	0	4/10
Gamito et al. (2020) [56]	1	1	0	1	1	1	0	1	1	1	1	8/10
Park et al. (2019) [63]	1	1	0	1	0	0	1	1	1	1	1	7/10
Park (2022) [62]	1	1	0	1	1	0	1	1	1	1	1	8/10
Optale et al. (2010) [70]	1	1	0	1	0	0	1	1	0	1	1	6/10
Tarnanas et al. (2014) [54]	1	1	0	1	0	1	1	1	0	0	1	6/10
Oliveira et al. (2021) [60]	1	1	0	1	0	0	0	1	0	1	1	5/10
Studies' degree of compliance (%)	91.16	75	0	100	16.66	16.66	58.33	100	66.66	91.16	91.16	

A score of 1 indicates that the study satisfied a specific criterion, while a score of 0 indicates that the study did not meet that criterion. It is important to note that the eligibility criteria item is not included in the calculation of the total PEDro score. The degree of compliance with the criteria of the different studies is expressed as a percentage of the total number of studies

Table 2 Characteristics of the participants of the included studies

Authors and year of publication	Sample (n)	Diagnosis	Mean Age (Years) (SD)	Male/Female	Years of study (Years) (SD)	Dropouts	City, Country
Foloppe et al. (2018) [53]	1	pAD	79	0/1	6	DNM	Angers, France
Schreiber et al. (1999) [58]	14 (EG: 7; ACG: 7)	AD	EG: 80.86 (4.6); ACG: 78.86 (6.72)	EG: 2/5; ACG: 1/6	DNM	DNM	Düsseldorf, Germany
Zhu et al. (2022) [68]	31 (MCI: 18; MD: 13)	MCI, MD	MCI: 82.94 (6.44); MD: 85.76 (4.67)	MCI: 6/12; MD: 3/10	MCI: 11.00 (3.97); MD: 11.23 (4.71)	4 (MD: 1; MCI: 3)	Hong Kong, China
Man et al. (2012) [59]	44 (EG: 20; ACG: 24)	pAD	EG: 80.30 (1.21); ACG: 80.28 (1.31)	EG: 3/17; ACG: 2/22	EG: Un: 16; 1 year: 2; more: 2; ACG: Un: 14; 1 year: 4; more: 6	DNM	Hong Kong, China
Panerai et al. (2021) [64]	42 (EG. 24; AGC: 18)	AD	EG: 68.5; ACG: 64.0	EG: 13/11; ACG: 6/12	EG: 8; ACG: 8	DNM	Troina, Italy
Masoumzadeh et al. (2020) [57]	10 (H: 2; MCI: 4; AD: 4)	Dt	H: 85 (6); MCI: 79 (10.5); AD: 69 (7.1)	3/7	DNM	1 (H)	Winnipeg, Canada
Fasilis et al. (2018) [55]	10	Dt	73.6	DNM	DNM	DNM	Athens, Greek
Hofmann et al. (2003) [69]	28 (AD: 9; D: 9; H: 10)	AD, Dp	AD: 68.1 (14.7); D: 67.3 (9.4); H: 69.3 (5.8)	AD: 2/7; D: 2/7; H: 3/7	AD: 11.9 (5.4); D: 12.0 (5.7); H: 12.1 (5.2)	DNM	Basel, Switzerland
Kang et al. (2021) [61]	41 (EG: 23; PCG: 18)	sCD, MCI	EG: 75.48 (4.67); PCG: 73.28 (6.96)	EG: 6/17; PCG: 6/12	EG: 7.7 (4.1); PCG: 8.56 (4.83)	4 (EG: 2; PCG: 2)	Incheon, South Korea
Yamaguchi et al. (2012) [51]	4 (AD: 2; H: 2)	AD	AD: 78.5; H: 82.5	AD: 0/2; H: 1/1	8	DNM	Angers, France
Park (2022) [62]	32 (EG: 16; PCG: 16)	MCI	EG: 72.3 (5.13); PCG: 70.9 (4.51)	EG: 9/7; PCG: 6/10	EG: 7.56 (3.93); PCG: 7.50 (2.89)	DNM	Asan, South Korea
Maeng et al. (2021) [66]	47 (MCI: 24; H: 23)	MCI, H	MCI: 73.2 (7.3); H: 71.6 (4.4)	MCI: 8/23; H: 3/22)	MCI: 9.5 (4.7); H: 8.9 (3.4)	9 (MCI: 7; H: 2)	Incheon, South Korea
Kim et al. (2021) [67]	44 (MCI: 22; H: 22)	MCI, H	MCI: 74.23 (7.5); H: 71.45 (3.95)	MCI: 5/17; H: 2/20	MCI: 8.68 (4.61); H: 8.91 (3.16)	11 (MCI: 9; H: 2)	Incheon, South Korea
Park et al. (2019) [63]	21 (EG: 10; ACG: 11)	MCI	EG: 70.5 (4.2); ACG: 72.6 (5.3)	EG: 2/8; ACG: 2/9	EG: 7.09 (3.36); ACG: 7.09 (3.36)	DNM	Daegu, South Korea
Gamito et al. (2019) [65]	25	H	74 (5.27)	4/21	6 (2.42)	DNM	Benfica, Portugal
Gamito et al. (2020) [56]	43	H	75 (5.43)	9/34	DNM	DNM	Lisbon, Portugal
Optale et al. (2010) [70]	31 (EG: 15; ACG: 16)	MCI y Mdf	EG: 78.5 (10.9); ACG: 81.6 (5)	EG: 5/10; ACG: 5/11	EG: 5.3 (2.4); ACG: 6 (3.5)	5 (EG: 3; ACG: 2)	Venetia, Italy
Tarnanas et al. (2014) [54]	105 (EG: 32; ACG: 39; PCG: 34)	MCI	EG: 70.5; ACG: 69.7; PGC: 70.9	EG: 12/20; ACG: 16/23; PCG: 13/21	DNM	9 (EG: 7; PCG: 2)	Kozani, Greek,
Oliveira et al. (2021) [60]	17 (EG: 10; PCG: 7)	AD	83.24 (5.66)	EG: 3/7; EG: 2/5	EG: Un: 2, Pri: 6, Sec or more: 2; CG: Un: 0, Pri: 5, Sec or more: 2	EG: 1	Lisbon, Portugal

H: Healthy, Dt: Dementia, pAD: Probable Alzheimer's Disease, Dp: Depression, sCD: Subjective Cognitive Impairment, Un: Below than primary school, Pri: Primary education, DNM: Does not mention, Mdf: Memory deficit, SD: standard deviation, Sec: Secondary Education

kitchen and a virtual kitchen. A driving simulator was described in [57], a museum in [54], and auditory training in everyday places in [70]. There are also combined tasks (kitchen and apartment) [59], virtual supermarket, kitchen and apartment [55], and various tasks (including supermarket and kitchen tasks) in five studies [56, 60, 61, 64, 65].

d) *Level of immersion.* Regarding the levels of immersion with which VR is applied, seven studies [57, 61, 63, 66–68, 70] used immersive environments, while in the rest of the studies, tasks were performed in non-immersive environments [51, 53–56, 58–60, 62, 64, 65, 69]. One of the negative effects that immersive virtual environments can produce is cybersickness, which includes dizziness, disorientation, headaches, eye pain, and other related pain. Four studies [57, 61, 66, 68] reported the presence of these symptoms (mostly mild).

e) *Number of sessions and duration.* The average number of sessions was 17.6 (14.74), with a minimum of 2 [51] and a maximum of 60 [70]. One intervention [64] was conducted in group sessions (with 5 participants), and in the study of Park [62], it is unclear whether it was individual or group-based. The duration of each session was not mentioned in the study of Hofmann et al. [69], resulting in an average session time of 12.81 (13.79) hours per person on average. Regarding the type of VR applied, the duration of the sessions in interventions with immersive VR ranged from 20/30 min to 50/60 min. Interventions with non-immersive VR had a duration ranging between 30 and 90 min. The interventions ranged from a minimum of 3 [51] and 4 [61] hours, to a maximum of 60 h [54]. Interventions lasting less than 10 h were proposed in eleven studies [51, 56–61, 63, 65–67], while four studies [53, 55, 62, 64] used between 10 and 19 h, and three studies [54, 68, 70] used 20 h or more. Medication use (pharmacotherapy) during the intervention was reported in three studies [61, 64, 69]. Follow-up or maintenance evaluations were not performed in 18 studies, while in [53], two follow-up assessments were conducted (at one month and six months later), and Hofmann et al. [69] conducted a follow-up after three weeks.
f) *Administrators of the interventions.* Occupational therapists administered the intervention in eight studies [51, 53, 58, 59, 62, 63, 66, 70]. In five studies, the treatment was administered by a clinical psychologist [54, 56, 64, 65, 68], whereas in two studies, a clinical neuropsychologist was responsible [60, 61] Finally, four studies did not mention who conducted the intervention [55, 57, 67, 69].
g) *Country.* South Korea had the most interventions (n = 5) [61–63, 66, 67], followed by Portugal (n = 3) [56, 60, 65]. Other countries, such as France [51, 53], Greece [54, 55], Italy [64, 70] and China [59, 68], contributed two studies each. Canada [57], Germany [58] and Switzerland [69] contributed one study each.

Table 3 shows the main characteristics of the interventions, including who administered the interventions, the design, type of intervention and level of immersion, virtually simulated place, duration of treatment, outcome measurements, main findings, and conclusions. Since some tasks (e.g. supermarket) can include different subtasks, we also include in Table 4 all the subtasks corresponding to these high-level activities.

Discussion

This systematic review focused on evaluating the use of VR as a therapy in cognitively healthy older adults and those with cognitive disorders, specifically, MCI and different types of dementia, which are degenerative processes that gradually evolve over time. The reason for including healthy older adults was to provide a comprehensive perspective of the impact of virtual reality on both normal and pathological cognitive aging. This review brings important evidence about iADL-VR applications that report improvement in the cognitive domains involved in these activities and even in motivational and behavioral aspects. Previous studies have already reported moderate to large improvements in global cognition, memory, and executive function in VR interventions [31]. Furthermore, VR has been found to promote the reactivation of some areas of the cortex by boosting the processes of neuroplasticity, language, executive function, short-term and working memory, attention, movement, and balance [28]. According to Vallejo et al. [71], studies that also simulate everyday tasks could have a greater effect on executive functions, prospective memory, and retrospective memory.

Cognitive improvement

Virtual environments that simulate activities of iADL can increase ecological validity and have positive effects on general cognitive function [68] and learning new information [66]. In the context of aging, tasks related to shopping maintain and improve independent daily functioning, planning, and problem-solving abilities [45]. These tasks are more complex and require participants to plan, organize, problem-solving, and multitask in a spatial and visual context, making them particularly relevant for autonomous daily living [72]. The review included studies that reported shopping, food preparation, and cleaning as the most common iADL performed by older adults. However, some complex iADLs were not considered in the interventions, possibly because they require more skill or resources [73]. Gamito et al. [56] simulated several ADLs and found a 14% improvement in global cognition in the intervention group, while Foloppe et al. [53] reported greater autonomy and reduced need for instructions.

Increased retention of visual-figurative material [58], general memory [68], visuospatial memory [56, 57, 63] and working memory [57, 63] has been identified. Additionally, improvements have been observed in executive functions [57, 68], retention, rigid thinking [55], cognitive flexibility [66], attention [68] and specifically selective attention (shopping list in a virtual supermarket) [66]. Improvements have also been reported in total and episodic encoding, total and directed recall [59, 61],

Table 3 Characteristics of the interventions in the included studies

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Foloppe et al. (2018) [53]	Single case	Non-Immersive CRE	Virtual and real cooking tasks	4d × 4w × 60 min	Patient: MMSE, IADL-9, RDES, ADRQL-F. Caregiver: MiniZarit, RSES, ADRQL-F	Memory, attention, planning, sequencing, basic motor skills, iADL	The patient showed a modest but significant improvement in assisted autonomy when relearning cooking activities with VR (15.4% in the virtual condition, 11.3% in the real condition) The need for assistance decreased, although instrumental activities of daily living did not change Mini-Zarit (caregiver burden) was reduced from moderate to mild	VR enabled the AD patient to improve in cooking tasks, with stable results up to a 6-month follow-up. However, there was no knowledge transfer to other iADLs Hybrid programs combining VR and real environments may be beneficial in achieving generalization to other activities Therefore, VR interventions should be tailored to individual needs and histories

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Schreiber et al. (1999) [58]	Pilot pretest–post-test	Non-Immersive CTR	Virtual apartment	5d × 2 w × 30 min	NAI Picture Test, NAI Figure Test, RBMT Picture Test, RBMT Route Learning (immediate and delayed)	Immediate and late retention and visual-figurative and topographic material	VR training improved the retention of significant visual-figurative and topographic information, with notable differences between the training and control groups on the NAI Picture Test ($P = 0.006$) and the RBMT Route Learning, delayed ($P = 0.025$) Subjects with dementia experienced real improvements in training and achieved lower difficulty levels on delayed retention	Pre- and post-training neuropsychological assessment indicated a direct transfer to real-life situations in the training group Standardized psychometric tests revealed a positive effect of computer-based training in certain memory domains, specifically in the target areas

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Zhu et al. (2022) [68]	Pilot pretest–post-test	Immersive CTR	Virtual Supermarket	3 d × 5 w × 20/30 min	MoCA-CS, MMSE, AVLT, STT, SDMT, PSS, GDS	Executive function, attention, memory, general cognition	Both groups (MCI and MD) showed significant improvements in all measures of cognitive function The MD group improved overall cognitive function significantly more than the MCI group in MoCA, SDMT, STT, and AVLT In addition, an intervention effect was found in improving perceived stress	VR-based intervention protocol was effective in improving the general cognitive function (memory, executive function, and attention) of patients with MCI and MD Adjusting task difficulty according to the baseline cognitive level of patients with MD positively improved cognitive function
Man et al. (2012) [59]	RCT	Non-Immersive CTR	Virtual apartment, Virtual supermarket	2/3 d × 4 w × 30 min	FOME-TE, FOME-TR, FOME-DR, MMQ-contentment, MMQ-ability, MMQ-strategy, HK Lawton IADL	episodic memory, total recall, delayed recall, memory, satisfaction with performance, iADL	The VR group showed significant improvements in total encoding, total recall and delayed recall (FOME), and MMQ strategy The active control group improved total recall, delayed recall (FOME), and MMQ satisfaction	Virtual training significantly improved memory performance (immediate and delayed episodic memory recall) regardless of educational level VR environments with audiovisual stimuli can improve information encoding

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Panerai et al. (2021) [64]	CT	Non-Immersive CTR	1) Follow instructions 2) Medication intake 3) Fill a suitcase 4) Virtual supermarket	5d × 6w × 3 h (5-people group)	MMSE, CPM, CBT, DS, RAVL (immediate, delayed), FAB, IADL	General cognition, ecological memory, visual-auditory memory, selective attention,verbal memory, iADL	The experimental group (EG) showed improvements in correct responses, missing responses, number of cues and execution times compared to the active control group (ACG) There was no improvement in the iADL scale in both groups A spontaneous transfer of re-learned functional skills to iADL in EG is suggested	VR showed ecological validity, improving functional skills in patients with early-stage dementia Daily living skills need specific training to be relearned Skill generalization is related to cognitive functioning and hippocampal integrity
Masoumzadeh et al. (2020) [57]	Pilot pretest–post-test	Immersive CTR	Driving simulator (VRDS)	5d × 4w × 30 min	MWT, SSQ, MADRS	spatial cognition, independence, mood, depression	Significant advances in spatial cognition (Morris test) and learning in older adults with varying degrees of dementia Improvements in mood and cognitive functions More training time is suggested for patients with MCI and AD	VRDS training had positive effects on older adults' spatial cognition, even on those with different degrees of dementia There were also improvements in mood and cognitive functions

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Fasilis et al. (2018) [55]	Pilot pretest–post-test	Non-Immersive CRE	Virtual supermarket, Virtual cooking tasks, home arrangement and cleaning	3d × 5w × 40 min	DS, BSRT, TMT-A, Hanoi Tower, FAB, WCST	Working memory, attention, problem-solving, rigid thinking, executive function	Significant improvements in working memory, memory retention, executive functions, and rigid thinking Statistically significant increase in FAB battery (executive functions) between pre-and post-training Knowledge transfer to daily activities observed	Relative improvement in the total cognitive variables considered Possible ceiling effect in healthy participants. Therapeutic benefits and transferability to real-life situations in 3D virtual environments Need for further research to assess the "therapeutic effect"
Hofmann et al. (2003) [69]	CT	Non-Immersive CTR	Virtual Supermarket	3d × 4w	CDR, MMSE, TMT-A, MADRS	Navigation, decision making, memory, basic motor skills	Improvement trend in all three groups, but only the reduction in errors in patients with AD was significant Improvements in all groups up to 3 weeks later Patients with depression presented higher latency than healthy patients, and no correlation was found between MADRS and performance	The intervention showed promising results, especially in reducing errors in patients with AD However, further research is needed to address methodological limitations and assess the ecological validity of computer-based ADL applications in different patient groups

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Kang et al. (2021) [61]	RCT	Immersive CTR	Find differences, select objects to perform tasks, Virtual supermarket, find a path, place furniture in a space, catch animals in a certain order	2d × 4w × 20/30 min	ROCF, MMSE, DS, TMT-A, K-BNT, SVLT, COWAT, SCWT, TMT-B, GDS, AES, PANAS-P, PANAS-N, QoL-AD	Visuospatial processing, naming ability, verbal memory, phonetic fluency, frontal executive function and psychiatric symptoms	The intervention showed significant improvements in the EG in the total score and basic components of the RCFT Non-significant improvements were found in naming skills, delayed verbal memory recall, and phonetic fluency Improvements in psychiatric symptoms such as apathy, affect, and quality of life in the EG	The intervention positively affected various cognitive functions and psychiatric conditions, as well as increased frontal-occipital functional connectivity in older people in the predementia state Future research with larger samples and control groups is needed to validate these results
Yamaguchi et al. (2012) [51]	Pilot pretest–post-test	Non-Immersive Re-learning	Virtual cooking tasks	2d × 1w × 90 min	Written ILM, Self-recorded ILM	Ability to learn and perform ADL in virtual environments	Patients with AD take longer in daily functional activities. Error-free learning methods in virtual environments could benefit patients with AD Participants reported difficulties with mouse use and needed more time to become familiar with virtual tasks	Training in virtual environments may increase functional autonomy in patients with AD However, further studies are required to confirm these results, considering the limitations, such as the low number of participants, differences in AD stages, and few training sessions

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Park (2022) [62]	RCT	Non-Immersive CTR	Virtual supermarket	2d × 8w × 60 min	EFPT-K, K-IADL	Visual memory, attention, navigation, executive function, iADL	The study found that virtual shopping training significantly improved executive functions and iADLs in patients with MCI compared to the control group, supporting the ecological validity of this approach	Virtual shopping training is clinically effective in improving executive function and iADLs in patients with MCI Shopping in virtual environments can be an effective form of training, as it requires complex cognitive skills and helps patients cope with distractions
Maeng et al. (2021) [66]	CT	Immersive CTR	Virtual supermarket	2d × 4w × 50/60 min	CERAD-K, KQOL-AD, GDS, SSQ, Presence Q, Presence S	Memory, attention, executive function	Improvements in cognition in patients with MCI and healthy older adults Both groups improved in learning new information, visuospatial construction, and frontal lobe function The MCI group specifically improved in word recall and recognition and TMT-A performance, while the healthy older adult group improved on the Korean-Boston naming test	VRCT improves cognition in patients with MCI and healthy older adults Despite limitations, such as a small sample size and lack of follow-up, the study suggests that VRCT programs may be applicable and effective in populations with reduced cognitive ability

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Kim et al. (2021) [67]	CT	Immersive CTR	Virtual supermarket	2d × 4w × 50/60 min	CERAD neuropsychological battery, CRI (total, education, working activity, leisure time)	Memory, attention, executive function, verbal memory, visuo-spatial processing, learning capacity	Greater improvement in the total CERAD score was found for cognitively normal participants with higher versus lower scores on the Education subdomain of the CRIq Healthy older adults and patients with MCI improved on CERAD tests after using a cognitive training application Education was associated with better CERAD scores, whereas leisure time showed a negative correlation	The results suggest that cognitive training benefits healthy older adults and patients with MCI Education is an important factor in cognitive rehabilitation, while leisure time and age also influence outcomes Sex showed no relationship with the results
Park et al. (2019) [63]	Pilot pretest–post-test	Immersive CTR	Virtual apartment	3d × 6w × 30 min	CERAD-K, TMT-A, TMT-B, CDR, MMSE, BDI, MBI	Attention, visual-auditory memory, verbal memory, executive function	Significant improvement in the experimental group in the constructive recall test, which measures visuospatial working memory and recalls in visuospatial tasks There were no significant interactions in the other tests	Mixed Reality-based cognitive training may benefit visuospatial working memory in patients with MCI Further research with larger samples, longer sessions, and longer follow-ups is required

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Gamito et al. (2019) [65]	CT	Non-Immersive CST	Virtual cooking tasks, remembering TV news, choosing clothes and shoes arrangement	2d × 6w × 30 min	MoCA, FAB, WCST, RCFT, d2, ECQ, BDI- II	visual-auditory memory, attention, cognitive flexibility, executive function, working memory	Statistically significant improvements in attention (d2), in visual memory (RCFT) and in two indicators of cognitive flexibility (WCST) The magnitude of improvements is highest for individuals with lower levels of cognitive functioning at baseline No effects of age or education were found	Attention improved more in people with greater impairment, making the system more efficient for training patients with signs of cognitive decline The specific functions in which significant differences were observed (attention, memory, and cognitive flexibility) are required in daily activities
Gamito et al. (2020) [56]	CT	Non-Immersive CST	Personal hygiene, virtual cooking tasks, virtual supermarket, tasks related to TV news, clothes, shoes, art gallery visit)	EG: 2d × 6w × 30 min y ACG: 1d × 6w × 60 min	MoCA, FAB, RCFT, d2, WMS-R, GDS, SWLS, IADL	General cognition, attention, concentration, executive function, working memory, iADL	Significant improvements in EG in global cognition (14%), EF (13%), memory (WMS-R), attention (d2), and visual memory (RCF) There were no improvements in functionality or subjective well-being Results in well-being and functionality were not significant in any of the groups	The virtual SLB environment is more effective than traditional methods in improving general cognition, attention, memory, and EF in older adults No improvements in well-being or functionality were observed Further studies are needed to assess the effects on well-being and functioning in cognitively impaired adults

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Optale et al. (2010) [70]	RCT	Immersive CTR	Auditory and VR experience sessions in everyday environments	TR: 3d × 12w × 30 min; reinforcement: 2d × 12w × 30 min	MMSE, MS, DS, VSR, PVF, DTP, CET, CDT; ADL-F, ADL-M, GDS, IADL	General cognition, verbal memory, executive function, visual-auditory memory, visuospatial processing, depression, iADL	Improvements in the EG in general cognitive skills, verbal memory, and executive functions with VRMT; the CG had decreases in the same areas The booster sessions consolidated the effects of the training (MMSE, short-term and long-term memory, and DTP) with small effects No differences were found in visuospatial processing, iADL, or GDS	VRMT showed positive effects on long-term memory and stimulated cognitive abilities Improvements in executive functions soon faded, and there were no improvements in visuospatial skills
Tarnanas et al. (2014) [54]	RCT	Non-Immersive CST	Virtual Museum	2d × 20w × 90 min	RAVLT, ROCF, DS, SCWT, TMT-A, TMT-B, BNT, MMSE, GDS, Category fluency, Letter fluency	Memory, attention, executive function, navigation, visuospatial processing	After five months of intervention, there were significant improvements in the RAVLT, King Test, Trail-making B, and MMSE tests in the experimental group (EG) There was also an improvement in the GDS scale, although not statistically significant, and an overall improvement in the participants' scores	The training proved effective in improving visual arrays' textual and spatial processing. This approach also showed improvements in untrained tasks and the perceived cognitive performance of older adults with aMCI in everyday life However, it is suggested that physical exercise interventions may be more effective in addressing executive function impairment in this population

Table 3 (continued)

Authors and year of publication	Study type	Intervention and VR type	Task/place simulated	Duration (Days × weeks × minutes)	Outcome measurements	Specific cognitive abilities	Main findings	Conclusions
Oliveira et al. (2021) [60]	RCT	Non-Immersive CST	Personal hygiene, virtual cooking tasks, virtual supermarket, tasks related to TV news, clothes, shoes, art gallery visit	2d × 5w × 45 min	FAB, MMSE, IADL, TMT-A, TMT-B, CDT, GDS, CDR	Executive function, general cognition, depression, iADL	Increase in mean FAB score and a significant and large effect on global cognition between pre- and post-treatment assessments However, no improvements in executive functions iADL were found	Mixed effects on cognitive function when using VR as an intervention Despite the lack of improvements in specific cognitive functions, an improvement in global cognitive functioning was observed Cognitive reserve (CR) theory could explain individual differences in the ability to maintain cognitive function in the presence of brain pathology

ADL-F: Activities of Daily Living–Functions; ADL-M: Activities of Daily Living–Mobility; ADRQL-F: Alzheimer's Disease-Related Quality of Life—French version; AES: Apathy Evaluation Scale; aMCI: amnestic Mild Cognitive Impairment; AVLT: Auditory Verbal Learning Test; BDI: Beck Depression Inventory; BNT (K-): Boston Naming Test (Korean version); CBT: Corsi Block-tapping Task; CDR: Clinical Dementia Rating; CDT: Clock Drawing Test; CERAD (-K): Consortium to Establish a Registry for Alzheimer's Disease (Korean version); CET: Cognitive Estimation Test; CPM: Colored Progressive Matrices; CRIq: Cognitive Reserve Index questionnaire; DNR = Does not report; DS: Digit Span Test; DTP: Dual Task Performance; d2: d2 Test of Attention; ECQ: Everyday Competence Questionnaire; EFPT(-K): Executive Function Performance Test (Korean version); FAB: Frontal Assessment Battery; FOME (-TE, -TR, -DR): Fuld Object Memory Evaluation (-total encoding, -total retrieval, -delayed recall); GDS: Geriatric Depression Scale; IADL-9; Instrumental Activities of Daily Living Scale – 9 items; ILM: Instruction Learning Methods; Lawton IADL (HK, K-): Lawton Instrumental Activities of Daily Living scale (Hong Kong Chinese version, Korean version); MADRS: Montgomery-Asberg Depression Rating Scale; MBI: Modified Barthel Index; MMQ: Multifactorial Memory Questionnaire; MMSE: Mini-Mental State Examination; MoCA (-CS): Montreal Cognitive Assessment Scale (Chinese-Changsha version); MS: Mental Status in Neurology; MWT: VR Morris water test; NAI: Nuremberg Aging Inventory; PANAS-N: Positive and Negative Affect Schedule-negative affect; PANAS-P: Positive and Negative Affect Schedule-positive affect; Presence Q: Measuring presence of VR contents; Presence S: Measuring presence of VR content users; PSS: Perceived Stress Scale; P300: Peak of the Event-related-potencial occurring at a latency of 300 ms.; QoL-AD (K): Quality of Life-Alzheimer's Disease (Korean version); RAVLT: Rey Auditory Verbal Learning Test; RBMT: Rivermead Behavioral Memory Test; RCFT: Rey Complex Figure Test; RE = Cognitive rehabilitation; ROCF: Rey–Osterrieth complex figure test; RSES: Rosenberg Self-Esteem Scale; SBL: Systemic Lisbon Battery; SCT: Stroop Color Test; SCWT: Stroop Color and Word Test; SDMT: Symbol Digit Modalities Test; SSQ: Simulator Sickness Questionnaire; ST = Cognitive stimulation; STT: Shape Trail Test; SVLT: Seoul Verbal Learning Test; SWLS: Satisfaction with Life Scale; TMT-A: Trail Making Test Part A; TMT-B: Trail Making Test Part B; TR = Cognitive training; VD = Virtual department; VS = Virtual supermarket; VSR: Verbal Story Recall Test; WCST: Wisconsin Card Sorting Test; WMS-R: Wechsler Memory Scale-Revised

Table 4 Description of the subtasks for each study

Author	Task	Subtasks
Foloppe et al. (2018) [53]	Virtual and real cooking tasks	10 different tasks. Namely, setting the table for two people, making a cup of coffee with a coffee machine, making a cup of coffee with an espresso machine, making a cup of sweet tea with a kettle, making breakfast, making a salad with three ingredients, heating soup in a microwave, preparing frozen vegetables with an electric or induction stove, making a sandwich, and cooking a chocolate cake with an electric oven
Schreiber et al. (1999) [58]	Virtual apartment	The virtual apartment consisted of five rooms, one of which was a corridor connected to all the other rooms. In stimulus set I, a room was chosen and subjects were asked to find certain targets. In stimulus set II, subjects were asked to find certain rooms in the apartment
Zhu et al. (2022) [68]	Virtual Supermarket	A list of 3 to 12 familiar virtual images and labels of common items (such as oranges or toothpaste) were showed to participants. After that, they were asked to memorize them in one and a half minutes. After memorizing the list, the participants played a number sorting game for 20 s before going to the supermarket to buy the items on the memorized list. Participants were then asked to locate the counter and pay in RMB bills
Man et al. (2012) [59]	Virtual apartment, convenient shop	Virtual apartment. The 3-min task involved moving around the apartment, reading and memorizing the items on a list placed on a table. They then took those items out of the refrigerator, after a period of distraction Virtual convenient shop. Participants were asked to search at the store and purchase the requested items. After that, they had to pay their bills to the cashier
Panerai et al. (2021) [64]	1) Follow instructions 2) Medication intake 3) Fill a suitcase 4) Virtual supermarket	1) Following instructions. Participants were asked to answer 30 questions of general knowledge, personal, family, spatial and temporal orientation, which appeared on the screen in verbal and written form 2) Medication. Five boxes of medicines placed on a kitchen table, verbal instructions and a visual reminder were presented. The subject had to indicate the correct time and the respective medication 3) Fill a suitcase. The subject was required to pack a suitcase for a weekend. The subject dragged the clothes from a shelf to the suitcase 4) Supermarket: A shopping list was displayed on the screen and items were dragged from the shelf to the cart. To do the payment, the participant had to drag the bills from the wallet
Masoumzadeh et al. (2020) [57]	Driving simulator (VRDS)	The user is asked to follow a path. The simulator recorded whenever the participant stopped with a red light, a stop sign and whenever they turned to the correct directions at intersections
Fasilis et al. (2018) [55]	Virtual supermarket, Virtual cooking tasks, home arrangement and cleaning	The first task was based on the activity of buying in a supermarket. The second task dealt with the preparation of breakfast, and the third task required the patient to fix and clean his/her house. (No more information was offered)
Hofmann et al. (2003) [69]	Virtual Supermarket	Participants were asked to learn a shopping list of three items. The correct item had to be freely recalled and/or chosen from a multiple-choice list. Also, 10 multiple-choice questions related to the environment had to be answered

Table 4 (continued)

Author	Task	Subtasks
Kang et al. (2021) [61]	Find differences, select objects to perform tasks, Virtual supermarket, find a path, place furniture in a space, catch animals in a certain order	(i) Find differences), (ii) select items needed to perform certain tasks, (iii) prepare an exact amount of money to pay, (iv) find a way using a memorized map, (v) place furniture in space exactly based on a memorized drawing, (vi) remember words, (vii) remember flags and symbols, and (viii) catch animals in a certain order
Yamaguchi et al. (2012) [51]	Virtual cooking tasks	Breakfast task. To place two toasts in an electric toaster, press a lever, place the toasts on two different plates, put butter and jam on each bread Coffee task. To open the coffee pot, put the filter and put coffee, fill the pot with water, put the coffee pot on the heater and turn on. Serve the coffee in a cup, add sugar and milk
Park (2022) [62]	Virtual supermarket	A list of purchases was showed on the screen and the user selects them by touching the screen. Then the participant had go to the cashier and pay by choosing the precise amount of money
Maeng et al. (2021) [66]	Virtual supermarket	A list of items was given for 10 s at the entrance of the supermarket and then participants visited seven sections. Participants could use a hint button to display the list for 10 more seconds
Kim et al. (2021) [67]	Virtual supermarket	A list of items was given for 10 s at the entrance of the supermarket and then participants visited seven sections. Participants could use a hint button to display the list for 10 more seconds
Park et al. (2019) [63]	Virtual apartment	Living room: to turn on a child's favorite cartoon TV channel, to make a phone call, and to play a game of cards Kid's room: to make a kid clean his room, to choose books to read to a child, to match picture blocks, to pack a child's school bag, to see shopping items, to color, to hang clothes and to play a matching game of colors Cooking: make sandwiches and prepare a bowl of cereals Toilet: to brush a child's teeth and to teach him to use the toilet
Gamito et al. (2019) [65]	Virtual cooking tasks, remembering TV news, choosing clothes and shoes arrangement	Morning hygiene: to brush teeth Shoes arrangement: to put the shoes in order Wardrobe: to combine clothes to get dressed Virtual kitchen: to choose the ingredients from a list that is displayed on the screen Newscast: to turn on the TV and change the channels until finding the news channel. Remember the news Supermarket: to look at a shopping list, choose the items and pay. Pharmacy: to look at a shopping list, choose the items and pay Art Gallery: to browse the art gallery viewing the paintings Outdoors: to walk through the city and cross the streets carefully

Table 4 (continued)

Author	Task	Subtasks
Gamito et al. (2020) [56]	Personal hygiene, virtual cooking tasks, virtual supermarket, tasks related to TV news, clothes, shoes, art gallery visit)	Morning hygiene: to brush teeth Shoes arrangement: to put the shoes in order Wardrobe: to combine clothes to get dressed Virtual kitchen: to choose the ingredients from a list that is displayed on the screen Newscast: to turn on the TV and change the channels until finding the news channel. Remember the news Supermarket: to look at a shopping list, choose the items and pay. Pharmacy: to look at a shopping list, choose the items and pay Art Gallery: to browse the art gallery viewing the paintings Outdoors: to walk through the city and cross the streets carefully
Optale et al. (2010) [70]	Auditory and VR experience sessions in everyday environments	Listening sessions in familiar settings, such as the family home from childhood or a park. The participant had to remember different paths that were shown. Afterwards, the participant had to walk through them without losing orientation. These paths were individualized with color or shape indicators
Tarnanas et al. (2014) [54]	Virtual Museum	Listen and Plan. Participants followed instructions to locate and find items in the museum Storytelling. Participants listened to story segments of museum items and answer a series of questions Exercise games. Participants developed a "scene" based on archaeological artifacts or their multimedia description
Oliveira et al. (2021) [60]	Personal hygiene, virtual cooking tasks, virtual supermarket, tasks related to TV news, clothes, shoes, art gallery visit	Morning hygiene: to brush teeth Shoes arrangement: to put the shoes in order Wardrobe: to combine clothes to get dressed Virtual kitchen: to choose the ingredients from a list that is displayed on the screen Newscast: to turn on the TV and change the channels until finding the news channel. Remember the news Supermarket: to look at a shopping list, choose the items and pay. Pharmacy: to look at a shopping list, choose the items and pay Art Gallery: to browse the art gallery viewing the paintings Outdoors: to walk through the city and cross the streets carefully

constructive recall [63], verbal learning [57, 70] and phonetic fluency [61]. With regard to the transfer of knowledge to real life and even to other ADLs, several scales have been used, such as the Lawton scale [74], which was the most commonly used in the reviewed studies. It is worth mentioning that this scale uses a questionnaire rather than performance observation, which could lead to overestimation or underestimation of a skill. However, the cognitive domains developed in the different interventions are necessary for the functional development of ADLs. For example, the cognitive, visual-perceptual processing, and attention that were developed in simulated household tasks in the work of Fasilis et al. [55], or the improvements in cognitive flexibility, attention, and memory achieved by participants in the work of Gamito et al. [63]. A recent meta-analysis concluded that cognitive training achieves little transfer to functions that have not been trained [75].

Regarding performance on the different memory tasks included in the review, most research emphasizes that cognitively healthy individuals perform better [27, 76], followed by those with mild cognitive impairment [30, 77, 78], due to the typical learning difficulties associated with the disease [64]. For example, in virtual supermarket tasks, it was shown that patients with AD have worse performance and longer execution times [69], which are frequent in patients with neurological problems when executing ADLs [79]. In line with the meta-analysis of Kim et al. [80], the positive effects of VR are more noticeable in people with cognitive impairments. It has also been mentioned that VR could promote the activation of the intuitive system and the transfer of knowledge to another context but in the early stages of Alzheimer's disease [64]. This was also confirmed by Hofmann et al. [69], where AD patients reduced errors as the training program progressed. It is important to note that the effectiveness ceiling may be a factor to consider in analyzing the results, especially in improving specific cognitive tasks already at high levels in the target population. Further studies are needed to assess whether there are significant differences in cognitive improvement between healthy individuals and those diagnosed with a cognitive disorder.

Level of immersion in VR

The level of immersion in VR interventions for memory training remains a topic of debate. In our review, almost half of the interventions were immersive, and almost all were developed within the last four years. This contrasts with the review conducted by Kim et al. in 2019, which included only one immersive study [80]. The authors concluded that semi-immersive technology was more effective than fully immersive technology based on the effect sizes of the different studies. However, the low presence of interventions with immersive systems makes it difficult to generalize these findings to the present day, where the technology is further developed. Regarding performance in memory tasks, studies such as that of Krokos et al. [81] and Huttner et al. [82] reported better results using immersive environments compared to non-immersive ones. However, both Maidenbaum et al. [83] and Varela-Aldás et al. [9] found no significant differences in spatial memory performance between using a standard computer screen and a VR device (HMD). These results indicate that, to date, findings are inconclusive; therefore, there is a need for future research in this constantly evolving field.

VR immersion provides a distraction-free environment for participants to focus on completing the activity [70]. Additionally, a purely immersive environment provides a playful aspect that can motivate patients to participate in training [84]. When designing VR interventions, the relationship between presence and immersion in virtual environments should be considered. Immersion, understood as the feeling of "being inside" the virtual environment, measures how much a user feels involved in the environment. On the other hand, presence refers to the perception of "being there" in the virtual environment. Several studies have shown that immersion is closely related to presence, i.e., the more immersive the experience is, the more presence the user experiences [85, 86]. It has been suggested that high levels of presence, related to the level of immersion, explain the effectiveness of training in virtual environments [46]. VR has a high potential to help people overcome mental health problems if high levels of presence are achieved in situations that capture their attention, as described in [87].

Patients with impaired cognitive functions may have a different sense of presence in virtual experiences than healthy people. Low immersion in a VR application was identified as one of the reasons for not obtaining significant improvements in AD patients in one of the studies included in this review [60]. However, the effect of immersion on training outcomes may be weak, as no differences in presence were observed between healthy and MCI groups in the virtual supermarket training conducted by Maeng et al. [66]. This agrees with what Witmer and Singer expressed [88]; a weak but consistent positive relationship exists between presence and task performance in VEs. Considering Howard's model [89], in VR, presence can increase users' autonomous motivation by making tasks more meaningful and satisfying, which, in turn, can increase their engagement with the activity. Despite this, more studies are still needed to demonstrate this and present commensurate results.

Visual or auditory help messages have been identified to increase immersion in VR applications and improve iADLs [66, 68]. Auditory cues were provided in a virtual apartment training study [51], while visual cues such as arrows and landmarks were found to assist AD and MCI patients during navigation exercises in a virtual environment [90]. Written and/or verbal instructions have also been shown to be successful in patients with disorganization problems [91], and feedback through verbal reinforcement increases confidence during exercises [64] and motivates the participant [53]. In the study of Park et al. [63], several ADLs were simulated with mixed reality, to which sensory feedback and proprioception were added.

Immersive VR systems include head-mounted displays (HMDs) and hand controls that may cause discomfort to some participants. Non-immersive systems are less likely to cause discomfort in older adults [92], but some studies have reported difficulties using a computer mouse to perform cooking tasks in non-immersive VR interventions [51]. This is related to cybersickness, a potential problem with highly immersive VR interventions, as reported by Zhu et al. [68]. A usability test (SSQ) administered at the beginning of the experiment could help identify participants with increased sensitivity and exclude them from the study [68]. Gradual increases in the duration and difficulty of VR training sessions have been recommended to reduce the incidence of cybersickness [93, 94]. According to the study of Kourtesis et al. [95], the maximum duration for an immersive VR session should range between 55 and 70 min, to avoid experiencing VR-induced symptoms and effects. The session duration of the studies included in our review did not exceed 60 min. No study reported adverse effects except the study of Zhu et al. [68]. In the study, although the duration of each session was 30 min, eight participants had mild cybersickness symptoms in the first 4 activities (measured via the Simulator Sickness Questionnaire [96]), but after the fifth intervention, there were no reports of simulator disease.

Nevertheless, strategies can be applied to mitigate these effects. For example, HMD manufacturers suggest taking short breaks to alleviate the effects of VR, although evidence supporting this recommendation is limited. The study of Szpak et al. [97] does not support the idea that short pauses are effective in mitigating after-effects, as participants reported that these pauses negatively affected their perceived performance in VR compared to longer continuous exposures. More research is needed to determine optimal break durations and improve training programs. Cargenie et al. [98] suggested modifying visual motion cues in VR environments. For example, by tilting visual content on the VR screen, users have to tilt their head and maintain proper viewing while interacting with the app. Haptic feedback, such as vibrations or haptic resistance, could be a consideration to improve interaction and minimize these effects and even redesign HMDs depending on user needs[99].

Limitations

Based on the studies reviewed, VR interventions have the potential to improve cognitive function in people with mild cognitive impairment and dementia. However, there are several limitations to consider when interpreting the results. One limitation is the variability in the number of sessions, duration, and weekly frequency, making comparing results between studies difficult. In addition, the different instruments used to assess the cognitive domains in the studies also make it difficult to analyze and generalize the results.

Although the interventions have positive effects, they have not been reflected in significant changes in one of the most commonly used scales to assess iADLs, such as the Lawton scale [74]. However, this may be due to the low sensitivity of the test and the ceiling effect reported in other studies [64, 74, 100]. Additionally, long-term follow-up studies to assess the lasting effects of these interventions are lacking. The few studies that have conducted follow-up evaluations, such as the study of Foloppe et al. [53], reported sustained effects up to 6 months after the intervention.

The studies reviewed included individuals with different diagnoses (MCI, MD, AD), which may affect the effectiveness of the interventions. Therefore, caution should be exercised when generalizing results to other populations. Despite these limitations, the evidence suggests that VR interventions may be a promising tool for cognitive training in people with mild cognitive impairments. Future studies with larger sample sizes, standardized cognitive assessments, and longer follow-up periods are needed to further evaluate the effectiveness of these interventions.

Another limitation to be considered in VR interventions for cognitive training is the need for more analysis of the type of motivation that interventions simulating iADLs generate in the participant. Howard's Self-Determination Theory (SDT) [89] proposes that motivation to engage in a task can be autonomous or controlled. Autonomous motivation occurs when an individual feels that he or she has choices and personal relevance to the task, whereas controlled motivation is based on external pressure or rewards. Studies have shown that interventions that align with autonomous motivation are more effective and have longer-lasting effects than those that rely on controlled motivation. Therefore, it is essential to design VR interventions that provide a sense of autonomy, choice, and personal relevance, such as those that allow users to select and customize tasks or goals.

Implications for practice

The implications for the practice of VR interventions in cognitive rehabilitation are multifaceted. Motivating participants to engage in tasks is critical for success, as previous studies have shown a high likelihood of dropout [66], possibly due to discomfort or a lack of openness to treatment [101]. It is also important to personalize and tailor interventions to each participant to increase satisfaction, quality of life, and affect [61] while reducing stress, depression, and apathy [61, 68]. The involvement of caregivers is also crucial, as they can promote active participation during and after these types of interventions [53]. As previously mentioned, information on the efficacy of VR interventions is provided in Howard's Self-Determination Theory (SDT) [89], as studies have shown that interventions that align with autonomous motivation, such as those that provide a sense of autonomy, choice, and personal relevance, are more effective and have longer-lasting effects than those that rely on controlled motivation [53]. Therefore, it is essential to promote and motivate participation, possibly through lectures and demonstration meetings, to reduce the number of dropouts and increase engagement [68].

Another noteworthy aspect is that occupational therapists, psychologists, and clinical neuropsychologists performed most of the interventions in the studies included in this review, ensuring that participants receive appropriate cues and corrections tailored to their clinical condition and based on technical criteria. Although many VR-based applications do not require the intervention of a therapist or family member, studies have shown that satisfaction with cognitive function performance is higher with therapist guidance and accompaniment [59, 102].

Postintervention evidence has demonstrated a likely direct transfer of knowledge to real-life settings, underscoring the potential benefits of VR-based interventions for improving activities of daily living [58]. However, it is important to note that transfer to other daily activities may not always be clear-cut [53]. The Lawton scale, which was used in several reviewed studies, has shown low sensitivity for assessing changes in ADLs. Therefore, the use of other tests, such as the Bayer ADL scale (B-ADL) or the Interview for the Assessment of the Quality of Life in Dementia (QoL-AD), may be more appropriate for this purpose [103]. These scales show greater discrimination than the MMSE in diagnosing dementia in a population with low cultural status and are not influenced by age, education, sex, or country of origin [103]. In addition, the Pfeffer Functional Activities Questionnaire, which assesses each activity on a scale of 0 to 3, may allow greater sensitivity in assessing ADL changes.

Implications for research

As a common note to many of the reviews found in the literature, we insist on the need for studies of higher methodological quality (RCTs), together with an increase in sample size. There are studies [55, 104] that recommend the use of a passive control group (PCG), since its absence does not allow evaluation of the true therapeutic effect of the variable throughout the period of training or clearly establish its feasibility, acceptability, and tolerability [68]. On the other hand, other studies, such as that of Kang et al. [61], also recommend including an active control group (ACG) to help confirm the clinical efficacy of the intervention. We must also note the need for homogeneous outcome measures in the different studies to perform meta-analyses that give us a better quantitative measure of effect sizes. All this will undoubtedly provide us with more scientific evidence on the role of iADL-VR in cognition.

The neuropsychological tests used to evaluate the participants in the studies have been very heterogeneous, and not all of them have focused on the measurement of EFs, which seem to play a crucial role in the correct performance of iADLs. For this reason, studies should use tests that measure cognitive improvements in EF. However, as Marino noted, it is difficult to perform an adequate neuropsychological evaluation of EFs due to the many functions and capacities involved [105]. That is why we recommend establishing adequate follow-up periods to determine if there is real transfer of knowledge of the skills learned within the experimental set-up. On the other hand, although the studies include a wide variety of measures related to cognition, such as functional memory, memory retention, attention, problem solving, executive functions and cognitive flexibility, spatial cognition, verbal memory, working memory, etc., they have not included measures for the evaluation of personality, socioemotional functioning or adaptive behavior, just as the practice guidelines of the American Academy of Clinical Neuropsychology recommend [106]. According to these guidelines, assessments should also include measures to assess personality, social-emotional functioning, adaptive behavior, etc. Only Kang's study [61] measured (as secondary outcomes) psychiatric symptoms such as affect, apathy, quality of life (QoL) and depression. Masoumzadeh and Moussavi [57] also included measures of depression, showing a decreasing trend of the participants' depression scores from baseline to post-intervention. Zhu's evaluation [68] also found significant improvements in perceived stress and depression in both groups at the end of the intervention. Different studies have previously demonstrated the effectiveness of this type of cognitive rehabilitation for improving mental health [107, 108] and for relieving anxiety and depression [109].

Something that the practice guidelines [106] suggest and that has not been done in the included studies, is the conduct of interviews with family members, especially in MCI or MD participants, to achieve a comprehensive neuropsychological evaluation. These interviews would also be of great importance when verifying the transfer of learned knowledge to real life, since many studies have reported that the effects of the intervention do not translate into greater patient autonomy (based on measures such as the Lawton IADL scale, for example).

Another very interesting line is the development of interventions using VR applications (immersive or not) specifically focused on a certain cognitive disorder and thus verifying their effectiveness [63]. The development of iADL-VR applications is also proposed for the rehabilitation of other sudden cognitive disorders, such as the presence of a stroke or traumatic brain injury [110]. It has been verified in this systematic review that sometimes the applications designed are complicated for the groups with greater cognitive deterioration, for which we suggest that the pathology of the patients be taken into account, and tailor-made applications be carried out, considering both personal and clinical characteristics [64] to maximize the cost–benefit. For example, Maeng et al. [66] recommended that easy-to-operate devices and interfaces be developed to improve the usability level of applications. This ensures that the intervention focuses on cognitive stimulation, not sensorimotor or psychosensometric coordination. Otsuka et al. [111] showed that the adequate adjustment of the difficulty of the tasks and the motivational incentives reduces the frustration of patients with MD, contributing to the benefits of rehabilitation. Based on the -decomposition hypothesis-, all daily tasks are complex, but if they are broken down, they can be executed more easily [112]. Varela-Aldás et al. [113] proposed some improvement ideas, especially for purely immersive systems, such as hand tracking incorporated in the most recent models of HMDs, to improve the usability and concentration of participants.

Regarding the participants' level of education and performance in the different memory tasks implemented, there is no clear evidence of a discernible relationship between them, in the different studies included in the review, so it seems reasonable to conduct studies fully focused on the effects that education can have on performance on memory tasks. For example, in one of the works included in this review [65], no association was found between performance and education, perhaps because the population was healthy. Other studies that have implemented memory tasks in healthy people [9, 114] did not find differences in performance based on the level of formal education either. Participants with more years of education are expected to have greater processing and conceptualization capacity since the volume of gray and white matter in the brain is greater [115]. In one of the studies included in this review [67], significant differences were found with respect to education, taking into account the results of the Cognitive Reserve Index (CRQ) questionnaire. Those adults with a higher CRI-Education score improved more than those with lower CRI-Education (between pre- and post- intervention). However, Man et al. [59] found evidence that those with less education and MD could benefit more from ADL training. This last idea is related to the study conducted by Mondini et al. [116], where the authors concluded that those with low cognitive reserve can benefit more from rehabilitation. Other factors that may influence the neuropsychological evaluation process should also be taken into account. They include socioeconomic, cultural, linguistic or disability issues, among others [106]. For example, Tarnanas et al. [54] indicated in their study that interindividual genetic variability modulates the transfer of training to untrained tasks. Therefore, individual differences in cognitive training outcomes should be addressed in future works.

Although many studies affirmed that the use of VR contextualized in IADLs contributes to improving the motivation of the participants and to retaining patients during the interventions, in none of them has an evaluation of motivation and effort been carried out. Failing that, the introduction of common sense methods to optimize the participant's performance is interesting. In this sense, only one study [70] included activities (for both groups), such as reading/discussing newspapers and magazines, watching TV documentaries, and creative and painting workshops. The inclusion of such activities can minimize anxiety, physical discomfort, and other factors that may interfere with optimal motivation and effort [106].

It would also be convenient to incorporate the use of fMRI in these investigations to explore the neuronal plastic changes that can positively affect a person's cognition. The positive findings found by Optale et al. [70] support the theories of plasticity in the neuronal system in patients with impaired cognitive functions. Similarly, there is evidence of these processes in cognitively healthy elderly individuals [117] and those with AD [118]. Furthermore, multidomain training may be more effective in improving neuroplasticity mechanisms [119].

Finally, an aspect that can be analyzed and has not been considered so far deals with people's social activity as an extension of an iADL (social participation) since these activities are also performed daily [9]. The study conducted by Tomioka et al. [120] found a strong association between participation in social groups and the execution of iADLs independently by the participants. Perhaps the design of VR tasks based on this type of activity would give us a new dimension on the path towards improving independence in performing these tasks [78].

Conclusions

In recent years, VR has gained popularity as a complementary intervention for treating cognitive impairment. Specifically, VR applications based on instrumental activities of daily living (iADL-VR) have emerged as a promising approach to train, rehabilitate, or stimulate cognitive functions in people with cognitive impairment, Alzheimer's disease, or healthy adults. This systematic review aimed to synthesize the effects of iADL-VR interventions on cognitive function in older adults and people with cognitive impairment. The results of this review indicate that iADL-VR interventions have the potential to improve cognitive function, with almost all studies showing improvements in some or all of the outcomes after the intervention, generally being greater in the iADL-VR group than in the control group.

Furthermore, the ecological component of these tasks makes them suitable for transferring what has been learned to the real world, emphasizing the potential benefits of these interventions for improving activities of daily living. However, further research with larger and more homogeneous samples and longer follow-up periods is needed to confirm the transferability of these interventions to the real world. The limitations of the current studies must be addressed in future research, including variability in the number of sessions, duration, and frequency of intervention, as well as the use of different instruments for assessing cognitive domains. Future studies should also consider the potential role of factors such as motivation and autonomy support in enhancing the effectiveness of these interventions.

This systematic review highlights the potential of iADL-VR interventions as a promising approach to cognitive rehabilitation, training, and stimulation in older adults and people with cognitive impairment. However, further research is needed to better understand the mechanisms underlying the efficacy of these interventions and optimize the design and implementation of iADL-VR interventions to maximize their effectiveness.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-023-01292-8.

Additional file 1. Supplement Table A1. Databases and search terms used

Author contributions

JB: Resources, Data curation, Methodology, Formal analysis, Software, Writing—original draft. JV-A: Conceptualization, Methodology, Formal analysis. GP-N: Conceptualization, Methodology, Writing—review & editing, Supervision. Validation.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author details

[1]SISAu Research Group, Facultad de Ingeniería, Industria y Producción, Universidad Indoamérica, Ambato, Ecuador. [2]Centro de Investigaciones de Ciencias Humanas y de la Educación (CICHE), Universidad Indoamérica, Ambato, Ecuador. [3]Department of Electronic Engineering and Communications, University of Zaragoza, Teruel, Spain.

Received: 14 June 2023 Accepted: 7 December 2023
Published online: 19 December 2023

References

1. Corbetta M, Shulman GL. Control of goal-directed and stimulus-driven attention in the brain. Nat Rev Neurosci. 2002;3:201–15.
2. Weintraub S, Wicklund AH, Salmon DP. The neuropsychological profile of Alzheimer disease. Cold Spring Harb Perspect Med. 2012;2: a006171.
3. Chaytor N, Schmitter-Edgecombe M. The ecological validity of neuropsychological tests: a review of the literature on everyday cognitive skills. Neuropsychol Rev. 2003;13:181–97.
4. Pashmdarfard M, Azad A. Assessment tools to evaluate Activities of Daily Living (ADL) and Instrumental Activities of Daily Living (IADL) in older adults: a systematic review. Med J Islam Repub Iran. 2020;34:33.
5. Oort Q, Taphoorn MJB, Sikkes SAM, Uitdehaag BMJ, Reijneveld JC, Dirven L. Evaluation of the content coverage of questionnaires containing basic and instrumental activities of daily living (ADL) used in adult patients with brain tumors. J Neurooncol. 2019;143:1–13.
6. Zhang Y, Xiong Y, Yu Q, Shen S, Chen L, Lei X. The activity of daily living (ADL) subgroups and health impairment among Chinese elderly: a latent profile analysis. BMC Geriatr. 2021;21:30.
7. Roley SS, DeLany JV, Barrows CJ, Brownrigg S, Honaker DL, Sava DI, et al. Occupational therapy practice framework: domain & process 2nd edition. Am J Occup Ther. 2008;62:625–83.
8. Ward G, Jagger C, Harper W. A review of instrumental ADL assessments for use with elderly people. Rev Clin Gerontol. 1998;8:65–71.
9. Varela-Aldás J, Buele J, Amariglio R, García-Magariño I, Palacios-Navarro G. The cupboard task: an immersive virtual reality-based system for everyday memory assessment. Int J Hum Comput Stud. 2022;167: 102885.
10. Tulliani N, Bissett M, Fahey P, Bye R, Liu KPY. Efficacy of cognitive remediation on activities of daily living in individuals with mild cognitive impairment or early-stage dementia: a systematic review and meta-analysis. Syst Rev. 2022;11:156.
11. Iribarne C, Renner V, Pérez C, de Guevara DL. Trastornos del Ánimo y Demencia. Aspectos clínicos y estudios complementarios en el diagnóstico diferencial. Rev Médica Clínica Las Condes. 2020;31:150–62.
12. Zhang X-X, Tian Y, Wang Z-T, Ma Y-H, Tan L, Yu J-T. The epidemiology of Alzheimer's disease modifiable risk factors and prevention. J Prev Alzheimers Dis. 2021;1–9.

13. Iadecola C, Duering M, Hachinski V, Joutel A, Pendlebury ST, Schneider JA, et al. Vascular cognitive impairment and dementia. J Am Coll Cardiol. 2019;73:3326–44.
14. Román GC. Vascular dementia may be the most common form of dementia in the elderly. J Neurol Sci. 2002;203–204:7–10.
15. American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders. 5th ed. Arlington: American Psychiatric Publishing; 2013.
16. Perry RJ, Hodges JR. Fate of patients with questionable (very mild) Alzheimer's disease: longitudinal profiles of individual subjects' decline. Dement Geriatr Cogn Disord. 2000;11:342–9.
17. Nichols E, Steinmetz JD, Vollset SE, Fukutaki K, Chalek J, Abd-Allah F, et al. Estimation of the global prevalence of dementia in 2019 and forecasted prevalence in 2050: an analysis for the Global Burden of Disease Study 2019. Lancet Public Health. 2022;7:e105–25.
18. Zhong D, Chen L, Feng Y, Song R, Huang L, Liu J, et al. Effects of virtual reality cognitive training in individuals with mild cognitive impairment: a systematic review and meta-analysis. Int J Geriatr Psychiatry. 2021;36:1829–47.
19. Lampit A, Hallock H, Valenzuela M. Computerized cognitive training in cognitively healthy older adults: a systematic review and meta-analysis of effect modifiers. PLoS Med. 2014;11: e1001756.
20. Cicerone KD, Goldin Y, Ganci K, Rosenbaum A, Wethe JV, Langenbahn DM, et al. Evidence-based cognitive rehabilitation: systematic review of the literature from 2009 through 2014. Arch Phys Med Rehabil. 2019;100:1515–33.
21. Spector A, Thorgrimsen L, Woods B, Royan L, Davies S, Butterworth M, et al. Efficacy of an evidence-based cognitive stimulation therapy programme for people with dementia: randomised controlled trial. Br J Psychiatry. 2003;183:248–54.
22. Negut A. Cognitive assessment and rehabilitation in virtual reality: theoretical review and practical implications. Romanian J Appl Psychol. 2014;16:1–7.
23. Tarnanas I, Schlee W, Tsolaki M, Müri R, Mosimann U, Nef T. Ecological validity of virtual reality daily living activities screening for early dementia: longitudinal study. JMIR Serious Games. 2013;1: e2778.
24. Dawson DR, Marcotte TD. Special issue on ecological validity and cognitive assessment. Neuropsychol Rehabil. 2017;27:599–602.
25. Maggio MG, De Luca R, Molonia F, Porcari B, Destro M, Casella C, et al. Cognitive rehabilitation in patients with traumatic brain injury: a narrative review on the emerging use of virtual reality. J Clin Neurosci. 2019;61:1–4.
26. Draganski B, Gaser C, Busch V, Schuierer G, Bogdahn U, May A. Neuroplasticity: changes in grey matter induced by training. Nature. 2004;427:311–3.
27. Shah TM, Weinborn M, Verdile G, Sohrabi HR, Martins RN. Enhancing cognitive functioning in healthly older adults: a systematic review of the clinical significance of commercially available computerized cognitive training in preventing cognitive decline. Neuropsychol Rev. 2017;27:62–80.
28. Maggio MG, Maresca G, De Luca R, Stagnitti MC, Porcari B, Ferrera MC, et al. The growing use of virtual reality in cognitive rehabilitation: fact, fake or vision? A scoping review. J Natl Med Assoc. 2019;111:457–63.
29. Skurla MD, Rahman AT, Salcone S, Mathias L, Shah B, Forester BP, et al. Virtual reality and mental health in older adults: a systematic review. Int Psychogeriatr. 2022;34:143–55.
30. Coyle H, Traynor V, Solowij N. Computerized and virtual reality cognitive training for individuals at high risk of cognitive decline: systematic review of the literature. Am J Geriatr Psychiatry. 2015;23:335–59.
31. Papaioannou T, Voinescu A, Petrini K, Stanton FD. Efficacy and moderators of virtual reality for cognitive training in people with dementia and mild cognitive impairment: a systematic review and meta-analysis. J Alzheimers Dis. 2022;88:1341–70.
32. Yu D, Li X, Lai FH. The effect of virtual reality on executive function in older adults with mild cognitive impairment: a systematic review and meta-analysis. Aging Ment Health. 2023;27:663–73.
33. Lange B, Koenig S, Chang C-Y, McConnell E, Suma E, Bolas M, et al. Designing informed game-based rehabilitation tasks leveraging advances in virtual reality. Disabil Rehabil. 2012;34:1863–70.
34. Chiang TH-C. Investigating effects of interactive virtual reality games and gender on immersion, empathy and behavior into environmental education. Front Psychol. 2021. https://doi.org/10.3389/fpsyg.2021.608407.
35. Ma M, Zheng H. Virtual Reality and Serious Games in Healthcare. In: Brahnam S, Jain LC, editors. Adv Comput Intell Paradig Healthc 6 Virtual Real Psychother Rehabil Assess. Berlin, Heidelberg: Springer Berlin Heidelberg; 2011. p. 169–92. https://doi.org/10.1007/978-3-642-17824-5_9.
36. Yang S, Chun MH, Son YR. Effect of virtual reality on cognitive dysfunction in patients with brain tumor. Ann Rehabil Med. 2014;38:726.
37. Alcañiz M, Bigné E, Guixeres J. Virtual Reality in Marketing: A Framework, Review, and Research Agenda. Front Psychol. 2019. https://doi.org/10.3389/fpsyg.2019.01530.
38. García-Betances RI, Jiménez-Mixco V, Arredondo MT, Cabrera-Umpiérrez MF. Using virtual reality for cognitive training of the elderly. Am J Alzheimers Dis Dementias. 2015;30:49–54.
39. Martirosov S, Bureš M, Zítka T. Cyber sickness in low-immersive, semi-immersive, and fully immersive virtual reality. Virtual Real. 2022;26:15–32.
40. Kemeny A, Chardonnet J-R, Colombet F. Getting Rid of Cybersickness: In Virtual Reality, Augmented Reality, and Simulators. Cham: Springer International Publishing; 2020. https://doi.org/10.1007/978-3-030-59342-1.
41. Corregidor-Sánchez A-I, Segura-Fragoso A, Criado-Álvarez J-J, Rodríguez-Hernández M, Mohedano-Moriano A, Polonio-López B. Effectiveness of virtual reality systems to improve the activities of daily life in older people. Int J Environ Res Public Health. 2020;17:6283.
42. Kurz A. Cognitive stimulation, training, and rehabilitation. Dialogues Clin Neurosci. 2019;21:35–41.
43. Romero-Ayuso D, Castillero-Perea Á, González P, Navarro E, Molina-Massó JP, Funes MJ, et al. Assessment of cognitive instrumental activities of daily living: a systematic review. Disabil Rehabil. 2021;43:1342–58.
44. Parsons TD, Carlew AR, Magtoto J, Stonecipher K. The potential of function-led virtual environments for ecologically valid measures of executive function in experimental and clinical neuropsychology. Neuropsychol Rehabil. 2017;27:777–807.
45. Doniger GM, Beeri MS, Bahar-Fuchs A, Gottlieb A, Tkachov A, Kenan H, et al. Virtual reality-based cognitive-motor training for middle-aged adults at high Alzheimer's disease risk: a randomized controlled trial. Alzheimers Dement Transl Res Clin Interv. 2018;4:118–29.
46. Rand D, Weiss PL, Katz N. Training multitasking in a virtual supermarket: a novel intervention after stroke. Am J Occup Ther. 2009;63:535–42.
47. Moseley AM, Herbert RD, Sherrington C, Maher CG. Evidence for physiotherapy practice: a survey of the Physiotherapy Evidence Database (PEDro). Aust J Physiother. 2002;48:43–9.
48. Macedo LG, Elkins MR, Maher CG, Moseley AM, Herbert RD, Sherrington C. There was evidence of convergent and construct validity of Physiotherapy Evidence Database quality scale for physiotherapy trials. J Clin Epidemiol. 2010;63:920–5.
49. Teasell RW, Foley NC, Bhogal SK, Speechley MR. An evidence-based review of stroke rehabilitation. Top Stroke Rehabil. 2003;10:29–58.
50. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann Intern Med. 2009;151:264–9.
51. Yamaguchi T, Foloppe DA, Richard P, Richard E, Allain P. A dual-modal virtual reality kitchen for (re)learning of everyday cooking activities in Alzheimer's disease. Presence Teleoperators Virtual Environ. 2012;21:43–57.
52. Palacios-Navarro G, Hogan N. Head-mounted display-based therapies for adults post-stroke: a systematic review and meta-analysis. Sensors. 2021;21:1111.
53. Foloppe DA, Richard P, Yamaguchi T, Etcharry-Bouyx F, Allain P. The potential of virtual reality-based training to enhance the functional autonomy of Alzheimer's disease patients in cooking activities: a single case study. Neuropsychol Rehabil. 2018;28:709–33.
54. Tarnanas I, Tsolakis A, Tsolaki M. Assessing virtual reality environments as cognitive stimulation method for patients with MCI. Stud Comput Intell. Springer Verlag; 2014. p. 39–74. https://doi.org/10.1007/978-3-642-45432-5_4.
55. Fasilis T, Patrikelis P, Siatouni A, Alexoudi A, Veretzioti A, Zachou L, et al. A pilot study and brief overview of rehabilitation via virtual environment in patients suffering from dementia. Psychiatr Psychiatr. 2018;29:42–51.

56. Gamito P, Oliveira J, Alves C, Santos N, Coelho C, Brito R. Virtual reality-based cognitive stimulation to improve cognitive functioning in community elderly: a controlled study. Cyberpsychol Behav Soc Netw. 2020;23:150–6.
57. Masoumzadeh S, Moussavi Z. Does practicing with a virtual reality driving simulator improve spatial cognition in older adults? A Pilot Study. Neurosci Insights. 2020;15.
58. Schreiber M, Schweizer A, Lutz K, Kalveram KT, Jäncke L. Potential of an interactive computer-based training in the rehabilitation of dementia: an initial study. Neuropsychol Rehabil. 1999;9:155–67.
59. Man DWK, Chung JCC, Lee GYY. Evaluation of a virtual reality-based memory training programme for Hong Kong Chinese older adults with questionable dementia: a pilot study. Int J Geriatr Psychiatry. 2012;27:513–20.
60. Oliveira J, Gamito P, Souto T, Conde R, Ferreira M, Corotnean T, et al. Virtual reality-based cognitive stimulation on people with mild to moderate dementia due to Alzheimer's disease: a pilot randomized controlled trial. Int J Environ Res Public Health. 2021;18:5290.
61. Kang JM, Kim N, Lee SY, Woo SK, Park G, Yeon BK, et al. Effect of cognitive training in fully immersive virtual reality on visuospatial function and frontal-occipital functional connectivity in predementia: randomized controlled trial. J Med Internet Res. 2021;23:e24526.
62. Park JH. Does the virtual shopping training improve executive function and instrumental activities of daily living of patients with mild cognitive impairment? Asian J Psychiatry. 2022;69: 102977.
63. Park E, Yun BJ, Min YS, Lee YS, Moon SJ, Huh JW, et al. Effects of a mixed reality-based cognitive training system compared to a conventional computer-assisted cognitive training system on mild cognitive impairment: a pilot study. Cogn Behav Neurol. 2019;32:172–8.
64. Panerai S, Gelardi D, Catania V, Rundo F, Tasca D, Musso S, et al. Functional living skills: a non-immersive virtual reality training for individuals with major neurocognitive disorders. Sensors. 2021;21:1–15.
65. Gamito P, Oliveira J, Morais D, Coelho C, Santos N, Alves C, et al. Cognitive stimulation of elderly individuals with instrumental virtual reality-based activities of daily life: pre-post treatment study. Cyberpsychology Behav Soc Netw. 2019;22:69–75.
66. Maeng S, Hong JP, Kim WH, Kim H, Cho SE, Kang JM, et al. Effects of virtual reality-based cognitive training in the elderly with and without mild cognitive impairment. Psychiatry Investig. 2021;18:619–27.
67. Kim H, Hong JP, Kang JM, Kim WH, Maeng S, Cho SE, et al. Cognitive reserve and the effects of virtual reality-based cognitive training on elderly individuals with mild cognitive impairment and normal cognition. Psychogeriatrics. 2021;21:552–9.
68. Zhu KY, Zhang QY, He BW, Huang MZ, Lin R, Li H. Immersive virtual reality-based cognitive intervention for the improvement of cognitive function, depression, and perceived stress in older adults with mild cognitive impairment and mild dementia: pilot pre-post study. JMIR Serious Games. 2022;10:1–12.
69. Hofmann M, Rösler A, Schwarz W, Müller-Spahn F, Kräuchi K, Hock C, et al. Interactive computer-training as a therapeutic tool in Alzheimer's disease. Compr Psychiatry. 2003;44:213–9.
70. Optale G, Urgesi C, Busato V, Marin S, Piron L, Priftis K, et al. Controlling memory impairment in elderly adults using virtual reality memory training: a randomized controlled pilot study. Neurorehabil Neural Repair. 2010;24:348–57.
71. Vallejo V, Wyss P, Rampa L, Mitache AV, Müri RM, Mosimann UP, et al. Evaluation of a novel Serious Game based assessment tool for patients with Alzheimer's disease. PLoS ONE. 2017;12: e0175999.
72. Burgess PW, Alderman N, Forbes C, Costello A, Coates LMA, Dawson DR, et al. The case for the development and use of "ecologically valid" measures of executive function in experimental and clinical neuropsychology. J Int Neuropsychol Soc. 2006;12:194–209.
73. Dickerson AE, Meuel DB, Ridenour CD, Cooper K. Assessment tools predicting fitness to drive in older adults: a systematic review. Am J Occup Ther. 2014;68:670–80.
74. Graf C. The Lawton instrumental activities of daily living scale. Am J Nurs. 2008;108:52–62.
75. Nguyen L, Murphy K, Andrews G. Immediate and long-term efficacy of executive functions cognitive training in older adults: a systematic review and meta-analysis. Psychol Bull. 2019;145:698–733.
76. Tetlow AM, Edwards JD. Systematic literature review and meta-analysis of commercially available computerized cognitive training among older adults. J Cogn Enhanc. 2017;1:559–75.
77. Ge S, Zhu Z, Wu B, McConnell ES. Technology-based cognitive training and rehabilitation interventions for individuals with mild cognitive impairment: a systematic review. BMC Geriatr. 2018;18:1–19.
78. Mrakic-Sposta S, Di Santo SG, Franchini F, Arlati S, Zangiacomi A, Greci L, et al. Effects of combined physical and cognitive virtual reality-based training on cognitive impairment and oxidative stress in MCI patients: a pilot study. Front Aging Neurosci. 2018;10:1–11.
79. Humphreys GW, Forde EME. Disordered action schema and action disorganisation syndrome. Cogn Neuropsychol. 1998;15:771–811.
80. Kim O, Pang Y, Kim JH. The effectiveness of virtual reality for people with mild cognitive impairment or dementia: a meta-analysis. BMC Psychiatry. 2019;19:1–10.
81. Krokos E, Plaisant C, Varshney A. Virtual memory palaces: immersion aids recall. Virtual Real. 2019;23:1–15.
82. Huttner J-P, Qian Z, Robra-Bissantz S. A Virtual Memory Palace and the User's Awareness of the Method of Loci. Proc 27th Eur Conf Inf Syst ECIS. Stockholm & Uppsala, Sweden; 2019.
83. Maidenbaum S, Patel A, Stein E, Jacobs J. Spatial Memory Rehabilitation in Virtual Reality—Extending findings from Epilepsy Patients to the General Population. 2019 Int Conf Virtual Rehabil ICVR . 2019 [cited 2023 Oct 6]. p. 1–7. Available from: https://ieeexplore.ieee.org/abstract/document/8994573.
84. Dede C. Immersive interfaces for engagement and learning. Science. 2009;323:66–9.
85. Slater M. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philos Trans R Soc B Biol Sci. 2009;364:3549–57.
86. Meehan M, Insko B, Whitton M, Brooks FP. Physiological measures of presence in stressful virtual environments. ACM Trans Graph. 2002;21:645–52.
87. Freeman D, Reeve S, Robinson A, Ehlers A, Clark D, Spanlang B, et al. Virtual reality in the assessment, understanding, and treatment of mental health disorders. Psychol Med. 2017;47:2393–400.
88. Witmer BG, Singer MJ. Measuring presence in virtual environments: a presence questionnaire. Presence Teleoperators Virtual Environ. 1998;7:225–40.
89. Howard MC. A meta-analysis and systematic literature review of virtual reality rehabilitation programs. Comput Hum Behav. 2017;70:317–27.
90. Cogné M, Auriacombe S, Vasa L, Tison F, Klinger E, Sauzéon H, et al. Are visual cues helpful for virtual spatial navigation and spatial memory in patients with mild cognitive impairment or Alzheimer's disease? Neuropsychology. 2018;32:385–400.
91. Dechamps A, Fasotti L, Jungheim J, Leone E, Dood E, Allioux A, et al. Effects of different learning methods for instrumental activities of daily living in patients with Alzheimer's dementia: a pilot study. Am J Alzheimers Dis Other Demen. 2011;26:273–81.
92. Somrak A, Humar I, Hossain MS, Alhamid MF, Hossain MA, Guna J. Estimating VR Sickness and user experience using different HMD technologies: an evaluation study. Future Gener Comput Syst. 2019;94:302–16.
93. Duzmanska N, Strojny P, Strojny A. Can simulator sickness be avoided? A review on temporal aspects of simulator sickness. Front Psychol. 2018;9:2132.
94. Kawano N, Iwamoto K, Ebe K, Aleksic B, Noda A, Umegaki H, et al. Slower adaptation to driving simulator and simulator sickness in older adults. Aging Clin Exp Res. 2012;24:285–9.
95. Kourtesis P, Collina S, Doumas LAA, MacPherson SE. Validation of the virtual reality neuroscience questionnaire: maximum duration of immersive virtual reality sessions without the presence of pertinent adverse symptomatology. Front Hum Neurosci. 2019. https://doi.org/10.3389/fnhum.2019.00417.
96. Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG. Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int J Aviat Psychol. 1993;3:203–20.
97. Szpak A, Richards A, Michalski S, Loetscher T. Getting the most out of virtual reality: evaluating short breaks to reduce cybersickness and cognitive aftereffects. 2022. p. 537.
98. Carnegie K, Rhee T. Reducing visual discomfort with HMDs using dynamic depth of field. IEEE Comput Graph Appl. 2015;35:34–41.

99. Stanney K, Fidopiastis C, Foster L. Virtual reality is sexist: but it does not have to be. Front Robot AI. 2020. https://doi.org/10.3389/frobt.2020.00004.
100. Sikkes SAM, de Lange-de Klerk ESM, Pijnenburg YAL, Scheltens P, Uitdehaag BMJ. A systematic review of Instrumental Activities of Daily Living scales in dementia: room for improvement. J Neurol Neurosurg Psychiatry. 2009;80:7–12.
101. Liu L, Watson B, Miyazaki M. VR for the elderly: quantitative and qualitative differences in performance with a driving simulator. Cyberpsychol Behav. 1999;2:567–76.
102. Man DWK, Soong WYL, Tam SF, Hui-Chan CWY. A randomized clinical trial study on the effectiveness of a tele-analogy-based problem-solving programme for people with acquired brain injury (ABI). NeuroRehabilitation. 2006;21:205–17.
103. Villarejo A, Puertas-Martín V. Utilidad de los test breves en el cribado de demencia. Neurologia. 2011;26:425–33.
104. Robert PH, König A, Amieva H, Andrieu S, Bremond F, Bullock R, et al. Recommendations for the use of serious games in people with Alzheimer's disease, related disorders and frailty. Front Aging Neurosci. 2014;6:54.
105. Marino JC. Actualización en Tests Neuropsicológicos de Funciones Ejecutivas. Rev Argent Cienc Comport. 2010;2:34–45.
106. Board of Directors. American Academy of Clinical Neuropsychology (AACN) Practice Guidelines for Neuropsychological Assessment and Consultation. Clin Neuropsychol. 2007;21:209–31.
107. Hill NTM, Mowszowski L, Naismith SL, Chadwick VL, Valenzuela M, Lampit A. Computerized cognitive training in older adults with mild cognitive impairment or dementia: a systematic review and meta-analysis. Am J Psychiatry. 2017;174:329–40.
108. Fleming TM, Bavin L, Stasiak K, Hermansson-Webb E, Merry SN, Cheek C, et al. Serious games and gamification for mental health: current status and promising directions. Front Psychiatry. 2017. https://doi.org/10.3389/fpsyt.2016.00215/full.
109. Qian J, McDonough DJ, Gao Z. The effectiveness of virtual reality exercise on individual's physiological, psychological and rehabilitative outcomes: a systematic review. Int J Environ Res Public Health. 2020;17:4133.
110. Faria AL, Latorre J, Silva Cameirão M, Bermúdez i Badia S, Llorens R. Ecologically valid virtual reality-based technologies for assessment and rehabilitation of acquired brain injury: a systematic review. Front Psychol. 2023;14:1233346.
111. Otsuka T, Tanemura R, Noda K, Nagao T, Sakai H, Luo Z-W. Development of computer-aidedcognitive training program for elderly and its effectiveness through a 6 months group intervention study. Curr Alzheimer Res. 2015;12:553–62.
112. Anderson JR, Bothell D, Fincham JM, Anderson AR, Poole B, Qin Y. Brain regions engaged by part-and whole-task performance in a video game: a model-based test of the decomposition hypothesis. J Cogn Neurosci. 2011;23:3983–97.
113. Varela-Aldás J, Buele J, López I, Palacios-Navarro G. Influence of hand tracking in immersive virtual reality for memory assessment. Int J Environ Res Public Health. 2023;20:4609.
114. García-Magariño I, Fox-Fuller JT, Palacios-Navarro G, Baena A, Quiroz YT. Visual working memory for semantically related objects in healthy adults. Rev Neurol. 2020;71:277–84.
115. Liberati G, Raffone A, Belardinelli MO. Cognitive reserve and its implications for rehabilitation and Alzheimer's disease. Cogn Process. 2012;13:1–12.
116. Mondini S, Madella I, Zangrossi A, Bigolin A, Tomasi C, Michieletto M, et al. Cognitive reserve in dementia: implications for cognitive training. Front Aging Neurosci. 2016;8:84.
117. Chapman SB, Aslan S, Spence JS, Hart JJ, Bartz EK, Didehbani N, et al. Neural mechanisms of brain plasticity with complex cognitive training in healthy seniors. Cereb Cortex. 2015;25:396–405.
118. Belleville S, Clément F, Mellah S, Gilbert B, Fontaine F, Gauthier S. Training-related brain plasticity in subjects at risk of developing Alzheimer's disease. Brain. 2011;134:1623–34.
119. Ten Brinke LF, Davis JC, Barha CK, Liu-Ambrose T. Effects of computerized cognitive training on neuroimaging outcomes in older adults: a systematic review. BMC Geriatr. 2017;17:1–20.
120. Tomioka K, Kurumatani N, Hosoi H. Association between social participation and instrumental activities of daily living among community-dwelling older adults. J Epidemiol. 2016;26:553–61.

Publisher's Note

2.5. Artículo: Cognitive-motor interventions based on virtual reality and instrumental activities of daily living (iADL): an overview

frontiers | Frontiers in Aging Neuroscience

TYPE Mini Review
PUBLISHED 15 June 2023
DOI 10.3389/fnagi.2023.1191729

OPEN ACCESS

EDITED BY
Ju Gao,
University of Arizona, United States

REVIEWED BY
Hillel Finestone,
Élisabeth Bruyère Hospital, Canada

*CORRESPONDENCE
Jorge Buele
✉ jorgebuele@uti.edu.ec
Guillermo Palacios-Navarro
✉ guillermo.palacios@unizar.es

RECEIVED 22 March 2023
ACCEPTED 30 May 2023
PUBLISHED 15 June 2023

CITATION
Buele J and Palacios-Navarro G (2023) Cognitive-motor interventions based on virtual reality and instrumental activities of daily living (iADL): an overview. *Front. Aging Neurosci.* 15:1191729. doi: 10.3389/fnagi.2023.1191729

Cognitive-motor interventions based on virtual reality and instrumental activities of daily living (iADL): an overview

Jorge Buele[1,2]* and Guillermo Palacios-Navarro[2]*

[1]SISAu Research Group, Facultad de Ingeniería, Industria y Producción, Universidad Indoamérica, Ambato, Ecuador, [2]Department of Electronic Engineering and Communications, University of Zaragoza, Teruel, Spain

Non-invasive, non-pharmacological interventions utilizing virtual reality (VR) represent a promising approach to enhancing cognitive function in patients with degenerative cognitive disorders. Traditional "pen and paper" therapies often lack the practical engagement in everyday activities that older individuals encounter in their environment. These activities pose both cognitive and motor challenges, underscoring the necessity of understanding the outcomes of such combined interventions. This review aimed to assess the advantages of VR applications that integrate cognitive-motor tasks, simulating instrumental activities of daily living (iADLs). We systematically searched five databases—Scopus, Web of Science, Springer Link, IEEE Xplore, and PubMed, from their inception until January 31, 2023. Our review revealed that motor movements, coupled with VR-based cognitive-motor interventions, activate specific brain areas and foster improvements in general cognition, executive function, attention, and memory. VR applications that meld cognitive-motor tasks and simulate iADLs can offer significant benefits to older adults. Enhanced cognitive and motor performance can promote increased independence in daily activities, thereby contributing to improved quality of life.

KEYWORDS

cognitive disorders, daily living, instrumental activities, motor intervention, virtual reality

1. Introduction

Human life expectancy has seen a significant increase in recent decades (van Leeuwen et al., 2019). However, aging is accompanied by notable physical and cognitive changes that necessitate consideration (Elliott et al., 2021). Emerging technologies, including artificial intelligence, robotics, big data, telematics, and virtual and augmented reality, offer promising tools in health sciences to enhance individuals' quality of life (Palacios-Navarro et al., 2016; Baig et al., 2019; Wildenbos et al., 2019; Hülür and Macdonald, 2020). VR systems have been leveraged for diagnosing age-related diseases and abnormalities in older adults (Varela-Aldás et al., 2022). Beyond diagnosis, VR has revolutionized therapeutic, training, and rehabilitation processes by providing immersive three-dimensional experiences aimed at restoring or maintaining a wide range of cognitive functions often compromised in older adults (Appel et al., 2020).

Executive functions (EF) are responsible for mental manipulation of information, concept formation, problem solving, and cue-directed behavior (Weintraub et al., 2012). They entail advanced cognitive skills such as working memory, inhibitory control, cognitive flexibility, planning, reasoning, and problem-solving (Cristofori et al., 2019). Reduced performance of these functions is quite evident when Mild Cognitive Impairment (MCI) is already present. Alzheimer's disease (AD) in its early phase is particularly characterized by a diminished ability to mentally manipulate information (Elosúa et al., 2021). EF, related to working memory and attention, develop fully in adulthood and have direct links to cognitive efficiency, knowledge acquisition, academic performance, and autonomy (Baragash et al., 2022).

The reduction of autonomy generates problems in the person as it limits their ability to carry out their activities of daily living (ADL) (Tornero-Quiñones et al., 2020). EF interact with long-term memory in the episodic buffer, enabling the retrieval of previously learned information essential for problem-solving and new information processing for long-term storage (Oosterman et al., 2021). iADL demand greater effort from older adults, requiring continuous problem-solving related to their self-care (Cornelis et al., 2019). Key iADLs include meal preparation, budget planning, basic mathematical operations, and transportation use, necessitating active phonological loops to maintain auditory information in consciousness for immediate use (Weintraub et al., 2012). Patients with MCI or AD show significant impairments in long-term memory, EF, and spatial orientation (Murman, 2015).

Older adults often face physical limitations due to reduced motor and sensory system functionality (Khan et al., 2022), complicating both self-care activities (basic ADL or bADL) and mobility exercises such as walking, marching, or maintaining balance (Osoba et al., 2019). Research indicates that aerobic and balance physical training can increase muscle strength, thus reducing falls (Sherrington et al., 2019). It is important to note that while young and cognitively healthy adults generally do not exhibit postural and gait control problems, older adults or those with cognitive issues are vulnerable to cognitive distractions (dual or additional tasks) that may compromise postural control (Zhang et al., 2019). Studies like that of Sato (2017) have shown that EF partly governs the motor and sensory system, meaning that its malfunctioning is linked to falls. These findings underscore the need for cognitive interventions that also incorporate physical exercises, aiming for a comprehensive approach (Tromp et al., 2015).

Conventional cognitive therapies, or "paper and pencil" therapies, have long been used to treat cognitive impairments in older adults. These cost-effective, easily accessible, and clinically validated therapies include tabletop activities like puzzles, wooden blocks, card games, and mazes (Bernini et al., 2019). However, these therapies often struggle to assess patients' cognitive levels systematically and keep them engaged. Computer-based cognitive interventions, on the other hand, have emerged as a promising alternative, demonstrating effectiveness in improving cognitive function in both healthy older adults and those with neuropsychological disorders (Thapa et al., 2020; Zuschnegg et al., 2023). Unlike conventional therapies, these computer-based interventions are capable of systematically adjusting task difficulty according to the individual's cognitive level, offering a more diverse and engaging range of programs and activities (Wollesen et al., 2020). These interventions surpass static and straightforward training, providing interactive and immersive experiences.

While computer-based cognitive interventions offer many advantages, it is crucial to establish specific guidelines to assist healthcare professionals in determining the appropriate activities and clinical conditions for implementation (Goldstein and McNeil, 2012). Standardizing these guidelines can enhance the effectiveness and efficiency of computer-based interventions in clinical practice. Given the existing digital divide between younger and older adults, it's vital to consider how this might impact older individuals' access to modern technologies like VR. VR-based cognitive interventions, leveraging advancements in information technology, have shown great promise (Liao et al., 2020). While some older adults have successfully used these technologies for social interaction and cognitive enhancement (Gao et al., 2020), others may face social exclusion due to a lack of necessary skills and equipment. Addressing this digital divide is essential to ensure older individuals can fully benefit from VR/AR-based interventions for cognitive enhancement and overall wellbeing.

Research shows that VR can significantly enhance cognitive-motor interventions in older adults (Kwan et al., 2021). For instance, the study of Pichierri et al. (2012) incorporated traditional physical exercise and dance video games into cognitive-motor training. This dual-task exercise led to VR system users taking quicker steps than the passive control group, potentially preventing falls in real-life situations. Another study (Torpil et al., 2021) featured various serious games, including activities such as a boxing trainer, a running game controlled by jumping and body movements, a penalty kick game, and a skydiving game controlled by body and shoulder movements. The results showed improvements in visuospatial perception, organization, orientation, attention, and concentration compared to the control group. The study of Cameirão et al. (2016) demonstrated how mood and cognitive functioning can supplement physical rehabilitation, as post-stroke participants had to locate a target image within a set of 15 distractors for attention and memory training.

Several reviews have analyzed VR's effect on cognitive and motor functions. A systematic review conducted by Zhu et al. (2021) included 11 randomized controlled trials (RCTs), revealing a moderate impact of VR interventions on cognitive and motor function, including attention/execution, memory, global cognition, and balance in patients with mild cognitive impairment (MCI) and dementia. Gao et al. (2021) analyzed six VR interventions combined with traditional rehabilitation, showing significant improvements in general cognition, attention, and mood, though not in global cognition, motor function, and ADLs. In the review of Pichierri et al. (2011) computerized interventions (mostly VR) showed positive effects on various physical abilities in older adults with TBI and stroke compared to non-VR proposals. Participants displayed greater motivation and compliance with the computerized environment compared to regular physical training programs. A similar approach was used in the study of Schoene et al. (2014), where the use of technological tools in cognitive-motor rehabilitation was analyzed. The two studies that used a VR environment with a treadmill reported improvements in balance and mobility.

The benefits of VR in training older adults are evident based on the existing evidence. However, the heterogeneity of activities simulated in VR environments makes analysis challenging. Therefore, this review focuses solely on VR applications in which participants perform iADLs and motor tasks (iADL-m) to assess their impact on the cognitive functions of older adults.

2. Methods

2.1. Eligibility criteria

This review adheres to the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines for systematic reviews. Inclusion criteria encompass: (i) articles published in English; (ii) studies without temporal or spatial restrictions; (iii) interventions employing VR-iADL and motor applications; (iv) clinical trials and pilot studies; (v) studies involving healthy older adults with MCI or dementia; (vi) immersive and non-immersive systems; and (vii) studies both with and without a control group.

2.2. Exclusion criteria

Exclusion criteria include: (i) theoretical or descriptive studies; (ii) non-peer-reviewed articles and preprints; (iii) studies not employing VR; (iv) applications that do not simulate an iADL; (v) interventions solely cognitive in nature; (vi) literature reviews; (vii) interventions for disorders other than those specified; (viii) diagnostic or screening investigations; and (ix) interventions without a pretest and posttest.

2.3. Data sources and search strategy

Relevant articles were identified in Pubmed, Scopus, IEEE Xplore, Apa PsycNet, and the Web of Science databases, from their inception until January 2023. The search terms included keywords relating to virtual reality (e.g., "virtual," "computer"), cognitive-motor interventions (e.g., "cognitive," "motor," "memory," "executive," "rehabilitation," "training," "stimulation"), iADL (e.g., "daily," "ADL," "iADL," "store," "shopping," "supermarket," "cook," "cooking," "kitchen"), and cognitive disorders [e.g., "mild," "Alzheimer," "dementia," NOT ("stroke," "brain injury," "TBI")].

2.4. Study selection

Search terms were tailored to each database. The titles and abstracts of articles in each database were screened independently by two authors (JB and GP-N) in line with the specified inclusion and exclusion criteria. Duplicate studies were removed, and additional studies cited in the identified articles were included. The selected articles were then stored, organized, and assessed using the Mendeley bibliographic manager v1.19.8 (Mendeley Ltd., Elsevier, Netherlands).

3. Results

Upon identifying articles that met the inclusion and exclusion criteria, data were extracted from each article. This included the authors, the study design, the sample, the motor and cognitive intervention applied, and the main findings. **Table 1** presents the characteristics of each study.

4. Discussion

With advancing age, the ability to perform motor-related activities becomes increasingly challenging. As noted by Muir et al. (2012), elderly individuals with MCI demonstrate a reduction in gait speed and an elongated stride completion time when transitioning from a single task to a double one. Older adults with cognitive difficulties are at a higher risk of falls compared to their healthy counterparts, and this risk escalates when the walking speed drops below 1 m/s (Abellan Van Kan et al., 2009). Furthermore, elderly people with MCI are likely to make risky decisions when crossing streets (Rizzo et al., 1997). An increase in latency at the onset of a journey and a slower pace are also reported (Bahureksa et al., 2016), indicating a correlation between gait issues and the onset of Alzheimer's Disease (AD) due to associated visuospatial deficits (Fukui and Lee, 2009; Rosso et al., 2019). A reduction in walking speed is perceived as an indicator of cognitive frailty that impacts wellbeing and survival (Duan-Porter et al., 2019; Van Schooten et al., 2019; Beltz et al., 2022). From a cognitive standpoint, memory and executive functions (EF) are most frequently impacted by AD.

4.1. Benefits in cognitive functions

Cognitive-motor interventions have demonstrated potential as an effective method to boost cognitive functions and alleviate frailty. Evidence indicates that these interventions can enhance physical performance, brain functionality (as determined by resting functional magnetic resonance imaging), and cognitive capacities (Raichlen et al., 2020; Yue et al., 2020). The use of VR for such interventions has been successfully demonstrated in both healthy elderly individuals and those suffering from dementia (Yi et al., 2022).

A recent review highlighted that VR cognitive training can exert moderate to large effects on global cognition, attention, memory, and motor performance in individuals with Mild Cognitive Impairment (MCI), with additional benefits for executive function seen in people with dementia (Papaioannou et al., 2022). The VR-integrated ADL motor studies explored in our review have successfully motivated individuals to utilize learned skills in real life, with encouraging knowledge transfer outcomes (McDaniel et al., 2014). Several studies (Healy et al., 2005; Dahlin et al., 2008) propose that transferable skills are only developed through practice, suggesting that other non-iADL applications may not yield the same benefits. More specifically, evidence suggests that practicing an activity can facilitate the transfer of coordination skills in dual tasks, as demonstrated in the study by Schubert et al. (2017). The review conducted by Joubert and Chainay (2018) indicated

10.3389/fnagi.2023.1191729

TABLE 1 Characteristics of the included studies.

References	Design	Sample	VR intervention motor	Cognitive	Major findings
Liao et al., 2020, Taiwan	RCT	34 MCI patients (23F/11M)	Aerobic and resistance exercises, cleaning windows, tai chi, walking, bending and lifting objects at home	Shopping, preparing food, managing finances and transportation	Decreased activation in prefrontal areas indicating increased neural efficiency. Dual VR tasks (physical and cognitive) could have positive effects on several cognitive functions
Liao et al., 2019, Taiwan	RCT	34 MCI patients (23F/11M)	Aerobic and resistance exercises, walking, getting on and off a stool	Shopping, preparing food, managing finances and transportation	The training improved divided attention (cognitive and motor at the same time) and cognitive flexibility (aspects of EF). VR was able to increase motivation
Park et al., 2020, Republic of Korea	RCT	35 MCI patients (17F/18M)	Moto Cog: personal hygiene, driving, door opening, shampoo, use of handles	Card game, puzzle, construction activity with sticks and mazes	The VR group improved in the MoCA, TMT and DST tests performance. Motivation improved with positive effects on attention and short-term visuospatial memory
Doniger et al., 2018, Israel	RCT	34 healthy older adults with a history of Alzheimer's disease	Walking on a treadmill	View a virtual shopping list and pick up items, plan purchases with 100 shekels (Israel currency)	Shopping tasks are very important to maintain and/or regain independence. There was a neuroplastic change in DTI measures of the hippocampus in just 2 h of training
Mrakic-Sposta et al., 2018, Italy	Pilot Study	10 MCI and MD patients (6F/4M)	Cycling in a park, cross the road by bike avoiding cars	Virtual shopping: List of five items, choose the aisle and the product	Improvements in the MMSE, ROCFT, FAB and AM tests performance. Increased antioxidant capacity and reduction of lipid peroxidation and DNA damage. Better performance in real life thanks to self-perceived improvement and motivation
Arlati et al., 2017, Italy	Pilot Study	10 patients with MCI	Cycling in nature, cross and avoid cars by bike	buy five items	Patients showed better performance in real life (less forgetfulness). The trick words (distractors) did not change the results. Patients exhibited high levels of commitment and motivation
Kwan et al., 2021, China	RCT	17 MCI patients (15F/2M)	Bicycle exercise on an ergometer	Shopping, transportation, cooking, bird watching, reporting lost items	Patients reported better performance in real life because of self-perceived improvements. The intervention could improve cognition and frailty, reducing the risk of falls, disability and mortality.
McDaniel et al., 2014, United States	RCT	96 healthy older adults (61F/35M)	Setting the table with cutlery, flexibility exercises (aerobics)	Prepare breakfast: five foods, board game and remember health facts	Participants' performance did not improve in the kitchen task. Aerobic exercises did not show significant changes. Cognitive training did not transfer to other tasks.

AM, attentional matrices test; DST, digit span test (forward/backward); DTI, diffusion tensor imaging; F, female; FAB, frontal assessment battery; M, male; MMSE, mini-mental state examination; MoCA, montreal cognitive assessment; Moto cog, VR training program focused on improving upper extremity ADL performance; ROCFT, Rey-Osterrieth complex figure test; TMT, trail making test (A/B).

a slight superiority for combined physical and cognitive training over training conducted separately. However, separate training also influences different cognitive functions, warranting further research. The links between cognitive and motor processes are not new, and they likely share a similar evolutionary history (Leisman et al., 2016).

The study carried out by Liao et al. (2020) reported that the stimulation of dual tasks (physical and cognitive) simulating ADL in virtual environments can impact various cognitive functions, notably executive functions (EF) and memory (Lauenroth et al., 2016). In previous work, the authors (Liao et al., 2019) created a VR application simulating iADL-m, which aided in training divided attention and cognitive flexibility (aspects of EF), targeting individuals to achieve between 50 and 75% of their maximum heart rate. Concurrently, the results of the study of Mrakic-Sposta et al. (2018) revealed improvements in attention, EF, and memory in patients with MCI. Similar improvements in EF and walking speed were also observed in Kwan et al. (2021)'s study, consistent with a recent review (Papaioannou et al., 2022). These applications provide real-time feedback, leading to long-term benefits, such as the transfer of knowledge to the real world (Ross et al., 2016).

McDaniel et al. (2014) combined virtual food preparation, table setting, and flexibility exercises, showing benefits for prospective memory. This involves spontaneous recovery and care processes that enable defining the actions to be carried out based on the place and situation. High levels of physical activity correlated directly with the proper functioning of EF, suggesting a potential palliative measure (Galle et al., 2022). The study of Galle et al. (2023) showed that those who increased their physical activity by more than 30% displayed improvements in gait speed, aerobic capacity, EF, and global cognition compared to those who did not. Significant enhancements in spatial cognition were also reported, implying that orientation practice could potentially forestall the cognitive decline of the elderly. Applications simulating a virtual city and requiring street crossings could be beneficial to users (Waddington and Heisz, 2023).

According to the study of Doniger et al. (2018), dual processing speed (mobility) training offered protection against dementia. As demonstrated in the longitudinal study carried out by Edwards et al. (2016) cognitive-motor training reduced the experimental group's chances of developing dementia after 10 years by 33%. Although this study primarily aimed to improve cognitive function with simultaneous walking being an incidental action inherent to the shopping task, the results indicated that cognitive training benefited physical performance (PE) while physical training benefited memory. The study of Kwan et al. (2021) reported improvements in cognitive function as a result of virtual cognitive-motor training, which can be attributed to neural plasticity. This effect could be due to the super additive synergistic effects created by the multitasking requirement of simultaneous physical and cognitive exercises. This aligns with the findings of Herold et al. (2018), who suggested that motor training incorporating a cognitive task has the highest ecological validity. Interventions that encourage significant physical exercise, offer variable levels of difficulty, and maintain a task-focused approach have shown to be more effective in adapting to related tasks (Stanmore et al., 2019; Wollesen et al., 2020). This suggests that a comprehensive, multifaceted approach can be more beneficial for cognitive health and physical function.

4.2. Changes in brain function

Numerous research studies have underscored the advantages of physical exercise as a complementary approach in cognitive rehabilitation. Liao et al. (2020) reported that such exercise promotes the release of brain-derived neurotrophic factor, enhancing blood flow and exerting beneficial metabolic effects. Park et al. (2020) further emphasized this in a virtual cognitive-motor intervention study, indicating that physical exercise stimulates the hypothalamic-pituitary-adrenal axis, thereby increasing cortisol levels and enhancing learning and memory (Luger et al., 1987). Doniger et al. (2018) observed that groups engaged in cognitive-motor training demonstrated increased cerebral blood flow in the prefrontal, middle, and posterior cingulate cortices. This could be indicative of heightened brain activity, even though the motor task was mild, potentially sparking neuroplastic changes given the brain's cognitive reserve (Esiri and Chance, 2012; Chapman et al., 2015). This hypothesis aligns with animal studies demonstrating new neuronal and synaptic connections in advanced age, increased cortical thickness, enhanced brain weight, and changes in blood flow (Mora, 2013). Contrastingly, groups engaged solely in motor exercise exhibited changes in the hippocampus without modifications in cerebrovascular reactivity (Chapman et al., 2016).

Theories of brain plasticity have been at the forefront of recent research (Chiu et al., 2017; Yamada and Sumiyoshi, 2021). The combination of increased cerebral blood flow and its synergistic response on global cognitive function could foster the nervous system's ability to reorganize neuronal activity and function, a process known as neuroplasticity, thereby enhancing cognitive learning (Kwan et al., 2021). Diminished activation of prefrontal areas is linked with greater neural efficiency, while reduced activation of frontoparietal areas suggests improved cognitive performance post-training (Schättin et al., 2016; Vermeij et al., 2017). In a similar vein, Park et al. (2020) asserted that cognitive-motor interventions stimulate brain neurotransmitters, particularly the cholinergic and dopaminergic systems, thereby bolstering concentration and memory in older adults (Hwang et al., 2021; Yang et al., 2022). The literature consistently highlights the impact of physical exercise on cognitive functions, particularly executive functions, due to the release of brain-derived neurotrophic factor and increased hippocampal blood flow, both of which result in favorable metabolic effects (Liao et al., 2020).

4.3. Implications for practice

Traditional cognitive tests, primarily pencil-and-paper based, have received criticism for their inherent limitations, including the omission of key factors such as an individual's education level (Kessels, 2019; Palacios-Navarro et al., 2022). However, the emergence of VR and ecological momentary assessments through wearable devices present innovative alternatives capable of enhancing precision and sensitivity in cognitive assessments (Chan et al., 2018; Hartle et al., 2021). These methods not only supplement traditional tests but also pave the way for a new direction in rehabilitation interventions. The landscape of cognitive treatment methodologies is evolving, with both traditional and VR-based techniques demonstrating efficacy. Both conventional cognitive training programs and VR-based interventions have induced improvements in cognition and executive functions among older adults. Specifically, VR interventions shine in their capacity to simulate ADLs, thereby emerging as a promising tool for cognitive rehabilitation in early stage cognitive disorders (Wollesen et al., 2020; Matsangidou et al., 2023).

Immersive VR offers a stimulating and engaging experience for seniors, enhancing their motivation and enjoyment. Besides its adaptability and high level of automation, these features can alleviate the workload for caregivers and medical professionals (Bauer and Andringa, 2020). Immersive VR also fosters a sense of autonomy in older adults, which is vital for their emotional and cognitive wellbeing. The current review and recent studies suggest that older adults can tolerate and significantly benefit from immersive VR regarding cognitive and physical health (Yi et al., 2022; Matsangidou et al., 2023), as highlighted by Słyk et al. (2019) in their systematic review. However, it is of utmost importance to tailor these interventions to the individual needs and capabilities of participants, necessitating adjustments in task difficulty, session duration, and supervision during training.

Virtual reality, particularly when simulating iADLs, is carving a niche in cognitive-motor rehabilitation (Arlati et al., 2017). Such training programs are well received by patients and can be applied across various clinical environments, including community centers and senior care facilities (Kwan et al., 2021). Patient safety is paramount, requiring careful evaluation before inclusion in these programs and vigilant monitoring for symptoms of VR-induced dizziness post-training (Kwan et al., 2021). VR exhibits significant flexibility in its implementation, suitable for a range of clinical contexts from neurology clinics and rehabilitation centers to home care settings (McDaniel et al., 2014). Successful implementation, however, hinges on the availability of appropriate equipment and trained personnel. In conclusion, VR holds immense potential to revolutionize the treatment of cognitive disorders, offering a personalized and motivating approach to rehabilitation.

4.4. Future implications

When designing future studies that utilize iADL-m based VR interventions, it is imperative to consider the sociodemographic characteristics of participants. Factors such as age, education level, family history, and cognitive disorders should be accounted for, as these variables could potentially influence the results. Moreover, interventions need to be tailored to each participant's physical condition to avoid injury or loss of motivation. To this end, maintaining a heart rate between 50 and 75% of the maximum is suggested, which some may perceive as moderately intense. Notably, most participants in the reviewed studies were primary-educated women, highlighting the need to consider these variables when designing effective interventions for older adults.

The duration of interventions also requires careful consideration. The systematic review conducted by Kelly et al. (2014) evaluated training and cognitive stimulation in older adults and their influence on cognition and daily functioning. They identified that studies lasting at least 10 sessions and whose exercises are adapted to the conditions of the population using level advancements or hints have higher skill maintenance effects. It is important to consider that a high number of sessions could generate a repeated learning effect that promotes disinterest and unreliable results, as mentioned by Cooley et al. (2015). Furthermore, McDaniel et al. (2014) suggested that, although aerobic exercise can enhance certain tasks, repeating the same exercise for an extended period might decrease interest and motivation.

In terms of experimental design aimed at improving cognitive and physical health, the inclusion of an active control group is recommended for more accurate comparisons. It is also important for participants to follow similar training routines, either through comparable interactive applications or by conducting physical and cognitive exercises at home using accessible interactive headsets. Ensuring that the application is specially designed for the study population and adapts the difficulty levels to each individual's characteristics is crucial. Strategies such as incorporating clues or positive feedback in the systems, as suggested by Arlati et al. (2017), can help maintain participants' motivation. In the same vein, including distractors, like presenting several brands of the same product in a simulated supermarket task, can test the participants' concentration. However, it is essential to consistently use and position the same elements to prevent information bias (Arlati et al., 2017).

As mentioned by Wollesen et al. (2020), traditional interventions that combine cognitive and motor aspects, along with technology-based exercise games, have shown favorable impacts on general cognition and inhibitory capacity in older adults. However, due to the heterogeneity of studies concerning interventions, measurements, and results, caution is needed when interpreting these results. Future research may explore the benefits and challenges of a hybrid approach that combines "pencil and paper" activities with an exercise program, enhanced by interactive technology. Some proposals have suggested a training program that merges both real and virtual environments (Foloppe et al., 2018). This approach could potentially be replicated in a more diverse and representative sample. These integrated approaches have the potential to optimize cognitive and physical outcomes in older adults by leveraging the benefits of conventional therapies–which are accessible, affordable, easy to use, and clinically validated–and the personalization and motivation offered by interactive-based interventions.

By considering the unique needs and capabilities of older individuals, comprehensive interventions that combine physical and cognitive exercises can be developed. This holistic approach optimizes the potential for cognitive function improvement, promotes independence, and enhances older adults' overall quality of life. In particular, new technologies can supplement unsupervised home training methods, providing older individuals with a handy tool for conducting appropriate training sessions independently. By offering immersive and stimulating experiences, interactive technology can boost older adults' motivation and engagement, which may, in turn, positively impact their training outcomes and quality of life.

5. Conclusion

This review provides compelling evidence that iADL-based VR cognitive-motor interventions can notably enhance both cognitive function and motor skills in individuals with Mild Cognitive Impairment (MCI) and dementia. These interventions hold significant promise, particularly in enhancing independence, functional ability in ADL, cognitive functions, and reducing frailty among older adults. Moreover, these VR-based interventions potentially offer a more engaging and motivational alternative to conventional therapies, which could improve treatment adherence and outcomes.

The literature suggests that the relationship between cognitive exercise and motor functions is bidirectional–cognitive training can positively impact motor performance, and conversely, motor training can have beneficial effects on cognitive function. Moreover, practicing specific activities can enhance coordination skills in dual tasks, contributing to the training of divided attention and cognitive flexibility. Thus, VR cognitive-motor interventions centered on iADLs can effectively aid in the transfer of acquired skills to the performance of daily activities. However, the choice of the appropriate intervention should be tailored to each individual, considering their needs, personal goals, and physical and motor conditions. Combining physical and cognitive training may yield slightly better results than training these areas separately. Nonetheless, further research is needed to deepen our understanding of how each training type affects different cognitive domains.

Author contributions

JB and GP-N contributed to conception, design of the study, and wrote the first draft of the manuscript. JB organized the database. Both authors contributed to manuscript revision, read, and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abellan Van Kan, G., Rolland, Y., Andrieu, S., Bauer, J., Beauchet, O., Bonnefoy, M., et al. (2009). Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling older people an International Academy on Nutrition and Aging (IANA) task force. *J. Nutr. Health Aging* 13, 881–889. doi: 10.1007/s12603-009-0246-z

Appel, L., Appel, E., Bogler, O., Wiseman, M., Cohen, L., Ein, N., et al. (2020). Older adults with cognitive and/or physical impairments can benefit from immersive virtual reality experiences: A feasibility study. *Front. Med.* 6:329. doi: 10.3389/fmed.2019.00329

Arlati, S., Zangiacomi, A., Greci, L., Di Santo, S. G., Franchini, F., and Sacco, M. (2017). "Virtual environments for cognitive and physical training in elderly with mild cognitive impairment: A pilot study," in *Paper presented by Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, Cham.

Bahureksa, L., Najafi, B., Saleh, A., Sabbagh, M., Coon, D., Mohler, M. J., et al. (2016). The impact of mild cognitive impairment on gait and balance: A systematic review and meta-analysis of studies using instrumented assessment. *Gerontology* 63, 67–83. doi: 10.1159/000445831

Baig, M. M., Afifi, S., GholamHosseini, H., and Mirza, F. (2019). A systematic review of wearable sensors and IOT-based monitoring applications for older adults – a focus on ageing population and independent living. *J. Med. Syst.* 43:233. doi: 10.1007/s10916-019-1365-7

Baragash, R. S., Aldowah, H., and Ghazal, S. (2022). Virtual and augmented reality applications to improve older adults' quality of life: A systematic mapping review and future directions. *Digital Health* 8:205520762211320. doi: 10.1177/20552076221132099

Bauer, A. C. M., and Andringa, G. (2020). The Potential of Immersive Virtual Reality for Cognitive Training in Elderly. *Gerontology* 66, 614–623. doi: 10.1159/000509830

Beltz, S., Gloystein, S., Litschko, T., Laag, S., and van den Berg, N. (2022). Multivariate analysis of independent determinants of ADL/IADL and quality of life in the elderly. *BMC Geriatr.* 22:894. doi: 10.1186/s12877-022-03621-3

Bernini, S., Alloni, A., Panzarasa, S., Picascia, M., Quaglini, S., Tassorelli, C., et al. (2019). A computer-based cognitive training in Mild Cognitive Impairment in Parkinson's Disease. *Neurorehabilitation* 44, 555–567. doi: 10.3233/NRE-192714

Cameirão, M. S., Faria, A. L., Paulino, T., Alves, J., and BermúdezBadia, S. (2016). The impact of positive, negative and neutral stimuli in a virtual reality cognitivemotor rehabilitation task: A pilot study with stroke patients. *J. Neuroeng. Rehabil.* 13, 1–15. doi: 10.1186/s12984-016-0175-0

Chan, J. Y. C., Kwong, J. S. W., Wong, A., Kwok, T. C. Y., and Tsoi, K. K. F. (2018). Comparison of computerized and paper-and-pencil memory tests in detection of mild cognitive impairment and dementia: A systematic review and meta-analysis of diagnostic studies. *J. Am. Med. Dir. Assoc.* 19, 748–756.e5. doi: 10.1016/j.jamda.2018.05.010

Chapman, S. B., Aslan, S., Spence, J. S., Hart, J. J., Bartz, E. K., Didehbani, N., et al. (2015). Neural mechanisms of brain plasticity with complex cognitive training in healthy seniors. *Cereb. Cortex* 25, 396–405. doi: 10.1093/cercor/bht234

Chapman, S. B., Aslan, S., Spence, J. S., Keebler, M. W., DeFina, L. F., Didehbani, N., et al. (2016). Distinct brain and behavioral benefits from cognitive vs. Physical training: A randomized trial in aging adults. *Front. Hum. Neurosci.* 10:338. doi: 10.3389/fnhum.2016.00338

Chiu, H. L., Chu, H., Tsai, J. C., Liu, D., Chen, Y. R., Yang, H. L., et al. (2017). The effect of cognitive-based training for the healthy older people: A meta-analysis of randomized controlled trials. *PLoS One* 12:e0176742. doi: 10.1371/journal.pone.0176742

Cooley, S. A., Heaps, J. M., Bolzenius, J. D., Salminen, L. E., Baker, L. M., Scott, S. E., et al. (2015). Longitudinal change in performance on the montreal cognitive assessment in older adults. *Clin. Neuropsychol.* 29, 824–835. doi: 10.1080/13854046.2015.1087596

Cornelis, E., Gorus, E., Van Schelvergem, N., and De Vriendt, P. (2019). The relationship between basic, instrumental, and advanced activities of daily living and executive functioning in geriatric patients with neurocognitive disorders. *Int. J. Geriatr. Psychiatry* 34, 889–899. doi: 10.1002/gps.5087

Cristofori, I., Cohen-Zimerman, S., and Grafman, J. (2019). Executive functions. *Handb. Clin. Neurol.* 163, 197–219. doi: 10.1016/B978-0-12-804281-6.00011-2

Dahlin, E., Nyberg, L., Bäckman, L., and Neely, A. S. (2008). Plasticity of Executive Functioning in Young and Older Adults: Immediate Training Gains, Transfer, and Long-Term Maintenance. *Psychol. Aging* 23, 720–730. doi: 10.1037/a0014296

Doniger, G. M., Beeri, M. S., Bahar-Fuchs, A., Gottlieb, A., Tkachov, A., Kenan, H., et al. (2018). Virtual reality-based cognitive-motor training for middle-aged adults at high Alzheimer's disease risk: A randomized controlled trial. *Alzheimer Dement.* 4, 118–129. doi: 10.1016/j.trci.2018.02.005

Duan-Porter, W., Vo, T. N., Ullman, K., Langsetmo, L., Strotmeyer, E. S., Taylor, B. C., et al. (2019). Hospitalization-associated change in gait speed and risk of functional limitations for older adults. *J. Gerontol. Series A Biol. Sci. Med. Sci.* 74, 1657–1663. doi: 10.1093/gerona/glz027

Edwards, J. D., Xu, H., Clark, D., Ross, L. A., and Unverzagt, F. W. (2016). S2-01-02: The Active Study: what we Have Learned and what is Next? Cognitive Training Reduces Incident Dementia Across Ten Years. *Alzheimer Dement.* 12, 212–212. doi: 10.1016/j.jalz.2016.06.373

Elliott, M. L., Belsky, D. W., Knodt, A. R., Ireland, D., Melzer, T. R., Poulton, R., et al. (2021). Brain-age in midlife is associated with accelerated biological aging and cognitive decline in a longitudinal birth cohort. *Mol. Psychiatry* 26, 3829–3838. doi: 10.1038/s41380-019-0626-7

Elosúa, M. R., Ciudad, M. J., and Contreras, M. J. (2021). Executive-function tasks in patients with mild cognitive impairment and Alzheimer's Disease: Effects of decline and gender. *Appl. Neuropsychol.* doi: 10.1080/23279095.2021.1961142 [Epub ahead of print].

Esiri, M. M., and Chance, S. A. (2012). Cognitive reserve, cortical plasticity and resistance to Alzheimer's disease. *Alzheimer Res. Therapy* 4:7. doi: 10.1186/alzrt105

Foloppe, D. A., Richard, P., Yamaguchi, T., Etcharry-Bouyx, F., and Allain, P. (2018). The potential of virtual reality-based training to enhance the functional autonomy of Alzheimer's disease patients in cooking activities: A single case study. *Neuropsychol. Rehabil.* 28, 709–733. doi: 10.1080/09602011.2015.1094394

Fukui, T., and Lee, E. (2009). Visuospatial function is a significant contributor to functional status in patients with Alzheimr's disease. *Am. J. Alzheimer Dis. Other Dement.* 24, 313–321. doi: 10.1177/1533317509333903

Galle, S. A., Deijen, J. B., Milders, M. V., De Greef, M. H. G., Scherder, E. J. A., van Duijn, C. M., et al. (2023). The effects of a moderate physical activity intervention on physical fitness and cognition in healthy elderly with low levels of physical activity: a randomized controlled trial. *Alzheimer Res. Therapy* 15:12. doi: 10.1186/s13195-022-01123-3

Galle, S. A., Liu, J., Bonnechère, B., Amin, N., Milders, M. M., Deijen, J. B., et al. (2022). The long-term relation between physical activity and executive function in the Rotterdam Study. *Eur. J. Epidemiol.* 38, 71–81. doi: 10.1007/s10654-022-00902-4

Gao, Y., Ma, L., Lin, C., Zhu, S., Yao, L., Fan, H., et al. (2021). Effects of Virtual Reality-Based Intervention on Cognition, Motor Function, Mood, and Activities of Daily Living in Patients With Chronic Stroke: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. *Front. Aging Neurosci.* 13:866. doi: 10.3389/fnagi.2021.766525

Gao, Z., Lee, J. E., McDonough, D. J., and Albers, C. (2020). Virtual Reality Exercise as a Coping Strategy for Health and Wellness Promotion in Older Adults during the COVID-19 Pandemic. *J. Clin. Med.* 9:1986. doi: 10.3390/jcm9061986

Goldstein, L. H., and McNeil, J. E. (2012). *Clinical Neuropsychology: A Practical Guide to Assessment and Management for Clinicians.* Hoboken, NJ: John Wiley & Sons.

Hartle, L., Mendes-Santos, L., Barbosa, E., Balboni, G., and Charchat-Fichman, H. (2021). Evidence of the validity of a novel version of the computerized cognitive screening battery CompCog. *Dement. Neuropsychol.* 15, 485–496. doi: 10.1590/1980-57642021dn15-040010

Healy, A. F., Wohldmann, E. L., Parker, J. T., and Bourne, L. E. (2005). Skill training, retention, and transfer: The effects of a concurrent secondary task. *Memory Cogn.* 33, 1457–1471. doi: 10.3758/BF03193378

Herold, F., Hamacher, D., Schega, L., and Müller, N. G. (2018). Thinking while moving or moving while thinking - concepts of motor-cognitive training for cognitive performance enhancement. *Front. Aging Neurosci.* 10:228. doi: 10.3389/fnagi.2018.00228

Hülür, G., and Macdonald, B. (2020). Rethinking social relationships in old age: Digitalization and the social lives of older adults. *Am. Psychol.* 75, 554–566. doi: 10.1037/amp0000604

Hwang, N.-K., Choi, J.-B., Choi, D.-K., Park, J.-M., Hong, C.-W., Park, J.-S., et al. (2021). Effects of semi-immersive virtual reality-based cognitive training combined with locomotor activity on cognitive function and gait ability in community-dwelling older adults. *Healthcare* 9:814. doi: 10.3390/healthcare9070814

Joubert, C., and Chainay, H. (2018). Aging brain: The effect of combined cognitive and physical training on cognition as compared to cognitive and physical training alone – A systematic review. *Clin. Interv. Aging* 13, 1267–1301. doi: 10.2147/CIA.S165399

Kelly, M. E., Loughrey, D., Lawlor, B. A., Robertson, I. H., Walsh, C., and Brennan, S. (2014). The impact of cognitive training and mental stimulation on cognitive and everyday functioning of healthy older adults: A systematic review and meta-analysis. *Ageing Res. Rev.* 15, 28–43. doi: 10.1016/j.arr.2014.02.004

Kessels, R. P. C. (2019). Improving precision in neuropsychological assessment: Bridging the gap between classic paper-and-pencil tests and paradigms from cognitive neuroscience. *Clin. Neuropsychol.* 33, 357–368. doi: 10.1080/13854046.2018.1518489

Khan, M. J., Kannan, P., Wong, T. W. L., Fong, K. N. K., and Winser, S. J. (2022). A Systematic Review Exploring the Theories Underlying the Improvement of Balance and Reduction in Falls Following Dual-Task Training among Older Adults. *Int. J. Environ. Res. Public Health* 19:16890. doi: 10.3390/ijerph192416890

Kwan, R. Y. C., Liu, J. Y. W., Fong, K. N. K., Qin, J., Leung, P. K. Y., Sin, O. S. K., et al. (2021). Feasibility and effects of virtual reality motor-cognitive training in community-dwelling older people with cognitive frailty: Pilot randomized controlled trial. *JMIR Ser. Games* 9, e28400. doi: 10.2196/28400

Lauenroth, A., Ioannidis, A. E., and Teichmann, B. (2016). Influence of combined physical and cognitive training on cognition: A systematic review. *BMC Geriatr.* 16:141. doi: 10.1186/s12877-016-0315-1

Leisman, G., Moustafa, A. A., and Shafir, T. (2016). Thinking, Walking, Talking: Integratory Motor and Cognitive Brain Function. *Front. Public Health* 4:94. doi: 10.3389/fpubh.2016.00094

Liao, Y. Y., Hsuan Chen, I., Lin, Y. J., Chen, Y., and Hsu, W. C. (2019). Effects of virtual reality-based physical and cognitive training on executive function and dual-task gait performance in older adults with mild cognitive impairment: A randomized control trial. *Front. Aging Neurosci.* 10:162. doi: 10.3389/fnagi.2019.00162

Liao, Y. Y., Tseng, H. Y., Lin, Y. J., Wang, C. J., and Hsu, W. C. (2020). Using virtual reality-based training to improve cognitive function, instrumental activities of daily living and neural efficiency in older adults with mild cognitive impairment. *Eur. J. Phys. Rehabil. Med.* 56, 47–57. doi: 10.23736/S1973-9087.19.05899-4

Luger, A., Deuster, P. A., Kyle, S. B., Gallucci, W. T., Montgomery, L. C., Gold, P. W., et al. (1987). Acute Hypothalamic–Pituitary–Adrenal Responses to the Stress of Treadmill Exercise. *N. Engl. J. Med.* 316, 1309–1315. doi: 10.1056/nejm198705213162105

Matsangidou, M., Solomou, T., Frangoudes, F., Ioannou, K., Theofanous, P., Papayianni, E., et al. (2023). Affective Out-World Experience via Virtual Reality for Older Adults Living with Mild Cognitive Impairments or Mild Dementia. *Int. J. Environ. Res. Public Health* 20:2919. doi: 10.3390/ijerph20042919

McDaniel, M. A., Binder, E. F., Bugg, J. M., Waldum, E. R., Dufault, C., Meyer, A., et al. (2014). Effects of cognitive training with and without aerobic exercise on cognitively demanding everyday activities. *Psychol. Aging* 29, 717–730. doi: 10.1037/a0037363

Mora, F. (2013). Successful brain aging: Lasticity, environmental enrichment, and lifestyle. *Dial. Clin. Neurosci.* 15, 45–52. doi: 10.31887/dcns.2013.15.1/fmora

Mrakic-Sposta, S., Di Santo, S. G., Franchini, F., Arlati, S., Zangiacomi, A., Greci, L., et al. (2018). Effects of combined physical and cognitive virtual reality-based training on cognitive impairment and oxidative stress in MCI patients: A pilot study. *Front. Aging Neurosci.* 10:282. doi: 10.3389/fnagi.2018.00282

Muir, S. W., Speechley, M., Wells, J., Borrie, M., Gopaul, K., and Montero-Odasso, M. (2012). Gait assessment in mild cognitive impairment and Alzheimer's disease: The effect of dual-task challenges across the cognitive spectrum. *Gait Post.* 35, 96–100. doi: 10.1016/j.gaitpost.2011.08.014

Murman, D. L. (2015). The impact of age on cognition. *Semin. Hear.* 36, 111–121. doi: 10.1055/s-0035-1555115

Oosterman, J. M., Jansen, M. G., Scherder, E. J. A., and Kessels, R. P. C. (2021). Cognitive reserve relates to executive functioning in the old–old. *Aging Clin. Exp. Res.* 33, 2587–2592. doi: 10.1007/s40520-020-01758-y

Osoba, M. Y., Rao, A. K., Agrawal, S. K., and Lalwani, A. K. (2019). Balance and gait in the elderly: A contemporary review. *Laryngosc. Investig. Otolaryngol.* 4, 143–153. doi: 10.1002/lio2.252

Palacios-Navarro, G., Albiol-Pérez, S., and García-Magariño García, I. (2016). Effects of sensory cueing in virtual motor rehabilitation. A review. *J. Biomed. Inform.* 60, 49–57. doi: 10.1016/j.jbi.2016.01.006

Palacios-Navarro, G., Buele, J., Gimeno Jarque, S., and Bronchal García, A. (2022). Cognitive Decline Detection for Alzheimer's Disease Patients Through an Activity of Daily Living (ADL). *IEEE Trans. Neural Syst. Rehabil. Eng.* 30, 2225–2232. doi: 10.1109/TNSRE.2022.3196435

Papaioannou, T., Voinescu, A., Petrini, K., and Stanton Fraser, D. (2022). Efficacy and moderators of virtual reality for cognitive training in people with dementia and mild cognitive impairment: a systematic review and meta-analysis. *J. Alzheimer Dis.* 88, 1341–1370. doi: 10.3233/JAD-210672

Park, J. S., Jung, Y. J., and Lee, G. (2020). Virtual reality-based cognitive–motor rehabilitation in older adults with mild cognitive impairment: A randomized controlled study on motivation and cognitive function. *Healthcare* 8, 1–9. doi: 10.3390/healthcare8030335

Pichierri, G., Coppe, A., Lorenzetti, S., Murer, K., and de Bruin, E. D. (2012). The effect of a cognitive-motor intervention on voluntary step execution under single and dual task conditions in older adults: A randomized controlled pilot study. *Clin. Interv. Aging* 7, 175–184. doi: 10.2147/CIA.S32558

Pichierri, G., Wolf, P., Murer, K., and De Bruin, E. D. (2011). Cognitive and cognitive-motor interventions affecting physical functioning: A systematic review. *BMC Geriatr.* 11:29. doi: 10.1186/1471-2318-11-29

Raichlen, D. A., Bharadwaj, P. K., Nguyen, L. A., Franchetti, M. K., Zigman, E. K., Solorio, A. R., et al. (2020). Effects of simultaneous cognitive and aerobic exercise training on dual-task walking performance in healthy older adults: Results from a pilot randomized controlled trial. *BMC Geriatr.* 20:83. doi: 10.1186/s12877-020-1484-5

Rizzo, M., Reinach, S., McGehee, D., and Dawson, J. (1997). Simulated car crashes and crash predictors in drivers with alzheimer disease. *Arch. Neurol.* 54, 545–551. doi: 10.1001/archneur.1997.00550170027011

Ross, L. A., Edwards, J. D., O'Connor, M. L., Ball, K. K., Wadley, V. G., and Vance, D. E. (2016). The transfer of cognitive speed of processing training to older adults' driving mobility across 5 years. *J. Gerontol. Series B Psychol. Sci. Soc. Sci.* 71, 87–97. doi: 10.1093/geronb/gbv022

Rosso, A. L., Metti, A. L., Faulkner, K., Redfern, M., Yaffe, K., Launer, L., et al. (2019). Complex Walking Tasks and Risk for Cognitive Decline in High Functioning Older Adults. *J. Alzheimer Dis.* 71, S65–S73. doi: 10.3233/JAD-181140

Sato, N. (2017). "Memory processing in the nervous system," in *Advanced Information and Knowledge Processing*, ed. A. Schuster (Cham: Springer), doi: 10.1007/978-3-319-59090-5_5

Schättin, A., Arner, R., Gennaro, F., and de Bruin, E. D. (2016). Adaptations of prefrontal brain activity, executive functions, and gait in healthy elderly following exergame and balance training: A randomized-controlled study. *Front. Aging Neurosci.* 8:278. doi: 10.3389/fnagi.2016.00278

Schoene, D., Valenzuela, T., Lord, S. R., and De Bruin, E. D. (2014). The effect of interactive cognitive-motor training in reducing fall risk in older people: A systematic review. *BMC Geriatr.* 14:107. doi: 10.1186/1471-2318-14-107

Schubert, T., Liepelt, R., Kübler, S., and Strobach, T. (2017). Transferability of dual-task coordination skills after practice with changing component tasks. *Front. Psychol.* 8:956. doi: 10.3389/fpsyg.2017.00956

Sherrington, C., Fairhall, N. J., Wallbank, G. K., Tiedemann, A., Michaleff, Z. A., Howard, K., et al. (2019). Exercise for preventing falls in older people living in the community. *Cochrane Database Syst. Rev.* 1:CD012424. doi: 10.1002/14651858.CD012424.pub2

Słyk, S., Zarzycki, M. Z., Kocwa-Karnaś, A., and Domitrz, I. (2019). Virtual reality in the diagnostics and therapy of neurological diseases. *Expert Rev. Med. Dev.* 16, 1035–1040. doi: 10.1080/17434440.2019.1693892

Stanmore, E. K., Mavroeidi, A., De Jong, L. D., Skelton, D. A., Sutton, C. J., Benedetto, V., et al. (2019). The effectiveness and cost-effectiveness of strength and balance Exergames to reduce falls risk for people aged 55 years and older in UK assisted living facilities: A multi-centre, cluster randomised controlled trial. *BMC Med.* 17:49. doi: 10.1186/s12916-019-1278-9

Thapa, N., Park, H. J., Yang, J.-G., Son, H., Jang, M., Lee, J., et al. (2020). The Effect of a Virtual Reality-Based Intervention Program on Cognition in Older Adults with Mild Cognitive Impairment: A Randomized Control Trial. *J. Clin. Med.* 9:1283. doi: 10.3390/jcm9051283

Tornero-Quiñones, I., Sáez-Padilla, J., Espina Díaz, A., Abad Robles, M. T., and Sierra Robles, Á (2020). Functional Ability, Frailty and Risk of Falls in the Elderly: Relations with Autonomy in Daily Living. *Int. J. Environ. Res. Public Health* 17:1006. doi: 10.3390/ijerph17031006

Torpil, B., Azahin, S., Pekçetin, S., and Uyanlk, M. (2021). The effectiveness of a virtual reality-based intervention on cognitive functions in older adults with mild cognitive impairment: A Single-blind, randomized controlled trial. *Games Health J.* 10, 109–114. doi: 10.1089/g4h.2020.0086

Tromp, D., Dufour, A., Lithfous, S., Pebayle, T., and Després, O. (2015). Episodic memory in normal aging and Alzheimer disease: Insights from imaging and behavioral studies. *Ageing Res. Rev.* 24, 232–262. doi: 10.1016/j.arr.2015.08.006

van Leeuwen, K. M., van Loon, M. S., van Nes, F. A., Bosmans, J. E., de Vet, H. C. W., Ket, J. C. F., et al. (2019). What does quality of life mean to older adults? A thematic synthesis. *PLoS One* 14:e0213263. doi: 10.1371/journal.pone.0213263

Van Schooten, K. S., Freiberger, E., Sillevis Smitt, M., Keppner, V., Sieber, C., Lord, S. R., et al. (2019). Concern about falling is associated with gait speed, independently from physical and cognitive function. *Phys. Therapy* 99, 989–997. doi: 10.1093/ptj/pzz032

Varela-Aldás, J., Buele, J., Amariglio, R., García-Magariño, I., and Palacios-Navarro, G. (2022). The cupboard task: An immersive virtual reality-based system for everyday memory assessment. *Int. J. Hum. Comput. Stud.* 167:102885. doi: 10.1016/j.ijhcs.2022.102885

Vermeij, A., Kessels, R. P. C., Heskamp, L., Simons, E. M. F., Dautzenberg, P. L. J., and Claassen, J. A. H. R. (2017). Prefrontal activation may predict working-memory training gain in normal aging and mild cognitive impairment. *Brain Imag. Behav.* 11, 141–154. doi: 10.1007/s11682-016-9508-7

Waddington, E. E., and Heisz, J. J. (2023). Orienteering experts report more proficient spatial processing and memory across adulthood. *PLoS One* 18:e0280435. doi: 10.1371/journal.pone.0280435

Weintraub, S., Wicklund, A. H., and Salmon, D. P. (2012). The Neuropsychological Profile of Alzheimer Disease. *Cold Spring Harb. Perspect. Med* 2:a006171. doi: 10.1101/cshperspect.a006171

Wildenbos, G. A., Jaspers, M. W. M., Schijven, M. P., and Dusseljee- Peute, L. W. (2019). Mobile health for older adult patients: Using an aging barriers framework to classify usability problems. *Int. J. Med. Inform.* 124, 68–77. doi: 10.1016/j.ijmedinf.2019.01.006

Wollesen, B., Wildbredt, A., Van Schooten, K. S., Lim, M. L., and Delbaere, K. (2020). The effects of cognitive-motor training interventions on executive functions in older people: A systematic review and meta-analysis. *Eur. Rev. Aging Phys. Act.* 17:9. doi: 10.1186/s11556-020-00240-y

Yamada, Y., and Sumiyoshi, T. (2021). Neurobiological mechanisms of transcranial direct current stimulation for psychiatric disorders; neurophysiological, chemical, and anatomical considerations. *Front. Hum. Neurosci.* 15:631838. doi: 10.3389/fnhum.2021.631838

Yang, J. G., Thapa, N., Park, H. J., Bae, S., Park, K. W., Park, J. H., et al. (2022). Virtual reality and exercise training enhance brain, cognitive, and physical health in older adults with mild cognitive impairment. *Int. J. Environ. Res. Public Health* 19:13300. doi: 10.3390/ijerph192013300

Yi, Y., Hu, Y., Cui, M., Wang, C., and Wang, J. (2022). Effect of virtual reality exercise on interventions for patients with Alzheimer's disease: A systematic review. *Front. Psychiatry* 13:1062162. doi: 10.3389/fpsyt.2022.1062162

Yue, C., Zhang, Y., Jian, M., Herold, F., Yu, Q., Mueller, P., et al. (2020). Differential effects of Tai Chi Chuan (Motor-Cognitive Training) and walking on brain networks: A resting-state fMRI study in Chinese Women Aged 60. *Healthcare* 8:67. doi: 10.3390/healthcare8010067

Zhang, W., Low, L. F., Gwynn, J. D., and Clemson, L. (2019). Interventions to improve gait in older adults with cognitive impairment: A systematic review. *J. Am. Geriatr. Soc.* 67, 381–391. doi: 10.1111/jgs.15660

Zhu, S., Sui, Y., Shen, Y., Zhu, Y., Ali, N., Guo, C., et al. (2021). Effects of virtual reality intervention on cognition and motor function in older adults with mild cognitive impairment or dementia: A systematic review and meta-analysis. *Front. Aging Neurosci.* 13:217. doi: 10.3389/fnagi.2021.586999

Zuschnegg, J., Schoberer, D., Häussl, A., Herzog, S. A., Russegger, S., Ploder, K., et al. (2023). Effectiveness of computer-based interventions for community-dwelling people with cognitive decline: a systematic review with meta-analyses. *BMC Geriatr.* 23:229. doi: 10.1186/s12877-023-03941-y

2.6. Artículo: Effects of a dual intervention (motor and virtual reality-based cognitive) on cognition in patients with mild cognitive impairment: a single-blind, randomized controlled trial

Buele *et al. Journal of NeuroEngineering and Rehabilitation* (2024) 21:130
https://doi.org/10.1186/s12984-024-01422-w

Journal of NeuroEngineering and Rehabilitation

RESEARCH **Open Access**

Effects of a dual intervention (motor and virtual reality-based cognitive) on cognition in patients with mild cognitive impairment: a single-blind, randomized controlled trial

Jorge Buele[1,4], Fátima Avilés-Castillo[2,4], Carolina Del-Valle-Soto[3], José Varela-Aldás[2] and Guillermo Palacios-Navarro[4,5*]

Abstract

Background The increase in cases of mild cognitive impairment (MCI) underlines the urgency of finding effective methods to slow its progression. Given the limited effectiveness of current pharmacological options to prevent or treat the early stages of this deterioration, non-pharmacological alternatives are especially relevant.

Objective To assess the effectiveness of a cognitive-motor intervention based on immersive virtual reality (VR) that simulates an activity of daily living (ADL) on cognitive functions and its impact on depression and the ability to perform such activities in patients with MCI.

Methods Thirty-four older adults (men, women) with MCI were randomized to the experimental group ($n=17$; 75.41 ± 5.76) or control ($n=17$; 77.35 ± 6.75) group. Both groups received motor training, through aerobic, balance and resistance activities in group. Subsequently, the experimental group received cognitive training based on VR, while the control group received traditional cognitive training. Cognitive functions, depression, and the ability to perform activities of daily living (ADLs) were assessed using the Spanish versions of the Montreal Cognitive Assessment (MoCA-S), the Short Geriatric Depression Scale (SGDS-S), and the of Instrumental Activities of Daily Living (IADL-S) before and after 6-week intervention (a total of twelve 40-minutes sessions).

Results Between groups comparison did not reveal significant differences in either cognitive function or geriatric depression. The intragroup effect of cognitive function and geriatric depression was significant in both groups ($p < 0.001$), with large effect sizes. There was no statistically significant improvement in any of the groups when evaluating their performance in ADLs (control, $p=0.28$; experimental, $p=0.46$) as expected. The completion rate in the experimental group was higher (82.35%) compared to the control group (70.59%). Likewise, participants in the experimental group reached a higher level of difficulty in the application and needed less time to complete the task at each level.

*Correspondence:
Guillermo Palacios-Navarro
Guillermo.palacios@unizar.es

Full list of author information is available at the end of the article

Conclusions The application of a dual intervention, through motor training prior to a cognitive task based on Immersive VR was shown to be a beneficial non-pharmacological strategy to improve cognitive functions and reduce depression in patients with MCI. Similarly, the control group benefited from such dual intervention with statistically significant improvements.

Trial registration ClinicalTrials.gov NCT06313931; https://clinicaltrials.gov/study/NCT06313931.

Keywords Activities of daily living (ADL), Cognitive rehabilitation, Depression, Mild cognitive impairment (MCI), Motor rehabilitation, Virtual reality

Introducction

In recent decades, the increase in human longevity has been notable, with significant transformations in the physical and cognitive domains of aging that demand in-depth analysis [1]. This phenomenon brings significant transformations in the physical and cognitive aspects associated with aging, which requires detailed analysis [2]. Among the cognitive functions affected are perception, attention, language, memory, executive functions, among others [3]. These cognitive skills are essential for people to perform their routine tasks and maintain normal functioning in their environment [4]. The tasks and routines of daily living are called activities of daily living (ADL) and are essential for self-care and independence [5]. There are 11 activities that are considered instrumental (iADL) [6], since they contemplate a greater complexity than the basic activities of daily living (bADL). The decline in iADL performance becomes increasingly notable as MCI emerges [7], which presents a decline in cognitive functions as part of a human pathological state [8, 9].

MCI, also known as mild neurocognitive disorder [10], involves a decline in cognitive abilities that is more pronounced than expected for the individual's age [11, 12]. Those affected may have difficulties in memory, language, attention and other cognitive functions, but still maintain the ability to carry out daily activities, with less impairment than patients with dementia [13]. However, this review also mentions that cognitive decline is not normal and is a stage prior to the onset of dementia [13], which could generate medical and social repercussions [14]. The risk of MCI and dementia increases in adults over 65 years of age due to exposure to several adverse factors and conditions, including neurodegenerative diseases, dietary changes, and chronic diseases [15, 16]. Furthermore, elements such as gender and ethnicity influence the onset and severity of cognitive impairment [17]. For example, a higher prevalence of diseases such as Alzheimer's Disease (AD) has been observed in women and in certain ethnic groups [18, 19]. Early identification and intervention are critical to slowing or preventing further cognitive decline [20]. Addressing these disorders from their early stages can significantly improve quality of life, helping people manage the emotional and cognitive challenges that arise, such as frustration, anxiety and depression [21].

Depression in the context of neurodegenerative processes presents complex and significant characteristics. The affective disorders can manifest in various ways in patients with neurodegenerative diseases, exacerbating the clinical and emotional challenges of those who experience them. Depression not only affects patients' mood, but can also profoundly influence their cognitive ability, daily functioning, and quality of life [22]. Depressive symptoms may include persistent sadness, lack of interest in previously pleasurable activities, changes in appetite and sleep, as well as feelings of worthlessness or excessive guilt. These symptoms can be difficult to distinguish from the emotional and cognitive changes themselves associated with neurodegeneration, further complicating diagnosis and treatment [23]. From a neurobiological perspective, neurodegenerative processes have been observed to affect brain regions involved in mood regulation, such as the hippocampus and prefrontal cortex [24]. The complex interplay between neuronal degeneration and neurotransmitter systems, such as serotonin and dopamine, may contribute to both depressive symptoms and neurodegenerative disease progression. Comprehensive management of depression in patients with neurodegenerative diseases is crucial, not only to improve the patient's quality of life, but also to optimize cognitive and functional outcomes. Therapeutic strategies that include psychological, pharmacological and rehabilitative interventions may be necessary to adequately address both depressive symptomatology and the specific challenges of the neurodegenerative disease, thus offering a comprehensive and multidisciplinary approach to patient care [25].

Depression is a common comorbidity in people with neurodegenerative disorders, including MCI, often exacerbating cognitive symptoms and affecting overall quality of life. According to the study conducted by Lyketsos et al., depression is one of the neuropsychiatric symptoms that most frequently appear in people diagnosed with AD or MCI [26]. Malhi and Mann [27] mentioned that one out of five individuals experiences an episode of depression during their lifetime, with clinical depression being the third cause of disease burden worldwide according to the World Health Organization (WHO). Additionally, older individuals are more vulnerable to the harmful effects of depression [28, 29]. However, figures reflecting the prevalence of depression in adults present significant variations, influenced by various factors such as the underlying cause, the living environment, the intensity of the disorder, as well as gender and age differences [30–32]. Despite these discrepancies in the figures, it is clear that depression is a common phenomenon in the senile stage, showing a prevalence in depressive disorders [33]. A notable finding is that middle-aged women are almost twice as likely to experience an episode of depression compared to men [34]. This trend continues until advanced age, evidenced by studies such as the one conducted by Curran et al. [28] that indicated that 12% of women present depression as a comorbidity, compared to 8% of men. As Alblooshi et al. indicated, menopause increases vulnerability to depression and anxiety, perhaps through estrogen fluctuations that affect serotonin and gamma-aminobutyric acid (GABA) [35]. Furthermore, decreased estrogen and neurological deterioration after menopause increase women's vulnerability to developing AD [36].

Given this situation, studies have shown that exposure to cognitively and mentally stimulating activities throughout life protects against cognitive decline, and that engaging in these activities in old age is associated with better cognitive function [37]. Lifestyle factors such as exercise, diet, social participation, having a purpose in life, and cognitive activities can reduce the risk of dementia and improve cognitive function [38, 39]. Advances in computer science and information and communication technologies (ICT) have resulted in increased availability and accessibility of computerized cognitive training [40]. The integration of motor activities in therapeutic interventions has been shown to expand functional capacities in individuals. A systematic review conducted by Zhu et al. [41] included 11 randomized controlled trials that showed a moderate impact of VR-based interventions on improving cognitive and motor function. These improvements included aspects such as attention/execution, memory, global cognition and balance in patients with MCI impairment and dementia.

In aging research, VR emerges as a promising approach for dementia treatment in individuals with cognitive impairment [42]. VR immerses users in virtual environments, delivering visual, auditory, and sensory stimuli via a head-mounted display (HMD) [43]. The recent review by Chan et al. [44] indicated that most interventions utilized traditional desktop computers, followed by touchscreen computers and immersive VR, with the latter accounting for only 5.7% of the total. Despite VR technology not being entirely new, there is a pressing need for further expansion in the literature through new implementations. Gao et al. [45] analyzed six VR interventions combined with traditional rehabilitation, showing significant improvements in general cognition, attention, and mood, although not in global cognition, motor function, and ADL. Recently, cognitive-motor applications have been developed using VR to simulate iADL. A recent review [46] demonstrated that VR-based cognitive-motor interventions activate specific brain areas and improve general cognition, executive function, attention, and memory. While significant progress has been made in understanding VR's effects on cognition and physical functioning, there remains a notable gap in knowledge regarding its impact on mental health.

Studies such as those carried out by Liao et al. [47], Mrakic-Sposta et al. [48] and Kwan et al. [49] used VR to simulate iADL, examining the combined benefits of VR on physical and cognitive function. However, they did not evaluate the impact VR could have on mental health. Park et al. [50] simulated hygiene and driving activities using VR, highlighting that it could be used to increase motivation, fun and interest, which would improve feelings of depression and lethargy. Doniger et al. [51] conducted an experiment with a virtual supermarket and concluded that VR could not only delay the onset of depression but also standardize and monitor participants' responses effectively. Liao et al. [52] highlighted the effectiveness of VR in improving ADL performance, although they acknowledged that a significant limitation of their study was the lack of analysis of the impact on depression. These findings highlight the therapeutic potential of VR beyond its physical and cognitive applications, as well as the current limitations in the evaluation of associated variables such as mental health.

All previously presented research analyzing the effects that cognitive and motor VR applications can generate were carried out in high-income countries such as Italy, Taiwan, China, the Republic of Korea and Israel. The literature indicates that cognitive interventions can not only improve cognitive functions but also mitigate depressive symptoms due to the bidirectional relationship between these two domains. However, when analyzing studies that also seek to reduce mental disorders, the trend is similar [53–55]. The concentration of studies in high-income contexts leaves a gap in knowledge about how these interventions could work in regions with different socioeconomic and cultural contexts, such as Latin America (LATAM). This region, composed mostly of upper-middle-income countries, faces unique challenges such as income inequality [56], violence [57], mistreatment of the female gender [58], increased migration and deficiencies in health systems [59, 60].

Increasing life expectancy in the region also implies an increase in the elderly population [61], making the need to develop and adapt effective interventions to improve both cognitive and emotional health even more urgent. The analysis presented by Vigo et al. [62] showed that in South America, investment in mental, neurological and behavioral disorders is lower than the world average. Of the total government budget for the treatment of health conditions, less than 5% is allocated to mental health. This is supported by the literature, where only one VR application was found for detecting Alzheimer's symptoms but none for cognitive training [63]. In 2021, Brito et al. [64] carried out a sensorimotor intervention based on VR to reduce depression and anxiety in older adults, in Talca, Chile. Trueba et al. [65] presented a VR application, where the elderly were subjected to different nature scenes with the aim of reducing anxiety and depression levels in Quito, Ecuador.

In contrast, our study presents a VR system that fuses physical and cognitive training, simulating a daily life activity. Previous studies have demonstrated that this is the first trial that contrasts the effects of a VR-based cognitive-motor training program with an equivalent pencil and paper program, in a Latin American country. Based on recent studies that used VR to simulate iADL, it was hypothesized that the experimental group will have a significant improvement in cognitive functions post-training. However, uncertainty persists regarding its impact on depressive symptoms and the transfer of skills to daily life. Since these variables are considered secondary in the purpose of the study, we hope to generate novel results that can serve as a starting point for future research focused specifically on depression or on the transfer of skills to daily life, exploring the combination of VR with traditional techniques.

Materials and methods

Participants

Recruitment

Participants were recruited at a senior community center day care center for older adults in Patate, Ecuador. The center provides social and recreational services for people over 65 years. The center staff invited participants through advertising posters, in-person conversations and through social networks. Subsequently, the research team selected potential participants according to the proposed eligibility criteria.

Inclusion criteria

The inclusion criteria were: (1) age equal to or greater than 65 years; (2) attend a day care center without being institutionalized in a geriatric center; (3) maintain physical functionality (absence of any disability); (4) ability to understand the purpose of the study and voluntarily agree by signing the consent form; (5) present MCI; (6) have a Montreal Cognitive Assessment (MoCA) score between 19 and 25 points [66].

Exclusion criteria

We excluded patients who presented (1) clinical diagnosis of dementia; (2) probable dementia, with a MoCA score equal to or less than 18 points [66]; (3) neurological disorders, including stroke or traumatic brain injury (TBI) in the past 12 months; (4) history of mental or psychiatric disorders; (5) addiction to medication, drugs or alcohol; (6) difficulties using an HMD and operating the controller equipment; (7) medical conditions that could interfere with effective participation in and completion of the study; (8) visual and/or hearing impairment; (9) communication difficulties.

Ethics

This preliminary study was designed as a randomized controlled trial (RCT) with parallel groups, conducted at a single center and with single blinding. The objectives and requirements of the study were explained in detail to the participants, who voluntarily gave their consent by signing an informed consent form. Ethical approval was obtained from the Institutional Review Board of the Universidad Tecnólogica Indoamérica, under the code UTI-IIDI-074-2023, approval date May 25, 2023, before starting the study. The trial was registered with ClinicalTrials.gov (identifier number NCT06313931) on March 8th, 2024.

Randomization

Once baseline data was collected from all participants, the recruitment team evaluated and developed a list of subjects eligible to participate in the study. For their random assignment into groups, they were given a unique number. An independent research assistant then generated a sequence of random numbers (1 for the control group and 2 for the intervention group), using a spreadsheet. Based on this sequence, one author (FA-C) assigned participants to the respective intervention or control groups. This process ensured concealment of the allocation, thus guaranteeing the integrity of the allocation procedure. The person in charge of evaluating the results did not know which group each participant belonged to. However, it was not feasible to maintain anonymity in group assignment, both for those in charge of applying the interventions and for the participants themselves.

Intervention

Study design

This study used a pre-post experimental design with a control group to evaluate the impact of the VR-based cognitive-motor training program on cognitive function and depression. Older adults over 65 years who voluntarily expressed interest in participating and met the specified selection criteria were recruited. Two interventions were used: motor training and VR-based cognitive training (n=17) and motor training and traditional cognitive training (n=17), through randomization after taking initial measurements. Previous studies involving VR-based cognitive-motor training used similar samples [47, 50–52]. Five participants were excluded from the study, because they stopped attending the senior center (n=4) and one participant lacked of motivation. In the experimental group three participants stopped attending the senior center. Therefore, the study was completed with a sample of 26 older adults (Fig. 1). Considering that the participants returned to their homes, the usual development of other daily activities was not prohibited. The evaluations were carried out before the start of the motor training program based on VR or pencil and paper (baseline) and after the interventions. Both interventions were conducted twice a week for six weeks, and each session lasted approximately 40 min.

Outcome measurements

All training and coaching activities in this study were carried out by researchers with solid knowledge of the subject. To evaluate the effects of the motor-cognitive training programs in both groups, standardized tests were used.

Cognitive function was assessed using the Spanish version of the Montreal Cognitive Assessment (MoCA-S), adapted for use with Spanish-speaking older adults and which was validated in Latin America [67], based on the original MoCA developed by Nasreddine et al. [66]. The evaluation covered attention, verbal fluency, executive functions, short-term memory, visuospatial memory, language, temporal and spatial orientation, and calculations.

Depression was assessed using the Spanish version of the Short Form of Geriatric Depression Scale (SGDS-S), an adaptation designed to assess depression in older adults based on the Geriatric Depression Scale, originally developed by Yesavage et al. [68] and validated in the Ecuadorian population by Erazo et al. [69]. The general emotional state, interest, motivation, perspective, specific concerns and future comparisons were analyzed by means of this scale. The score on the SGDS-S scale ranges from 0 to 15, where a score less than 5 indicates a normal state, whereas a score from 5 to 9 points indicate moderate depression and a higher score indicates moderate to severe depression [69].

Functional ability was assessed using the Spanish version of the iADL scale (IADL-S) was used, an adaptation designed to evaluate the performance of iADL in older adults, validated by Vergara et al. [70]. This test is based on the iADL Scale, originally developed by Lawton and Brody, which is also known as the Philadelphia Geriatric Center-Instrumental Activities Daily Living (PGC-IADL) [71]. Thus, communication, self-care, financial management, mobility, health administration and daily activities were evaluated. Each of the eight items on the scale is coded with a score of 0 (unable or partially capable) or 1 (capable), and responses are summed to obtain a total score. The score range varies from 0 (low function, dependent) to 8 (high function, independent) [71].

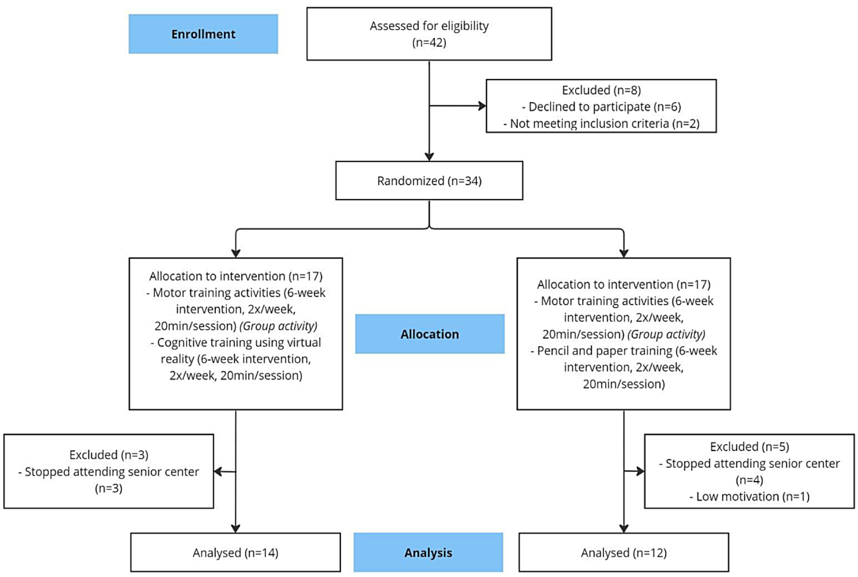


Fig. 1 Consort diagram

Experimental group

The training sessions were carried out in a senior community center. These activities complied with the recommendations of the American College of Sports Medicine and the American Heart Association for the older adult [72]. To stimulate the motor system, collective social interaction activities that included conversations between therapists and participants were carried out, promoting non-verbal language, the exchange of thoughts and jokes. Participants were instructed to actively participate in these conversations, use gestures, and share personal anecdotes to enhance interaction. Balance exercises were then performed such as walking in a straight line, placing one foot directly in front of the other, maintaining coordination. Participants were also instructed to focus on a fixed point ahead and maintain an upright posture to ensure stability. In addition, resistance exercises such as squats were performed, with an effort regulated according to the individual capabilities of each person. Participants were reminded to perform squats slowly, keeping their back straight and knees in line with their toes to avoid injury. Finally, a series of whole-body aerobic exercises were performed, such as brisk walking, an accessible exercise for older adults, going up and down stairs, and social dancing individually and in pairs. They were encouraged to maintain a constant rhythm and coordinate their movements with the rhythm of the music during social dancing.

Subsequently, individual cognitive training was performed using an immersive VR-based system that simulates a task of searching for ingredients in a kitchen cupboard. It includes an application that uses VR to simulate an instrumental activity of daily life (iADL), which was developed with the Unity game engine. The hardware consisted of the Oculus Quest 2 VR goggles and two wireless handheld controllers that allow interaction with the system. Participants were conveniently instructed on the correct use of the VR googles and holding the controllers. They were guided through the VR environment, with clear instructions on how to select and manipulate virtual objects. Since for some of the participants it was their first experience with VR, each session was supervised by a member of the research team, who also solved any technical problems that arose. Figure 2 depicts the intervention phase.

Figure 3 illustrates the dynamics of this serious game. At the beginning, the participant understands the commands to follow and visualizes the ingredients inside every cupboard compartment (registration and coding phase). The items are automatically and randomly placed inside the shelves and the doors are opened individually, with a learning waiting time set at 10 s (storage and consolidation phase). Finally, the participant locates the ingredients randomly requested, selecting both the door and the desired item (retrieval or evocation phase), for which he/she has 10 s per object or an error will be considered and the task will go on by asking a new question.

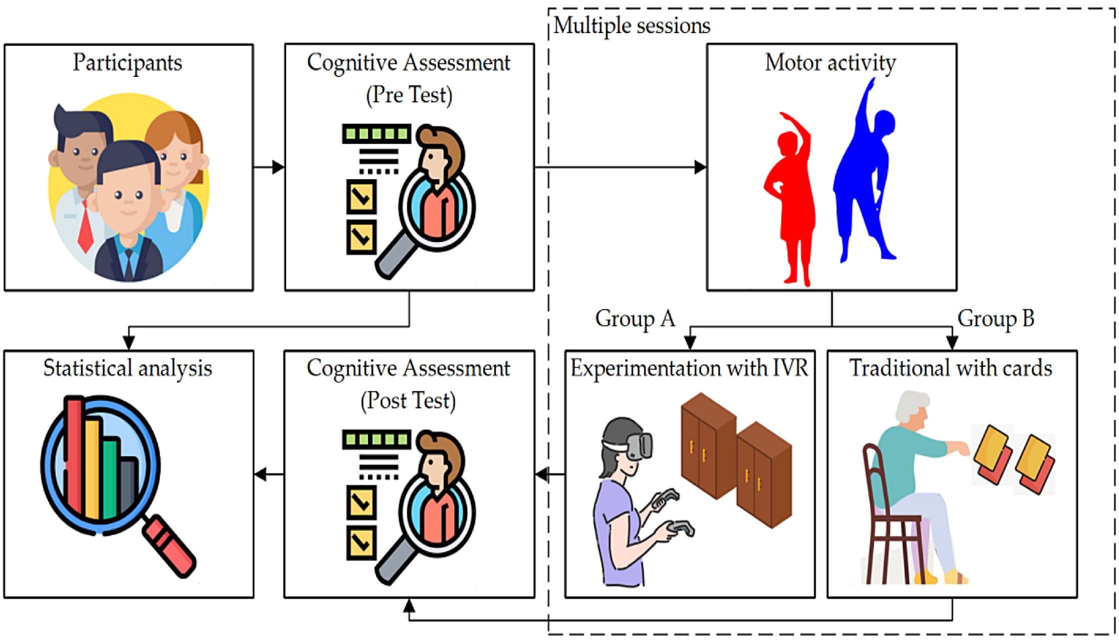


Fig. 2 General description of the intervention phases

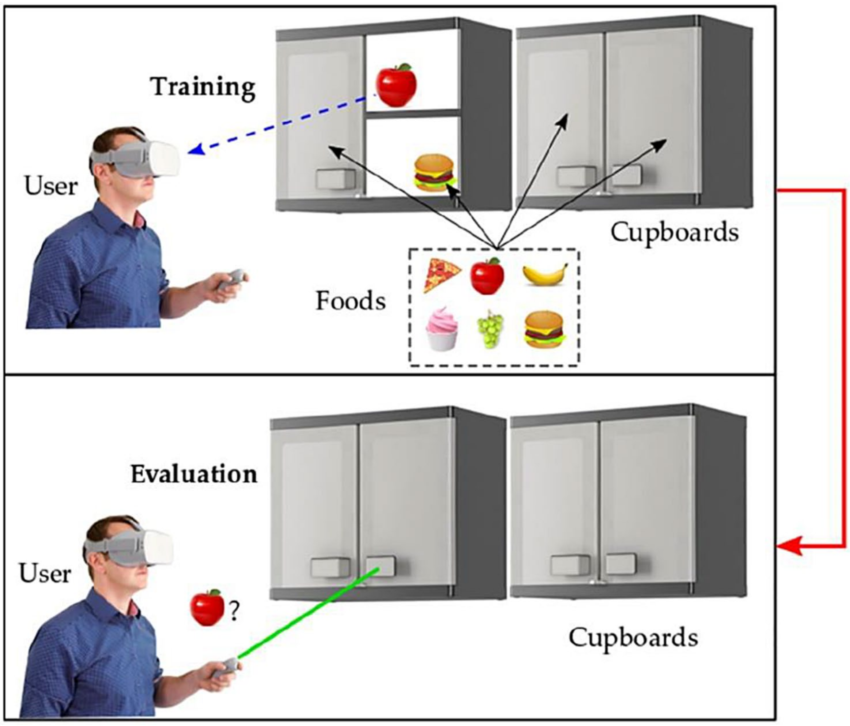


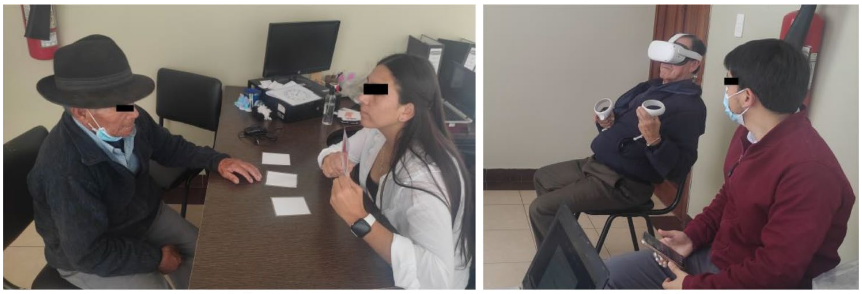
Fig. 3 Cupboard task implemented in the VR application

This task tests various cognitive functions such as visuospatial functions (orientation within the virtual environment), attention (registration phase), working memory (storage phase), executive functions (planning of activities), reaction time (responding within the set time).

Given the population under study, it was considered appropriate to start with level 4, which requests memorizing 4 cooking ingredients. Each participant performed the task twice, to prevent possible fatigue or boredom due to monotony. The randomization in the location of the objects allowed the participants to remain active and avoided biases in the performance results. When the participant completed the activity without any error for two consecutive times, the level was increased, i.e., one more item to memorize. The video game has auditory messages that indicate an error or congratulate the user when he/she found a hit. The goal of this design was to ensure that participants had enough time to learn through repeated practice, while at the same time feeling challenged to increase the level, while maintaining their motivation, through a sense of fun.

Control group

The intervention for the control group was performed under the same conditions as the experimental group maintaining the same sequential design, since the participants of this group also participated in the motor training through social activities, balance, resistance and low intensity aerobic exercises. After that, the individual cognitive training consisted of a task similar to that of the experimental group, but without the use of VR. Cards containing graphical representations of the same cooking ingredients as the virtual application were presented. A member of the research team was in charge of explaining the dynamics of the game to the participants and subsequently delivering the intervention. For 10 s the participant was allowed to memorize the picture of each of the cards and then the card was flipped over. In the recovery phase, the participant was asked to identify which card contained the requested ingredient and to turn it over to check that he/she got it right. Keeping the same instructions, the game started at level four and when the patient had no errors for two consecutive times, the level and therefore the number of elements to memorize increased. Considering that the reaction time could not be collected automatically as in the virtual application, another member of the team was in charge of taking these times with a stopwatch and recording them manually on a card. Like the experimental group, the participants played twice in each session, with the same weekly frequency and for the same total time period. Figure 4 shows some participants



(a) (b)

Fig. 4 Participants performing the pencil and paper task **(a)** and the virtual task **(b)**

developing the task in both groups, together with members of the research team.

Statistical analysis

Data were analyzed with SPSS version 24.0. Descriptive statistics, including mean, standard deviation (SD), were used to summarize the dependent variables within each group. Data normality was assessed with the Shapiro-Wilk's test and homoscedasticity with Levene's test. After checking the assumptions of normality and homoscedasticity, to evaluate the changes in cognitive function and depression status in older adults before and after the interventions, a paired t-test was performed to check within group differences whereas and independent sample t test was used to check for between groups differences. A one-way ANOVA with repeated measures was performed to check for differences in scores in each of the dependent variables at the two moments of time (pre and post intervention). The IADL-S scale data did not follow a normal distribution, so nonparametric tests were used to evaluate differences between measurements. The Wilcoxon signed-rank test (W) was used to analyze within-group changes over time, while the two-tailed Mann-Whitney (MW) test was used to compare differences between groups. As a complementary analysis, the Pearson's correlation was used to analyze the degree of association between the MOCA-S and SGDS-S scores. The relationship between the level of education and the MOCA-S test scores will also be analyzed. The relationship between the level of education and the level achieved in the VR-based cognitive task will be also analyzed for the experimental group. The significance level was set at 0.05.

Results

Baseline data

The mean ages of the control group ($n=17$) and the experimental group ($n=17$) were 77.35±6.75 years (range 65–84 years) and 75.41±5.76 years (range 65–86 years), respectively. In the control group, the majority of the population was women (13/17), while in the experimental group the percentage of women was 58.82% (10/17). The level of education (measured in years) was on average 4.76±3.25 years in the control group and 5.53±3.18 years in the experimental group. In the control group, no one had previous experience using VR, while in the experimental group only one person had previously used VR. Two (11.8%) participants with arthritis were identified in both groups. In the experimental group, two (11.8%) people were observed with thyroid-related problems, prostate problems and diabetes. In the control group, high blood pressure was observed in five (29.4%) participants and in three (17.6%) of the experimental group. In summary, both groups were homogeneous with respect to gender, age, education, VR experience and presence of illnesses, respectively. Table 1 shows the demographic characteristics of the participants.

As far as the results at baseline in MoCA-S, SGDS-S and IADL-S, there were no significant differences between the groups in any of them (see Table 2).

Table 1 Demographic characteristics of the groups

Variables	All ($N=34$)	Control ($n=17$)	Experimental ($n=17$)	*P*-value
Gender, n (%)				0.271*
Male	11 (32.4)	4 (23.5)	7 (41.2)	
Female	23 (67.6)	13 (76.5)	10 (58.8)	
Age, n, SD (range)	76.38, 6.25 (65–86)	77.35, 6.75 (65–86)	75.41, 5.76 (66–84)	0.373
Education, n, SD (range)	5.15, 3.19 (0–12)	4.76, 3.25 (1–12)	5.53, 3.18 (0–12)	0.493
VR experience, n (%)				0.142*
Yes	1 (2.9)	0 (0)	1 (5.9)	
No	33 (97.1)	17 (100)	16 (94.1)	
Number of pre-existing illnesses, n (%)				0.76*
0	19 (55.9)	11 (64.7)	8 (47.1)	
1	10 (29.4)	4 (23.5)	6 (35.3)	
2 or more	5 (14.7)	2 (11.8)	3 (17.6)	

*X^2 test

Table 2 Neuropsychological evaluation tests score at baseline

Variables	All ($N=34$)	Control ($n=17$)	Experi-mental ($n=17$)	P value
MoCA-S, n, SD (range)	21.74, 2.12 (19–27)	21.12, 1.73 (19–25)	22.35, 2.34 (19–27)	0.090
SGDS-S, n, SD (range)	5.00, 2.50 (1–10)	5.82, 2.16 (2–9)	4.18, 2.6 (1–10)	0.053
IADL-S, n, SD (range)	6.74, 1.58 (1–8)	6.47, 1.42 (3–8)	7.00, 1.73 (1–8)	0.12

MoCA-S: Spanish version of the Montreal Cognitive Assessment; SGDS-S: Spanish version of the Short Form of Geriatric Depression Scale; IADL-S: Spanish version of the Instrumental Activities of Daily Living Scale

Table 3 Cognitive function and geriatric depression scores for both experimental and control group

Group, outcomes	Pre, mean (SD)	Post, mean (SD)	t value	P value	Cohen d
Control ($n=12$)					
MoCA-S	20.83 (1.8)	23.67 (2.74)	-7.75	< 0.001	2.24
SGDS-S	5.58 (2.07)	2.75 (1.42)	7.34	< 0.001	2.11
Experimental ($n=14$)					
MoCA-S	22.36 (2.59)	25.29 (2.56)	-5.77	< 0.001	1.54
SGDS-S	3.93 (2.81)	2.29 (1.38)	3.37	0.005	0.90

MoCA-S: Spanish version of the Montreal Cognitive Assessment; SGDS-S: Spanish version of the Short Form of Geriatric Depression Scale

Post intervention results

Once the intervention was completed, the pre-posttest scores were analyzed and, depending on the distribution of the data, parametric or non-parametric tests were used. For the MoCA-S and SGDS-S tests (see Table 3), the paired samples t test was used, and the Wilcoxon test was used for the IADL scale (see Table 4).

The MoCA-S test scores showed an improvement in the cognitive functions of both groups, with a minimally greater effect in the control group (Fig. 5). The within group effect of cognitive function was significant in both groups ($p<0.001$). When analyzing the SGDS-S scores, it was identified that both groups had a reduction in feelings related to depression, with a greater effect in the control group, showing a within group effect also significant. After intervention, the changes in the IADL-S test scores were slightly higher in relation to baseline in both groups (but not significant). Nevertheless, Mann-Whitney test revealed statistically significant differences between groups (in favor of the experimental group) ($p=0.002$).

Task level of achievement

The intervention was completed by 70.59% ($n=12$) in the control group and 82.35% ($n=14$) in the experimental group, respectively. During the intervention period, each participant increased the level of difficulty within the task. At the end of the intervention, the maximum level reached by each participant was identified and these results were presented in Fig. 6. As can be seen, the majority ($n=7$) of participants in the control group reached level 6 (memorizing up to 6 elements) and ($n=2$) reached level 7. In the experimental group, the majority of the participants ($n=7$) reached level 7 and even ($n=1$) reached level 8.

At the same time, the time it took each participant to complete the task in each of the sessions was analyzed. An average of the time used to perform the task by level was reckoned, whose results are presented in Fig. 7. As it can be seen, at level 4 the total completion time of the task was similar in both groups. The control group had an average time of 37.76 s and the experimental group had 30.37 s on average. As the level increases, increasingly significant differences can be seen in the average time of each group. At level 7, the control group spent 94.48 s on average, while the experimental group spent 58.88 s. The only participant who reached level 8 spent 99.07 s (on average).

Gender differences

The MoCA-S test scores showed a statistically significant improvement in cognitive functions for both males and females in the experimental group (with very large effect sizes) and only for females in the control group (with an extra-large effect size). The SGDS-S scores showed a statistically significant reduction in depressive symptoms for females in both groups. The changes in the IADL-S test scores were slightly higher in relation to the baseline in both groups, but not significant. See Table 5 for details.

Correlational analysis

Considering that the data of the MOCA-S and SGDS-S variables met the criteria of normality and homoscedasticity, a Pearson bivariate analysis was performed to examine the relationship between both variables. In the control group, analyses revealed a statistically significant association between scores obtained on the MOCA-S and SGDS-S after the intervention (Pearson r = -0.583,

Table 4 Scores for iADLs performance for both experimental and control group

Group, outcomes	Pre, mean (SD)	Pre, median (min-max)	Post, mean (SD)	Post, median (min-max)	Z value	P value	Cohen d
Control ($n=12$)							
IADL-S	6.42 (1.08)	6 (5–8)	6.50 (1.00)	6 (5–8)	-1.00	0.317	0.28
Experimental ($n=14$)							
IADL-S	7.43 (0.85)	8 (5–8)	7.71 (0.47)	8 (7–8)	-1.63	0.102	0.46

IADL-S: Spanish version of the Instrumental Activities of Daily Living Scale

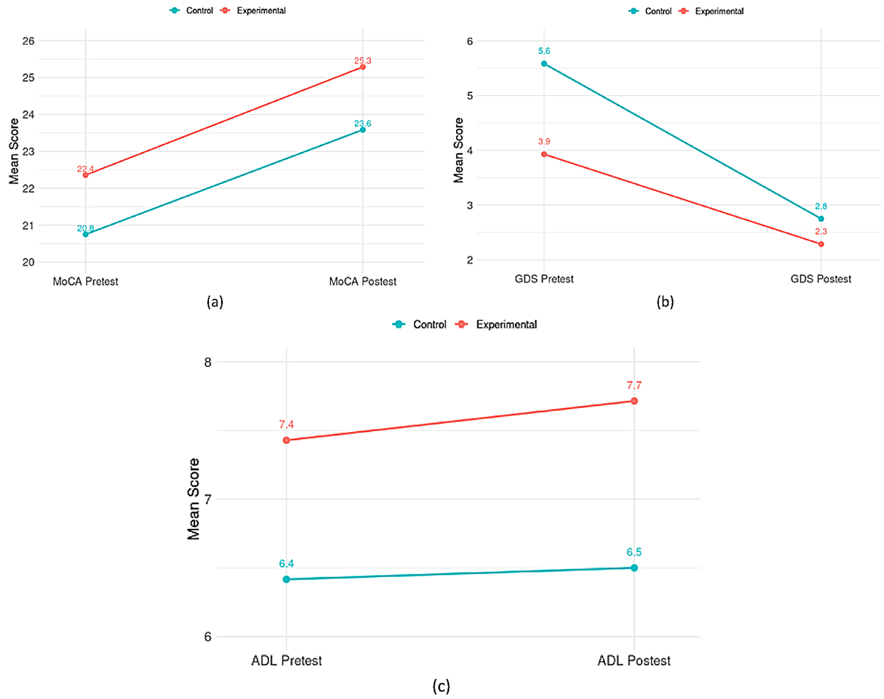


Fig. 5 Pre- and post- intervention scores for control and experimental groups, respectively. **(a)** cognitive function; **(b)** geriatric depression; **(c)** performance of iADLs

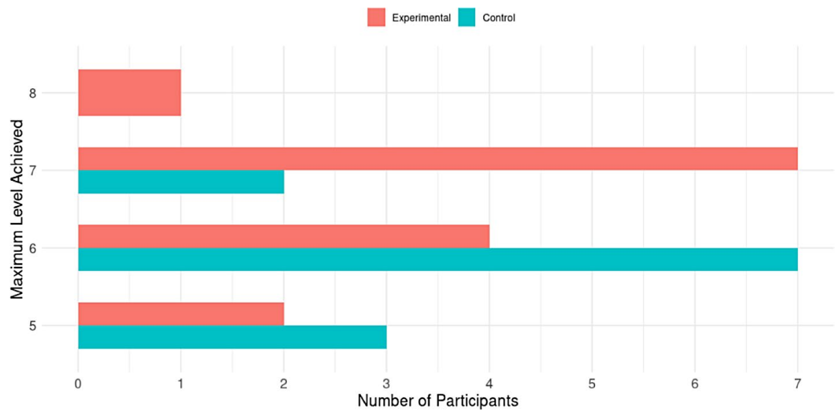


Fig. 6 Distribution of the maximum level achieved by participants in the task in both groups

$p=0.047$). This result could indicate that improvement or deterioration in cognitive function is associated with changes in depression levels. Additionally, level of education was found to correlate significantly with MOCA-S scores after the intervention ($r=0.706$, $p=0.010$). In the experimental group, there was no association between level of education and the maximum level achieved in the virtual task ($r=0.492$, $p=0.074$), suggesting that education does not have a positive impact on the cognitive task performance. By contrast, there was a statistically significant association between level of education and MOCA-S scores before ($r=0.610$, $p=0.009$) and after the intervention ($r=0.799$, $p=0.001$).

Discussion

The increasing incidence of AD emphasizes the need to address its complexity, caused by the interaction of genetic and environmental factors [48]. Given the limited effectiveness of pharmacological treatments in their initial phases or in their prevention, the importance of

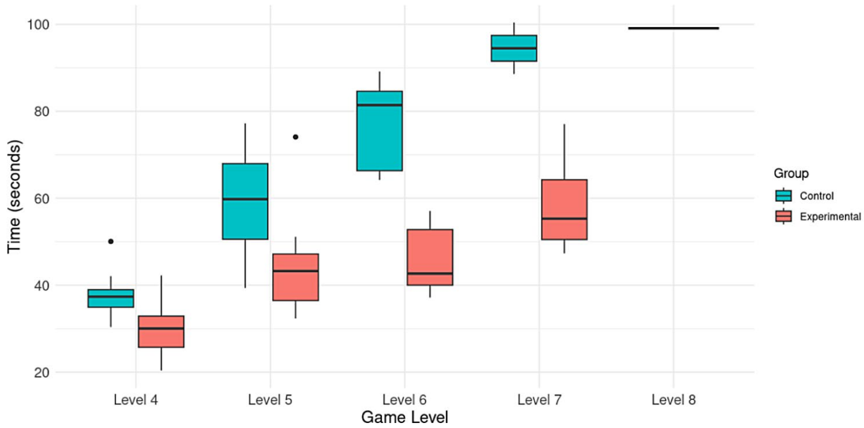


Fig. 7 Average performance time categorized by level of difficulty and group

Table 5 Performance scores in cognitive functions, geriatric depression and iADLs performance in both groups classified by gender

Group, index	Male (*n* = 9)				Female (*n* = 17)			
	Pre, mean (SD)	Post, mean (SD)	*p*-value	Cohen d	Pre, mean (SD)	Post, mean (SD)	*p*-value	Cohen d
Control								
MoCA	20.33 (1.53)	23.33 (3.06)	0.095	1.73	21.00 (1.94)	23.78 (2.82)	< 0.001	2.31
SGDS	5.67 (3.06)	3.67 (2.08)	0.184	1.15	5.56 (1.88)	2.44 (1.13)	< 0.001	2.67
IADL	5.67 (0.58)	5.67 (0.58)	1.00	0	6.67 (1.12)	6.78 (0.97)	0.317	0.33
Experimental								
MoCA	21.67 (1.51)	25.5 (2.07)	0.005	1.97	22.88 (3.18)	25.13 (3.00)	0.007	1.35
SGDS	4.83 (3.49)	3.17 (1.6)	0.105	0.94	3.25 (2.19)	1.63 (0.74)	0.035	0.92
IADL	7.17 (1.17)	7.67 (0.52)	0.180	0.60	7.63 (0.52)	7.75 (0.46)	0.317	0.34

exploring non-pharmacological alternatives arises [51]. Our study presented a behavioral intervention that, unlike pharmacological interventions, has broader eligibility criteria, which contributes to the generalization of results. This approach aligns with previous research conducted in Europe and Asia demonstrating that VR could be used as a preventive measure against dementia [47, 48].

This study was carried out in a Latin American population, seeking to contrast its findings with previous research in contexts where the use of virtual environments could be more common. We remark the good adherence and successful training in the sample. This approach also appears to be safe, as participants reported no adverse effects during the intervention. Preliminary results indicate that this program could be an effective tool to improve cognitive function in older adults with MCI. It is also suggested that there is efficacy in reducing depressive symptoms in this population. However, the results do not show a direct transfer of skills to everyday life situations, pointing out the need for more research to explore this aspect.

Effects on cognitive functions

Our study has shown that a dual intervention (sequential motor and cognitive training) can generate significant improvements in people with MCI. MoCA-S test scores reflected significant improvements in the cognitive functions of both groups. The control group showed notable progress, increasing its average score from 20.83 to 23.67, approaching the threshold of cognitive normality. Although there are studies such as that of Manser et al. [73], who mention that virtual environments could be a limitation due to the difficulty of using the system, our study showed promising results. The experimental group, which received the cognitive training via VR technology, increased MoCA-S test scores from 22.36 to 25.29, very close to normal cognitive performance. These improvements, in addition to being clinically significant, highlight the potential of VR-assisted cognitive rehabilitation.

The methodology used improved specific cognitive functions, including executive function, spatial navigation and memory. Our study was based on recent literature indicating that combined cognitive-motor training can exceed the effectiveness of isolated cognitive or motor training, as demonstrated by notable improvements in cognitive performance metrics [46, 74]. Doniger et al. [51] highlighted that cognitive and physical training exert distinct but complementary neurobiological benefits. Cognitive training has been shown to increase executive function by increasing cerebral blood flow (CBF) in the prefrontal cortex and medial/posterior cingulate cortex. On the contrary, physical training has been associated with improved memory, correlating with an increase in CBF in the hippocampus. These findings corroborate the premise that each training modality uniquely contributes to neurorehabilitation processes and promotes neuroplasticity, thereby facilitating brain repair and functional recovery [75].

The ability to strengthen cognitive reserve and stimulate neuroplasticity makes individuals with MCI ideal participants for this study [76]. Despite the neural declines associated with aging, different models have proposed explanations for how the brain can maintain optimal cognitive functions. One of these, the compensatory model, indicates that the brain achieves this through increased activation of certain specialized areas [77]. In this sense, virtual environments provide constant visual and spatial stimuli, via HMD, achieving interaction with real-time visualization. This not only increases CBF in the previously mentioned areas, but could also explain the improvement in neural efficiency observed in [78], suggesting better post-training cognitive performance. This impact has the potential to strengthen cognitive abilities and slow the progression of cognitive decline in older people at risk of developing dementia [48].

To achieve the expected results in any intervention, adherence to the training program is very important. In our intervention, there was a higher completion rate of participants in the experimental group, which shows the relevance of motivation for adherence to the program. This observation is consistent with the results of a meta-analysis highlighting the importance of motivation to increase active participation in this type of program [79]. The inclusion of VR technologies, by providing immediate feedback and generating a stimulating training environment, can overcome the demotivation frequently observed in cognitively impaired older adults [80]. It is argued that the increased engagement, motivated by the interest and enjoyment elicited by VR, activates neural mechanisms that promote concentration and memory through stimulation of neurotransmitter systems, such as cholinergic and dopaminergic systems [81]. It can also be added that using VR to simulate an everyday environment could be more effective in increasing motivation and thus achieving significant cognitive improvements, which is consistent with our study [52]. In contrast, traditional physical and cognitive training programs do not usually offer these motivational aspects.

In our research, we observed a statistically significant and positive relationship between the level of education of the participants and their MoCA-S scores, suggesting that a higher level of education is associated with better cognitive performance [82]. It is worth noting that, within our sample, only two participants completed their high school education, while the majority did not complete their basic education. However, they possess basic reading and numeracy skills. This observation aligns with the findings of Man et al. [83], who reported that individuals with lower educational level and mild dementia could derive greater benefits from training focused on ADL. Complementarily, Mondini et al. [84] concluded that those with lower cognitive reserve may be particularly susceptible to improvement through cognitive rehabilitation. Future research could focus on assessing the influence of additional factors, such as socioeconomic, cultural, linguistic context or disabilities.

Effects in depression

Depression in the geriatric population is a condition that can negatively affect cognitive function and quality of life. Although the main focus of the study was the improvement of cognitive functions, depressive symptoms are related and our results could provide relevant information [55]. The results of this study are encouraging, as they indicate that both traditional and VR-assisted interventions may be useful in reducing depressive symptoms. Initially, the control group was in the range of mild depression and, after the intervention, it was in a normal state (GSDS test from 5.58 to 2.75). While the experimental group had a reduction from 3.93 to 2.29, which, although it was already within the normal range, now presents even more reduced depressive symptoms. Both results are statistically significant ($p<0.001$ for the control and $p=0.005$ for the experimental), indicating that both intervention modalities were effective in reducing depression, although the improvement was slightly more pronounced in the control group.

Despite the benefits observed with the use of VR that highlight its potential as a complementary tool, the most significant results in terms of mental health were recorded in the control group. One interpretation of this phenomenon suggests that the pencil and paper task promoted a closer interaction between the therapist and the participant, favoring a communicative bond through conversations during breaks, aspects not contemplated in the original design of the study, but inherent to the therapeutic process. This agrees with [85] who mentions that cognitive training based on card games and accompanied by social interaction improves executive control in older adults. In the study of Langoni et al. [86], group exercises improved balance, mobility, and depressive symptoms in community-dwelling older adults with MCI. This finding highlights the positive impact of social integration and family support on the well-being of older adults, highlighting the importance of considering the environment in the design of the intervention.

The methodology of this study was designed to overcome the limitations of previous research, where the use of an inactive or low-contact control group has been criticized [87]. Previous studies, such as those carried out by Brito et al. [64] and Trueba et al. [65], did not incorporate active controls, which limits the interpretation of their findings. This omission restricts the ability to determine the genuine impact of their interventions. Our research chose to compare the use of VR with a control group that participated in active cognitive training accompanied by social interaction exercises. Additionally, analysis of the data by gender revealed that women in both groups showed a greater reduction in depressive symptoms compared to men. This finding is consistent with recent studies, such as that of Kim et al. [88], which showed the significant potential of VR applications to positively impact the female population.

The initial inclusion of motor, balance, and aerobic exercises not only promoted social interaction between participants and therapists in a real-world environment, but also established a foundation for effective social interaction [89, 90]. The use of VR in cognitive training added a unique dimension by providing visual and auditory feedback that recognized participants' achievements, fostering a sense of accomplishment and mitigating loneliness. This tool was especially valuable for those participants who, due to their advanced age or limitations, had distanced themselves from everyday activities such as food preparation, allowing them to interact in a virtual environment that simulated these tasks. This is relevant in developing countries, where, according to the meta-analysis by Zenebe et al. [32], the prevalence is almost three times higher compared to developed countries.

Another factor that could explain the difference in outcomes deals with the choice of an immersive system. A previous systematic review notes that older adults experience more positive effects when using commercial gaming systems such as Nintendo Switch or Xbox Kinect. This is attributed to the level of interaction, entertainment, and fun they offer, making them more engaging and potentially more effective in reducing depressive symptoms [55].

Effects in IADLs

A recent review highlighted how virtual environments that simulate iADLs could have greater ecological validity and foster autonomy in daily life [91]. The importance of these applications lies in their complexity and relevance, motivating participants to plan, organize, solve problems and manage multiple tasks simultaneously within a spatial and visual context [51]. This approach not only improves specific skills, but could ensure that learning is directly applicable to real situations, thus facilitating greater independence in daily activities [92]. Our intervention, based on the cupboard task, differs from applications that simulate more traditional IADL such as preparing food or shopping. Participants had to remember objects, for which they planned future actions, but the locations changed in each experiment to avoid monotony in the game. This approach trained participants in updating and managing dynamic information in their working memory, a relevant component of prospective memory, supporting cognitive flexibility and executive functions [93].

Despite the ecological validity of VR and the theoretical basis for real-life skill transfer, results did not demonstrate significant improvement on subsequent IADL tests, which can be interpreted as a lack of improvement in functional independence. This finding is consistent with the study of McDaniel et al. [87], who suggest a limit on the potential for improvement, due to a possible functional ceiling among some participants, who already have a high level of performance and, therefore, have less room to show significant improvements. On the other hand, some elderly people are under the care of relatives so they have lost autonomy to carry out tasks such as shopping or preparing food [94]. Fjordside and Morville [95] highlighted that older people have internal motivation to preserve their independence within their homes. This independence is compromised as the person becomes more dependent on the assistance of their caregivers. Therefore, people institutionalized in a geriatric center did not participate. The perception of autonomy of older people is closely related to their social relationships, the care practices of their caregivers and the residential environment, respecting their needs [96]. This context suggests that improving these skills in a short period may not be feasible.

Furthermore, Lawton and Brody's IADL scale may not have been sensitive enough to capture significant changes in participants' daily lives, given that the study was not designed to induce changes of such magnitude [97]. However, a specific improvement in smartphone use was observed, indicating an increase in comfort and motivation towards the use of smart devices among participants in the experimental group. The recent study of Wei and Guo [98] found that smartphone use had a positive effect on the health status of older adults. This specific result suggests that, although the intervention was not able to broadly improve IADL skills, it was able to positively influence specific aspects of interaction with technology.

Limitations

A systematic review suggested that to achieve maximum therapeutic efficacy, interventions should last at least six weeks [55]. Another meta-analysis stated that interventions should have a minimum of 10 sessions to facilitate transfer of learning [99]. Although our study complies with these conditions, we consider that a possible limitation was its duration and that a longer period would have allowed for greater consistency in the results. Our sample size is consistent with previous studies, but is still small, which limits confidence in the observed effects.

Another limitation is related to the lack of a follow-up evaluation, which was considered within the initial study to be carried out four months later. However, some participants stopped attending the senior community center and others did not wish to participate in the evaluations, which made this process impossible. In addition, the study was conducted exclusively in a senior center, thus limiting the generalizability of the results. The question arises as to whether the observed effects would be consistent in populations that do not frequent these centers, suggesting the need to expand the scope of future research to include diverse settings and populations.

An important aspect that should be controlled in future studies is the effect that social interaction can have on final performance. In our intervention, greater social interaction was revealed by the control group, which could have favored this group and justified the results obtained.

Conclusions

This study presented a VR-based intervention that obtained significant improvements in executive function, navigation and memory, as well as in the reduction of depressive symptoms. The results were comparable to those obtained with a traditional intervention that was provided by a therapist, which opens the door to the use of VR-based cognitive therapies in community-dwelling older adults provided by family members or caregivers, and without the permanent need of a therapist. The high rate of adherence to the program in the experimental group highlights the relevance of designing motivating and attractive VR interventions.

Future research should address the limitations of this study, such as its duration and sample size, to consolidate the current findings. Additionally, long-term follow-up evaluations should be conducted, as well as expand the scope of the research to a broader variety of contexts and populations. Investigating the effectiveness of VR in improving depressive symptoms and transferring cognitive skills to daily activities is promising field, which requires further exploration to maximize the therapeutic potential of this technology in healthy aging.

Author contributions

J.B.: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. F.A.-C.: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. J. V.-A.: Conceptualization, Software, Supervision. C.D.V.: Conceptualization, Supervision. G.P-N.: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Supervision. Validation.

Funding

Not applicable.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethical approval and consent to participate

Approval was obtained from the Institutional Review Board of the Universidad Tecnólogica Indoamérica on May 25, 2023 (protocol UTI-IIDI-074-2023). Participants provided written informed consent before they performed the tasks.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Carrera de Ingeniería en Tecnologías de la Información, Facultad de Ingeniería, Industria y Producción, Universidad Indoamérica, Ambato 180103, Ecuador
[2]Centro de Investigaciones de Ciencias Humanas y de la Educación (CICHE), Universidad Indoamérica, Ambato 180103, Ecuador
[3]Facultad de Ingeniería, Universidad Panamericana, Álvaro del Portillo 49, Zapopan, Jalisco 45010, México
[4]Department of Electronic Engineering and Communications, University of Zaragoza, Teruel, Spain
[5]Teruel Polytechnic School of Engineering, University of Zaragoza C/ Atarazana, 2, Teruel 44002, Spain

Received: 19 May 2024 / Accepted: 16 July 2024
Published online: 01 August 2024

References

1. van Leeuwen KM, van Loon MS, van Nes FA, Bosmans JE, de Vet HCW, Ket JCF, et al. What does quality of life mean to older adults? A thematic synthesis. PLoS ONE. 2019;14:e0213263.
2. Elliott ML, Belsky DW, Knodt AR, Ireland D, Melzer TR, Poulton R, et al. Brain-age in midlife is associated with accelerated biological aging and cognitive decline in a longitudinal birth cohort. Mol Psychiatry. 2021;26:3829–38.
3. Meng X, Li G, Jia Y, Liu Y, Shang B, Liu P, et al. Effects of dance intervention on global cognition, executive function and memory of older adults: a meta-analysis and systematic review. Aging Clin Exp Res. 2020;32:7–19.
4. Toth C, Tulliani N, Bissett M, Liu KP. The relationship between cognitive function and performance in instrumental activities of daily living in older adults. Br J Occup Therapy. 2022;85:120–9.
5. Pashmdarfard M, Azad A. Assessment tools to evaluate activities of Daily Living (ADL) and instrumental activities of Daily Living (IADL) in older adults: a systematic review. Med J Islam Repub Iran. 2020;34:33.
6. Roley SS, DeLany JV, Barrows CJ, Brownrigg S, Honaker D, Sava DI et al. Occupational Therapy Practice Framework: Domain & Process 2nd Edition. AJOT: American Journal of Occupational Therapy. 2008;62:625–84.
7. Ward G, Jagger C, Harper W. A review of instrumental ADL assessments for use with elderly people. Reviews Clin Gerontol. 1998;8:65–71.
8. Tulliani N, Bissett M, Fahey P, Bye R, Liu KPY. Efficacy of cognitive remediation on activities of daily living in individuals with mild cognitive impairment or early-stage dementia: a systematic review and meta-analysis. Syst Reviews. 2022;11:156.
9. Bruscoli M, Lovestone S. Is MCI really just early dementia? A systematic review of conversion studies. Int Psychogeriatr. 2004;16:129–40.

10. Bermejo-Pareja F, Contador I, del Ser T, Olazarán J, Llamas-Velasco S, Vega S, et al. Predementia constructs: mild cognitive impairment or mild neurocognitive disorder? A narrative review. Int J Geriatr Psychiatry. 2021;36:743–55.
11. Kasper S, Bancher C, Eckert A, Förstl H, Frölich L, Hort J, et al. Management of mild cognitive impairment (MCI): the need for national and international guidelines. World J Biol Psychiatry. 2020;21:579–94.
12. Golomb J, Kluger A, Ferris SH. Mild cognitive impairment: historical development and summary of research. Dialog Clin Neurosci. 2004;6:351–67.
13. Ma L, Depression. Anxiety, and Apathy in Mild Cognitive Impairment: Current Perspectives. Frontiers in Aging Neuroscience [Internet]. 2020 [cited 2024 Feb 13];12. https://www.frontiersin.org/articles/https://doi.org/10.3389/fnagi.2020.00009.
14. Lissek V, Suchan B. Preventing dementia? Interventional approaches in mild cognitive impairment. Neurosci Biobehavioral Reviews. 2021;122:143–64.
15. Scheltens P, Blennow K, Breteler MMB, de Strooper B, Frisoni GB, Salloway S, et al. Alzheimer's disease. Lancet. 2016;388:505–17.
16. Zhu L, Lei M, Tan L, Zou M. Sex difference in the association between BMI and cognitive impairment in Chinese older adults. J Affect Disord. 2024;349:39–47.
17. Pless A, Ware D, Saggu S, Rehman H, Morgan J, Wang Q. Understanding neuropsychiatric symptoms in Alzheimer's disease: challenges and advances in diagnosis and treatment. Front NeuroSci. 2023;17.
18. Mielke MM, Aggarwal NT, Vila-Castelar C, Agarwal P, Arenaza-Urquijo EM, Brett B, et al. Consideration of sex and gender in Alzheimer's disease and related disorders from a global perspective. Alzheimer's Dement. 2022;18:2707–24.
19. Min SH, Schnall R, Lee C, Topaz M. Examining racial differences in the network structure and properties of specific cognitive domains among older adults. GeroScience. 2024;46:1395–406.
20. He Z, Dieciuc M, Carr D, Chakraborty S, Singh A, Fowe IE, et al. New opportunities for the early detection and treatment of cognitive decline: adherence challenges and the promise of smart and person-centered technologies. BMC Digit Health. 2023;1:7.
21. Anderson ND. State of the science on mild cognitive impairment (MCI). CNS Spectr. 2019;24:78–87.
22. Prenkaj B, Aragona D, Flaborea A, Galasso F, Gravina S, Podo L, et al. A self-supervised algorithm to detect signs of social isolation in the elderly from daily activity sequences. Artif Intell Med. 2023;135:102454.
23. Tateno A, Nogami T, Sakayori T, Yamamoto K, Okubo Y. Depression as a Prodromal Symptom of neurodegenerative diseases. J Nippon Med Sch. 2023;90:157–64.
24. Li M, Long C, Yang L. Hippocampal-Prefrontal Circuit and Disrupted Functional Connectivity in Psychiatric and Neurodegenerative disorders. Biomed Res Int. 2015;2015:1–10.
25. Shusharina N, Yukhnenko D, Botman S, Sapunov V, Savinov V, Kamyshov G, et al. Modern Methods of Diagnostics and Treatment of neurodegenerative diseases and Depression. Diagnostics. 2023;13:573.
26. Lyketsos CG, Carrillo MC, Ryan JM, Khachaturian AS, Trzepacz P, Amatniek J, et al. Neuropsychiatric symptoms in Alzheimer's disease. Alzheimer's Dement. 2011;7:532–9.
27. Malhi GS, Mann JJ, Depression. Lancet. 2018;392:2299–312.
28. Evans J, Charness N, Dijkstra K, Fitzgibbons JM, Yoon J-S. Is episodic memory performance more vulnerable to depressive affect in older adulthood? Aging. Neuropsychol Cognition. 2019;26:244–63.
29. Schaakxs R, Comijs HC, Lamers F, Kok RM, Beekman ATF, Penninx BWJH. Associations between age and the course of major depressive disorder: a 2-year longitudinal cohort study. Lancet Psychiatry. 2018;5:581–90.
30. Gold SM, Köhler-Forsberg O, Moss-Morris R, Mehnert A, Miranda JJ, Bullinger M, et al. Comorbid depression in medical diseases. Nat Rev Dis Primers. 2020;6:1–22.
31. Maier A, Riedel-Heller SG, Pabst A, Luppa M. Risk factors and protective factors of depression in older people 65+. A systematic review. PLoS ONE. 2021;16:e0251326.
32. Zenebe Y, Akele B, W/Selassie M, Necho M. Prevalence and determinants of depression among old age: a systematic review and meta-analysis. Ann Gen Psychiatry. 2021;20:55.
33. Abdoli N, Salari N, Darvishi N, Jafarpour S, Solaymani M, Mohammadi M, et al. The global prevalence of major depressive disorder (MDD) among the elderly: a systematic review and meta-analysis. Neurosci Biobehavioral Reviews. 2022;132:1067–73.
34. Gavralas K, Brown L, Bryant C. Longitudinal relationships between self-compassion and depressive symptoms in midlife women. Climacteric. 2023;26:619–24.
35. Alblooshi S, Taylor M, Gill N. Does menopause elevate the risk for developing depression and anxiety? Results from a systematic review. Australas Psychiatry. 2023;31:165–73.
36. Hogervorst E, Craig J, O'Donnell E. Cognition and mental health in menopause: a review. Best Pract Res Clin Obstet Gynecol. 2022;81:69–84.
37. Wenzel KC, Van Puymbroeck M, Lewis S, McGuire F, Vidotto J. Characteristics and cognition of older adults engaged in lifelong learning. Educ Gerontol. 2024;0:1–20.
38. Hou J, Jiang T, Fu J, Su B, Wu H, Sun R et al. The Long-Term Efficacy of Working Memory Training in Healthy Older Adults: A Systematic Review and Meta-Analysis of 22 Randomized Controlled Trials. The Journals of Gerontology: Series B. 2020;75:e174–88.
39. Bell G, Singham T, Saunders R, John A, Stott J. Positive psychological constructs and association with reduced risk of mild cognitive impairment and dementia in older adults: a systematic review and meta-analysis. Ageing Res Rev. 2022;77:101594.
40. Irazoki E, Contreras-Somoza LM, Toribio-Guzmán JM, Jenaro-Río C, van der Roest H, Franco-Martín MA. Technologies for Cognitive Training and Cognitive Rehabilitation for people with mild cognitive impairment and dementia. A systematic review. Front Psychol. 2020;11.
41. Zhu S, Sui Y, Shen Y, Zhu Y, Ali N, Guo C, et al. Effects of virtual reality intervention on cognition and motor function in older adults with mild cognitive impairment or dementia: a systematic review and Meta-analysis. Front Aging Neurosci. 2021;13:586999.
42. Matsangidou M, Frangoudes F, Schiza E, Neokleous KC, Papayianni E, Xenari K, et al. Participatory design and evaluation of virtual reality physical rehabilitation for people living with dementia. Virtual Reality. 2023;27:421–38.
43. Palacios-Navarro G, Hogan N. Head-mounted Display-based therapies for adults Post-stroke: a systematic review and Meta-analysis. Sensors. 2021;21:1111.
44. Chan ATC, Ip RTF, Tran JYS, Chan JYC, Tsoi KKF. Computerized cognitive training for memory functions in mild cognitive impairment or dementia: a systematic review and meta-analysis. Npj Digit Med. 2024;7:1–11.
45. Gao Y, Ma L, Lin C, Zhu S, Yao L, Fan H et al. Effects of virtual reality-based intervention on cognition, motor function, Mood, and activities of Daily living in patients with chronic stroke: a systematic review and Meta-analysis of Randomized controlled trials. Front Aging Neurosci. 2021;13.
46. Buele J, Palacios-Navarro G. Cognitive-motor interventions based on virtual reality and instrumental activities of daily living (iADL): an overview. Front Aging Neurosci. 2023;15.
47. Liao Y-Y, Chen I-H, Lin Y-J, Chen Y, Hsu W-C. Effects of virtual reality-based physical and cognitive training on executive function and dual-Task Gait performance in older adults with mild cognitive impairment: a Randomized Control Trial. Front Aging Neurosci. 2019;11.
48. Mrakic-Sposta S, Di Santo SG, Franchini F, Arlati S, Zangiacomi A, Greci L et al. Effects of combined physical and cognitive virtual reality-based training on cognitive impairment and oxidative stress in MCI patients: a pilot study. Front Aging Neurosci. 2018;10.
49. Kwan RYC, Liu JYW, Fong KNK, Qin J, Leung PK-Y, Sin OSK, et al. Feasibility and effects of virtual reality motor-cognitive training in Community-Dwelling Older People with Cognitive Frailty: pilot randomized controlled trial. JMIR Serious Games. 2021;9:e28400.
50. Park J-S, Jung Y-J, Lee G. Virtual reality-based cognitive–motor Rehabilitation in older adults with mild cognitive impairment: a randomized controlled study on motivation and cognitive function. Healthcare. 2020;8:335.
51. Doniger GM, Beeri MS, Bahar-Fuchs A, Gottlieb A, Tkachov A, Kenan H et al. Virtual reality-based cognitive-motor training for middle-aged adults at high Alzheimer's disease risk: A randomized controlled trial. Alzheimer's & Dementia: Translational Research & Clinical Interventions. 2018;4:118–29.
52. Liao Y-Y, Tseng H-Y, Lin Y-J, Wang C-J, Hsu W-C. Using virtual reality-based training to improve cognitive function, instrumental activities of daily living and neural efficiency in older adults with mild cognitive impairment. Eur J Phys Rehabil Med. 2020;56:47–57.
53. Barbalat G, Franck N. Ecological study of the association between mental illness with human development, income inequalities and unemployment across OECD countries. BMJ Open. 2020;10:e035055.
54. Cifuentes M, Sembajwe G, Tak S, Gore R, Kriebel D, Punnett L. The association of major depressive episodes with income inequality and the human development index. Soc Sci Med. 2008;67:529–39.
55. Yen H-Y, Chiu H-L. Virtual reality exergames for improving older adults' cognition and depression: a systematic review and Meta-analysis of Randomized Control trials. J Am Med Dir Assoc. 2021;22:995–1002.

56. Busso M, Messina J. The Inequality Crisis: Latin America and the Caribbean at the Crossroads. IDB Publications. 2020.
57. Cyrus E, Sanchez J, Madhivanan P, Lama JR, Bazo AC, Valencia J, et al. Prevalence of intimate Partner Violence, Substance Use disorders and Depression among Incarcerated women in Lima, Perú. Int J Environ Res Public Health. 2021;18:11134.
58. Navarrete L, Nieto L, Lara MA. Intimate partner violence and perinatal depression and anxiety: social support as moderator among Mexican women. Sex Reproductive Healthc. 2021;27:100569.
59. Bojorquez I, Cabieses B, Arósquipa C, Arroyo J, Novella AC, Knipper M, et al. Migration and health in Latin America during the COVID-19 pandemic and beyond. Lancet. 2021;397:1243–5.
60. Abramo L, Cecchini S, Ullmann H. Addressing health inequalities in Latin America: the role of social protection. Ciênc saúde Coletiva. 2020;25:1587–98.
61. Mathers CD, Stevens GA, Boerma T, White RA, Tobias MI. Causes of international increases in older age life expectancy. Lancet. 2015;385:540–8.
62. Vigo DV, Kestel D, Pendakur K, Thornicroft G, Atun R. Disease burden and government spending on mental, neurological, and substance use disorders, and self-harm: cross-sectional, ecological study of health system response in the Americas. Lancet Public Health. 2019;4:e89–96.
63. Lopera F, Custodio N, Rico-Restrepo M, Allegri RF, Barrientos JD, Garcia Batres E, et al. A task force for diagnosis and treatment of people with Alzheimer's disease in Latin America. Front Neurol. 2023;14:1198869.
64. Brito H, Pham T, Vicente B. Effect of sensorimotor rehabilitation based on an immersive virtual reality model on mental health. International Journal of Geriatric Psychiatry [Internet]. 2022 [cited 2024 Mar 24];37. https://onlinelibrary.wiley.com/doi/abs/10.1002/gps.5541.
65. Trueba A, Crespo-Andrade C, Merino CA, Frank NAA, Garces MS, Cray HV, et al. Implementing affordable virtual reality interventions for older adults in Latin America: a feasibility study. Am J Geriatric Psychiatry. 2023;31:S134–5.
66. Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I, et al. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. J Am Geriatr Soc. 2005;53:695–9.
67. Loureiro C, Garcia C, Adana L, Yacelga T, Rodriguez-Lorenzana A, Maruta C. [Use of the Montreal Cognitive Assessment (MoCA) in Latin America: a systematic review]. Rev Neurol. 2018;66:397–408.
68. Yesavage JA, Brink TL, Rose TL, Lum O, Huang V, Adey M, et al. Development and validation of a geriatric depression screening scale: a preliminary report. J Psychiatr Res. 1982;17:37–49.
69. Erazo M, Fors M, Mullo S, González P, Viada C. Internal consistency of Yesavage Geriatric Depression Scale (GDS 15-Item version) in Ecuadorian older adults. INQUIRY. 2020;57:0046958020971184.
70. Vergara I, Bilbao A, Orive M, Garcia-Gutierrez S, Navarro G, Quintana JM. Validation of the Spanish version of the Lawton IADL Scale for its application in elderly people. Health Qual Life Outcomes. 2012;10:130.
71. Lawton MP, Brody EM. Assessment of older people: self-maintaining and instrumental activities of daily living. Gerontologist. 1969;9:179–86.
72. Nelson M, Rejeski W, Blair S, Duncan P, Judge J, King A, et al. Physical Activity and Public Health in older adults: recommendation from the American College of Sports Medicine and the American Heart Association. Circulation. 2007;116:1094–105.
73. Manser P, Adcock-Omlin M, De Bruin ED. Design considerations for an Exergame-based training intervention for older adults with mild neurocognitive disorder: qualitative study including Focus Groups with experts and Health Care professionals and Individual Semistructured In-depth patient interviews. JMIR Serious Games. 2023;11:e37616.
74. Joubert C, Chainay H. Aging brain: the effect of combined cognitive and physical training on cognition as compared to cognitive and physical training alone - a systematic review. Clin Interv Aging. 2018;13:1267–301.
75. Chapman SB, Aslan S, Spence JS, Hart JJ, Bartz EK, Didehbani N, et al. Neural mechanisms of brain plasticity with complex cognitive training in healthy seniors. Cereb Cortex. 2015;25:396–405.
76. Esiri MM, Chance SA. Cognitive reserve, cortical plasticity and resistance to Alzheimer's disease. Alzheimers Res Ther. 2012;4:7.
77. Lustig C, Shah P, Seidler R, Reuter-Lorenz PA. Aging, training, and the brain: a review and future directions. Neuropsychol Rev. 2009;19:504–22.
78. Vermeij A, Kessels RPC, Heskamp L, Simons EMF, Dautzenberg PLJ, Claassen JAHR. Prefrontal activation may predict working-memory training gain in normal aging and mild cognitive impairment. Brain Imaging Behav. 2017;11:141–54.
79. Zhong D, Chen L, Feng Y, Song R, Huang L, Liu J, et al. Effects of virtual reality cognitive training in individuals with mild cognitive impairment: a systematic review and meta-analysis. Int J Geriatr Psychiatry. 2021;36:1829–47.
80. Riaz W, Khan ZY, Jawaid A, Shahid S. Virtual reality (VR)-Based Environmental Enrichment in older adults with mild cognitive impairment (MCI) and mild dementia. Brain Sci. 2021;11:1103.
81. Yang S, Chun MH, Son YR. Effect of virtual reality on cognitive dysfunction in patients with brain tumor. Annals Rehabilitation Med. 2014;38:726–33.
82. Cervigni Garnero M, Martino P, Alfonso G, Politis D. Montreal Cognitive Assessment (MoCA): normas para la población del área metropolitana de Rosario. Argentina RevNeurol. 2022;75:51.
83. Man DWK, Chung JCC, Lee GYY. Evaluation of a virtual reality-based memory training programme for Hong Kong Chinese older adults with questionable dementia: a pilot study. Int J Geriatr Psychiatry. 2012;27:513–20.
84. Mondini S, Madella I, Zangrossi A, Bigolin A, Tomasi C, Michieletto M, et al. Cognitive Reserve in Dementia: implications for cognitive training. Front Aging Neurosci. 2016;8:84.
85. Kuo C-Y, Huang Y-M, Yeh Y-Y. Let's Play Cards: Multi-Component Cognitive Training With Social Engagement Enhances Executive Control in Older Adults. Front Psychol [Internet]. 2018 [cited 2024 Mar 17];9. https://www.frontiersin.org/journals/psychology/articles/https://doi.org/10.3389/fpsyg.2018.02482/full.
86. Langoni C, da Resende S, de Barcellos T, Cecchele AB, da Rosa B, Knob JN. The effect of group exercises on balance, mobility, and depressive symptoms in older adults with mild cognitive impairment: a randomized controlled trial. Clin Rehabil. 2019;33:439–49.
87. McDaniel MA, Binder EF, Bugg JM, Waldum ER, Dufault C, Meyer A, et al. Effects of cognitive training with and without aerobic exercise on cognitively demanding everyday activities. Psychol Aging. 2014;29:717–30.
88. Kim D-R, Moon E, Shin M-J, Yang Y-A, Park J-H. Effect of Individual Virtual Reality Cognitive Training Programs on cognitive function and depression in middle-aged women: Randomized Controlled Trial. JMIR Mental Health. 2023;10:e48912.
89. Creed C, Al-Kalbani M, Theil A, Sarcar S, Williams I, Inclusive. AR/VR: accessibility barriers for immersive technologies. Univ Access Inf Soc [Internet]. 2023 [cited 2024 Mar 12]; https://doi.org/10.1007/s10209-023-00969-0.
90. Uysal İ, Başar S, Aysel S, Kalafat D, Büyüksünnetçi AÖ. Aerobic exercise and dual-task training combination is the best combination for improving cognitive status, mobility and physical performance in older adults with mild cognitive impairment. Aging Clin Exp Res. 2023;35:271–81.
91. Buele J, Varela-Aldás JL, Palacios-Navarro G. Virtual reality applications based on instrumental activities of daily living (iADLs) for cognitive intervention in older adults: a systematic review. J Neuroeng Rehabil. 2023;20:168.
92. Burgess PW, Alderman N, Forbes C, Costello A, M-A.coates L, Dawson DR, et al. The case for the development and use of ecologically valid measures of executive function in experimental and clinical neuropsychology. J Int Neuropsychol Soc. 2006;12:194–209.
93. Hering A, Rendell PG, Rose NS, Schnitzspahn KM, Kliegel M. Prospective memory training in older adults and its relevance for successful aging. Psychol Res. 2014;78:892–904.
94. Burlá C, Pessini L, Siqueira JE, Nunes R. Aging and Alzheimer's Disease: reflections on the loss of autonomy and the challenges of care. 2014;22:85–93.
95. Fjordside S, Morville A. Factors influencing older people's experiences of participation in autonomous decisions concerning their daily care in their own homes: a review of the literature. Int J Older People Nurs. 2016;11 4:284–97.
96. Moilanen T, Kangasniemi M, Papinaho O, Mynttinen M, Siipi H, Suominen S, et al. Older people's perceived autonomy in residential care: an integrative review. Nurs Ethics. 2021;28:414–34.
97. Panerai S, Gelardi D, Catania V, Rundo F, Tasca D, Musso S, et al. Functional living skills: a non-immersive virtual reality training for individuals with Major Neurocognitive disorders. Sensors. 2021;21:5751.
98. Wei Y, Guo X. Impact of smart device use on objective and subjective health of older adults: findings from four provinces in China. Front Public Health [Internet]. 2023 [cited 2024 Mar 17];11. https://www.frontiersin.org/journals/public-health/articles/https://doi.org/10.3389/fpubh.2023.1118207/full.

99. Kelly ME, Loughrey D, Lawlor BA, Robertson IH, Walsh C, Brennan S. The impact of cognitive training and mental stimulation on cognitive and everyday functioning of healthy older adults: a systematic review and meta-analysis. Ageing Res Rev. 2014;15:28–43.

Publisher's Note

DISCUSIÓN GENERAL 3

3.1. Cribado cognitivo

3.1.1. Evaluación física basada en AVD

Los hallazgos de esta tesis promueven el potencial de las soluciones tecnológicas basadas en AVD para el cribado cognitivo en adultos mayores. Los resultados de la implementación de la tarea de los armarios físicos muestran su utilidad para detectar signos asociados a un deterioro cognitivo, ya que los pacientes con EA muestran un bajo rendimiento en aplicaciones que involucran AVD [71]. El enfoque que utilizamos basado en la tarea del armario aprovechó la inclusión de un contexto espacial y la simulación de una AIVD. Este enfoque es consistente con investigaciones que señalan que los entornos significativos (en este caso una cocina) permiten una evaluación más representativa del funcionamiento cognitivo cotidiano [72].

Además, actividades como abrir las puertas de los armarios y seleccionar objetos podrían ser sensibles a los cambios cognitivos tempranos característicos de un deterioro cognitivo patológico [50], [73]. Este diseño consolidó el vínculo entre el contexto espacial y la codificación de la memoria, por la asociación entre objeto y ubicación. Este elemento es importante en modelos teóricos de memoria que presentan la importancia del contexto espacial tanto en la función mnésica como en la evaluación de la memoria episódica y visoespacial [74], [75].

La tarea de los armarios se correlacionó significativamente con la escala MEC-35 (rho = 0,71, p = 0,010), una herramienta tradicional. Esto concuerda con investigaciones previas que han encontrado asociaciones similares entre pruebas innovadoras y métodos tradicionales, como el SDMT [41] y MoCA [76]. A diferencia de pruebas convencionales, que carecen de validez ecológica, nuestra tarea evaluó habilidades directamente relacionadas con la cotidianidad, lo que respalda su aplicabilidad clínica. La confiabilidad del test-retest (ICC = 0,757 para el grupo con EA y 0,821 para el grupo sano) muestra estabilidad en nuestra propuesta. Además, nuestro estudio concuerda con el de Baker et al. [77], donde los pacientes con EA presentaron menor rendimiento en una tarea de lista de compras, lo cual se asoció con problemas en la memoria episódica y espacial [78]. Sin embargo, se identificó el efecto techo en el grupo de participantes sanos. Dicho efecto suele presentarse en personas sanas, como lo indica Drolet et al. [79], al aplicar la RAVLT. ES por ello que en la siguiente aplicación se planificó implementar más elementos y niveles de dificultad para mejorar esta limitación. Además, al ser una actividad que se realiza de pie, los participantes con problemas de movilidad, como aquellos que utilizaban bastón, registraron tiempos de respuesta más altos. Vriendt et al. [80] reconoce que la pérdida de autonomía puede generar tiempos de reacción más prolongados y menor eficiencia. En la aplicación futura se propuso el desarrollo de las tareas en posición sedente, lo cual reducirá este inconveniente, asegurando que la evaluación de tiempos de reacción se centre en el desempeño cognitivo.

3.1.2. Aplicaciones inmersivas en AVD

Considerando las limitantes de la primera versión física, la tarea del armario en RVI reveló una alta concordancia con el método tradicional del palacio de la memoria (método de

Loci), alcanzando un ICC de 0,614 para el nivel 1 y 0,662 para el nivel 2. Estos valores, que representan un buen nivel de significancia clínica según los criterios de Cicchetti [81], muestran la confiabilidad del sistema desarrollado como una herramienta válida frente a las pruebas tradicionales, con potencial para su uso en contextos clínicos. Estos resultados muestran una ventaja significativa en comparación con otros estudios similares. Por ejemplo, trabajos como los de Moffat et al. [82] y Parsons y McMahan [57] reportaron correlaciones moderadas entre las tareas virtuales y las pruebas psicométricas tradicionales, utilizando coeficientes de Pearson. Por otro lado, Ouellet et al. [50] informaron una correlación moderada (r = 0,35) entre el recuerdo correcto en su tarea de tienda virtual y test tradicionales para la medida de la memoria episódica, sin encontrar asociaciones con cuestionarios como el MMQ [83].

El desempeño observado en la tarea del armario también fue sensible a las diferencias relacionadas con la edad, con adultos más jóvenes superando en precisión a los mayores, una tendencia común en tareas de memoria episódica y espacial [84]. Asimismo, los tiempos de reacción mostraron una correlación positiva con la edad, lo que es consistente con investigaciones que han encontrado tiempos de respuesta más prolongados en adultos mayores durante tareas en entornos virtuales [85], [86]. Por otro lado, el uso de un entorno virtual inmersivo pudo haber contribuido al buen desempeño general, ya que estudios recientes han indicado que los entornos inmersivos pueden mejorar la codificación y el recuerdo al ofrecer una experiencia más dinámica y realista en comparación con entornos no inmersivos [87], [88].

La evaluación de usabilidad del sistema se realizó con el cuestionario USEQ [70]. El resultado de 96,3% fue muy positivo, los participantes reportaron que la tarea del armario fue intuitiva y fácil de manejar, incluso para aquellos con poca experiencia en RV. Estos resultados coinciden con el estudio de Hassandra et al. [89] que utilizó RVI mediante HMD y tuvo una buena satisfacción por parte de personas mayores con síntomas de DCL. Sin embargo, uno de los comentarios recurrentes de los participantes fue la posibilidad de usar sus manos durante el desarrollo de la tarea, en lugar de los controles tradicionales.

3.1.3. Seguimiento de manos en el cribado cognitivo

Teniendo en cuenta lo anterior, se motivó que en el siguiente estudio evaluáramos el rendimiento cognitivo en la tarea del armario virtual utilizando el seguimiento de manos y lo comparáramos con el uso de controles, con el objetivo de identificar diferencias en la interacción y posibles mejoras en el desempeño. Los resultados mostraron diferencias no significativas en términos de precisión y tiempo de respuesta entre ambos métodos de interacción. La precisión promedio con controles fue un 7,08% superior y el tiempo de respuesta 0,27 segundos más rápido en comparación con el seguimiento de manos. Esto sugiere una ligera ventaja para los controles tradicionales en esta aplicación, lo que coincide con los hallazgos de Jamalian et al. [90].

La percepción de presencia, medida a través del cuestionario de presencia (PQ) [91], tampoco mostró diferencias significativas entre métodos (p = 0,21). Sin embargo, ciertas preguntas específicas destacaron diferencias importantes: los usuarios percibieron un mejor control (8,57% superior) y sensibilidad (9,29% superior) al usar controles, mientras que el seguimiento de manos se valoró más alto en consistencia sensorial (7,14% superior). Aunque ambos métodos obtuvieron puntuaciones altas en la prueba de usabilidad para la experiencia del usuario (UMUX) [92] y satisfacción en el USEQ [70], los controles tradicionales mostraron una ligera ventaja en facilidad de uso (2,14% superior) y precisión, demostrando su robustez en entornos de RVI. Estos hallazgos coinciden con García-Magariño et al., [86] y Robin et al. [74], que asocian la percepción de control con un mejor desempeño en tareas de memoria. Ouellet et al. [50] mencionaron que los controles tradicionales tienen una alta fiabilidad y son de fácil uso.

Aunque no se encontraron diferencias significativas en el desempeño cognitivo, la implementación del seguimiento de manos como método de interacción en tareas de memoria inmersiva presenta nuevas posibilidades. Este método facilita una experiencia más natural y por ello tanto las investigaciones futuras como los desarrolladores de hardware deberían centrarse en mejorar su sensibilidad y precisión. Esto permitiría su implementación en contextos clínicos y de evaluación cognitiva [88].

3.2. Entrenamiento cognitivo-motor

La simulación de AIVD en entornos virtuales se presenta como enfoque innovador en la intervención cognitiva, ya que permite replicar con alta fidelidad las actividades cotidianas que realiza el adulto mayor. Nuestro último estudio analizó el impacto de una intervención cognitivo-motora basada en RV y AIVD, comparada con una actividad de lápiz y papel. Se utilizó la tarea del armario en RV y se diseñó un ensayo controlado aleatorio simple ciego en adultos mayores con DCL. Tuvimos una alta tasa de adherencia al programa (82,35% en el grupo experimental) y ausencia de efectos adversos durante las sesiones, lo cual demuestra la viabilidad y seguridad de la intervención en este contexto. El uso de tecnología RVI, mantuvo el interés y compromiso de los participantes. Este hallazgo se alinea con lo reportado por Park et al. [67], quienes demostraron que los sistemas inmersivos promueven la participación y potencian los resultados cognitivos mediante la estimulación de neurotransmisores asociados con la motivación.

El grupo experimental mostró una mejora significativa en la evaluación de funciones cognitivas a través del MoCA-S, incrementando su puntuación promedio de 22,36 a 25,29 ($p < 0,001$). Esto es consistente con la literatura existente, ya que muestra los beneficios de implementar intervenciones donde se recrean AIVD en entornos virtuales. Estas intervenciones promueven mejoras notables en la atención, memoria general y memoria visoespacial, lo que refuerza la capacidad de los usuarios para procesar y recordar información visual [93], [94], [95]. Asimismo, favorece el desempeño de la memoria de trabajo, ya que son tareas que requieren manipulación constante de información [96], [97].

La tarea de los armarios se enfoca en entrenar la memoria, pero también fomenta el desarrollo de funciones ejecutivas, como la planificación, la organización y la toma de decisiones. La selección de objetos en este tipo de tareas estimula procesos cognitivos complejos, lo que fomenta mejoras en la capacidad de los participantes para estructurar y ejecutar actividades de manera eficiente [95], [98]. Estudios como los de Man et al. [99] y Yamaguchi et al. [100] también reportaron mejoras en la codificación total y dirigida, así como en la memoria episódica, funciones importantes para realizar actividades cotidianas.

La neuroplasticidad parece ser un mecanismo que explica estos beneficios. La exposición a escenarios virtuales fomenta la reactivación cortical, mejorando la conectividad neuronal y el procesamiento de información. Gamito et al. [121] documentaron un aumento del 14% en la cognición global tras intervenciones que combinaban diversas AIVD. Además, la integración de estímulos audiovisuales resultó eficaz para mejorar la codificación de información en memoria episódica, tanto inmediata como diferida [99].

Nuestros resultados mostraron una correlación positiva entre el nivel educativo y las puntuaciones en el MoCA-S. Los participantes con mayor educación lograron mejores resultados tanto antes como después de la intervención ($r = 0{,}799$, $p = 0{,}001$). Este hallazgo concuerda con el estudio de Mondini et al., [101] que sugieren que un mayor nivel educativo puede fortalecer la reserva cognitiva, lo que permite a las personas compensar el deterioro funcional asociado con el DCL.

Ambos grupos experimentaron una reducción significativa en los síntomas depresivos, con una disminución promedio en el SGDS-S ($p < 0{,}001$) y en el grupo experimental ($p = 0{,}005$). Sin embargo, la mejora fue más pronunciada en el grupo control. Una posible explicación es que las actividades tradicionales con lápiz y papel permitieron una mayor interacción directa con el terapeuta, fomentando un vínculo comunicativo y social que podría haber contribuido a la reducción de los síntomas depresivos. Este efecto ha sido descrito por Langoni et al. [102], quienes demostraron que los ejercicios grupales y las interacciones sociales pueden ser particularmente efectivos para mitigar la depresión en adultos mayores. Fjordside y Morville [103] describen que la percepción de autonomía y la interacción social contribuyen en su bienestar emocional.

El análisis por género mostró que las mujeres en ambos grupos experimentaron mejoras significativamente en el nivel de depresión y en las funciones cognitivas. Esto es consistente con el estudio de Kim et al. [104] que sugirieron que las mujeres pueden beneficiarse más de las intervenciones cognitivas y sociales debido a diferencias en la percepción emocional y en el procesamiento cognitivo.

Aunque las mejoras en las funciones cognitivas y motoras fueron evidentes, la transferencia de habilidades a las AVD no mostró diferencias estadísticamente significativas en las evaluaciones post-intervención. McDaniel et al. [105] sugieren que las intervenciones más prolongadas tienen un mayor potencial para promover transferencias funcionales a contextos cotidianos, lo que podría explicar esta mejoría limitada. Además, el metaanálisis de Nguyen et al. [106] se señaló que hay una limitada transferencia de los beneficios del entrenamiento cognitivo a funciones no entrenadas directamente, lo cual coincide con nuestros resultados.

Aunque la escala de Lawton es una de las herramientas validadas más utilizadas para evaluar la funcionalidad en las AIVD, pudo no ser lo suficientemente sensible para detectar cambios en el corto plazo de nuestra intervención, lo que coincide con el estudio de Panerai et al. [107]. No obstante, se observó una mejora específica en el uso de dispositivos como teléfonos inteligentes, lo que refleja un impacto positivo en la adaptación a nuevas tecnologías. El estudio de Wei y Guo [108] mostró que la adopción de tecnología puede tener efectos positivos en la salud y la autonomía del adulto mayor.

3.3. Consideraciones para el diseño de intervenciones

3.3.1. Diseño del protocolo

El protocolo debe estructurar la intervención considerando la duración de las sesiones, la frecuencia y el tiempo total del programa, buscando maximizar los beneficios cognitivos y físicos [109]. Nuestros hallazgos exponen que cada sesión en la que se usen aplicaciones inmersivas podría durar entre 30 y 60, mientras que las no inmersivas podrían durar entre 30 y 90 minutos. De acuerdo con Kourtesis et al. [110], una sesión RVI no debería exceder entre 55 y 70 minutos, con el objetivo de prevenir la aparición de síntomas o efectos adversos asociados a su uso. Este tiempo es suficiente para que el participante se involucre en la actividad sin llegar a experimentar fatiga. Es por esto que en el último artículo de esta tesis [111] se realizaron sesiones de 40 minutos aproximadamente, sin reportar incomodidad en los participantes.

Con respecto a la frecuencia, se pueden realizar 2 a 3 sesiones por semana, lo cual permite que el cerebro y el sistema motor asimilen y consoliden las habilidades aprendidas, garantizando un ritmo sostenido sin sobrecargar al usuario. Esto coincide con el estudio de Laver et al. [112], el cual señala que las sesiones de entrenamiento cognitivo asistido realizadas de 2 a 3 veces por semana, con una duración de 30 a 60 minutos y en grupos pequeños, resultaron ser efectivas.

En cuanto a la duración total, se sugiere que la intervención dure entre 10 y 12 sesiones, un periodo suficiente para observar mejoras significativas en las habilidades cognitivas y físicas. Según la revisión sistemática de Kelly et al. [113], diez sesiones pueden ser un número adecuado, ya que los estudios que analizaron indicaron que extender el periodo no necesariamente garantiza mejores resultados. No obstante, un mayor número de sesiones podría favorecer la formación de hábitos saludables en las personas participantes. En la intervención que se realizó en esta tesis, se ejecutaron dos sesiones semanales, acumulando un total de 12 sesiones, con resultados satisfactorios en la población de estudio.

3.3.2. Nivel de inmersión

Las intervenciones de RV dirigidas a adultos mayores deben considerar cómo el nivel de inmersión afecta la experiencia y los resultados terapéuticos. Los entornos inmersivos, que emplean HMD y simulaciones en 360 grados son adecuados para tareas que demandan planificación y resolución de problemas, es decir, funciones ejecutivas y memoria. Estos entornos recrean situaciones cotidianas de manera realista, por lo que se recomienda su uso para mejorar funciones ejecutivas, memoria y atención selectiva [88], [95]. El modelo de Howard [114] plantea que la sensación de presencia en entornos virtuales puede aumentar la motivación, lo que mejora el compromiso del usuario con el programa. Sin embargo, estos hallazgos deben considerarse con cautela debido a sus posibles efectos adversos, como desorientación y fatiga visual, que pueden limitar su uso en personas con mayor deterioro cognitivo o sensibilidad sensorial [97].

Por otro lado, los entornos semi-inmersivos se recomiendan para los adultos mayores con susceptibilidad a mareos o problemas para adaptarse a las tecnologías inmersivas, como sugieren Romero-Ayuso et al. [115]. Se pueden usar para tareas con menos exigencia cognitiva, como el manejo de medicamentos o ejercicios de memoria visual. Mientras que las aplicaciones no inmersivas son útiles para el entrenamiento cognitivo en etapas iniciales de deterioro o para usuarios con limitaciones motoras y sensoriales. A pesar de ello, en el estudio de Yamaguchi et al. [100] se informaron dificultades al usar un mouse de computadora para realizar tareas de cocina en una intervención de RV no inmersiva, lo cual demuestra que cada nivel tiene consideraciones que deben analizarse.

3.3.3. Ejercicios combinados

La integración de ejercicios cognitivos y motores demostraron resultados positivos, en parte debido al aumento del flujo sanguíneo asociado. No obstante, es relevante comprender mejor la contribución del componente motor en la intervención. Liao et al. [116] describieron que los participantes que alcanzaron entre el 50 y el 75% de su frecuencia cardíaca máxima durante las intervenciones experimentaron mejoras significativas en la flexibilidad cognitiva, la atención dividida y las funciones ejecutivas. Se evidenció una menor activación de áreas prefrontales, lo que puede interpretarse como una señal de mayor eficiencia cognitiva general. Este efecto se atribuye a la liberación de factores neurotróficos derivados del cerebro (BDNF), los cuales están asociados con mejoras en la plasticidad neuronal y el aprendizaje. La revisión de Raichlen et al. [117] respalda estos hallazgos, indicando que los ejercicios aeróbicos en este rango de esfuerzo optimizan el flujo sanguíneo cerebral y la conectividad en regiones asociadas con la memoria y la atención.

Galle et al. [118] reportaron que los participantes que incrementaron su actividad física mostraron mejoras en la velocidad de marcha, la capacidad aeróbica y las funciones ejecutivas. Estos cambios no solo reducen el riesgo de caídas, sino que también potencian la memoria de trabajo y la cognición global. Este efecto positivo también se relaciona con una mayor densidad sináptica y cambios en el grosor cortical, como señalan Chapman et al. [119]. Por su parte, Park et al. [67] reportaron que las intervenciones cognitivas-motoras estimulan el eje hipotalámico-pituitario-adrenal, lo cual mejora la memoria y el aprendizaje. Según Kwan et al. [120], al mejorar su independencia, también se reduce la carga emocional y logística sobre sus familias, creando un impacto positivo en la dinámica familiar.

3.3.4. Diseño según el estado cognitivo del paciente

La intervención debe diseñarse según el estado cognitivo de los participantes. En adultos mayores sanos, las intervenciones deben centrar en tareas que ejerciten la memoria y atención. Estudios como los de Gamito et al. [121] y Zhu et al. [95] demostraron mejoras significativas en la memoria de trabajo y la atención selectiva, con un aumento del 14% en la cognición global tras intervenciones que incluían múltiples tareas de AIVD. Esto puede utilizarse como una medida preventiva para retrasar la aparición de síntomas de deterioro cognitivos relacionados con la edad.

En participantes con DCL, las intervenciones deben abordar entrenar la memoria episódica y funciones ejecutivas como la planificación. Zhu et al. [95] reportaron que las tareas inmersivas como compras virtuales generaron avances significativos en funciones ejecutivas y memoria episódica, mostrando una efectividad superior en comparación con el grupo de control. Kwan et al. (2021) reportaron que los participantes con fragilidad cognitiva percibieron mejoras en tareas reales, como cruzar calles o gestionar compras, gracias al entrenamiento combinado en RV.

Para personas con demencia, las intervenciones se deben enfocar en mantener habilidades funcionales y reducir la carga cognitiva asociada a los entornos inmersivos. Las tareas simples, como organizar elementos o preparar alimentos, permiten reforzar la memoria episódica y la orientación visuoespacial. Masoumzadeh et al. [97] reconocen que las intervenciones en este grupo deben priorizar tareas con alto valor funcional y bajo riesgo de sobrecarga cognitiva. Foloppe et al. [44] encontraron que los entornos virtuales facilitaban el aprendizaje asistido en tareas como la cocina, promoviendo una mayor autonomía. Un estudio longitudinal realizado por Edwards et al. [122] demostró que el entrenamiento cognitivo-motor puede reducir significativamente el riesgo de desarrollar demencia. En este estudio, los participantes que realizaron ejercicios combinados un 33% menos de probabilidades de desarrollar Alzheimer tras un periodo de 10 años, por el efecto neuro protector asociado.

Las intervenciones actuales aún mantienen ciertas limitaciones como la falta de transferencia a otras AIVD no entrenadas, por ello se sugiere combinar estas intervenciones con programas complementarios en entornos reales. Los participantes con demencia en etapas más avanzadas podrían enfrentar mayores desafíos para beneficiarse de entornos inmersivos debido a efectos adversos como mareos o náuseas [95]. Recomendamos administrar el cuestionario de mareo por simulador (SSQ) al inicio del experimento para identificar a los participantes más sensibles y excluirlos si es necesario. También se puede implementar un aumento gradual en la duración y dificultad de las sesiones de entrenamiento en RV para reducir la incidencia de molestias [123], [124]. Las intervenciones deben ajustar los niveles de inmersión y las tareas según las capacidades cognitivas y físicas de cada grupo.

CONCLUSIONES 4

4.1. Conclusiones Principales

La primera publicación, “Cognitive Decline Detection for Alzheimer’s Disease Patients Through an Activity of Daily Living (ADL)”, ha demostrado que es posible desarrollar tareas de cribado basadas en AVD que proporcionen una evaluación precisa y ecológicamente válida para la detección temprana del deterioro cognitivo en adultos mayores. Este estudio contribuye a superar las limitaciones de las pruebas convencionales al ofrecer un entorno de evaluación que emula situaciones de la vida cotidiana, lo cual incrementa la precisión y la representatividad de los resultados para su aplicación clínica.

La segunda publicación, “The Cupboard Task: An Immersive Virtual Reality-Based System for Everyday Memory Assessment”, presentó una aplicación de RVI diseñada para evaluar la memoria en un contexto que simula una actividad diaria. Este estudio confirmó la viabilidad de utilizar un entorno virtual como herramienta para la evaluación de funciones cognitivas. Se validó que "Cupboard Task" es un método efectivo para medir la memoria y atención en una muestra controlada de adultos mayores, demostrando su utilidad para una implementación práctica en el cribado cognitivo.

La tercera publicación, "Influence of Hand Tracking in Immersive Virtual Reality for Memory Assessment," analizó cómo el seguimiento manual podría afectar la evaluación de memoria en entornos de RVI. Aunque se esperaban beneficios de la interacción con seguimiento manual, los resultados indicaron que la precisión, el tiempo de respuesta, la presencia, la usabilidad y la satisfacción no mostraron diferencias estadísticamente significativas frente al uso de controladores tradicionales. Este hallazgo sugiere que el método de interacción puede no ser un factor determinante en la evaluación cognitiva mediante RV y aun se requieren investigaciones futuras para explorar en mayor profundidad cómo el nivel de inmersión y la interacción impactan en el rendimiento cognitivo.

La cuarta publicación, “Virtual Reality Applications Based on Instrumental Activities of Daily Living (iADLs) for Cognitive Intervention in Older Adults: A Systematic Review”, proporcionó una revisión sistemática de las aplicaciones de RV que simulan AIVD en la intervención cognitiva de adultos mayores. Los resultados demostraron el potencial de la RV para mejorar funciones cognitivas como memoria, atención y funciones ejecutivas. También se destaca la importancia de la transferencia del conocimiento adquirido a situaciones de la vida diaria.

La quinta publicación, “Cognitive-Motor Interventions Based on Virtual Reality and Instrumental Activities of Daily Living (iADL): An Overview”, ofreció una visión general de las intervenciones cognitivo-motoras en RV, enfocadas en mejorar tanto las habilidades físicas como cognitivas de los adultos mayores. Este estudio muestra como las intervenciones que combinan entrenamiento motor y cognitivo en RV pueden incrementar la independencia funcional y reducir los riesgos asociados a la movilidad limitada. Un enfoque dual potencia la rehabilitación integral al incorporar las ventajas de cada tipo.

La sexta publicación, "Effects of a Dual Intervention (Motor and Virtual Reality-Based Cognitive) on Cognition in Patients with Mild Cognitive Impairment", presentó los resultados de una intervención dual en RV diseñada para mejorar la cognición en adultos mayores con deterioro cognitivo leve. Los hallazgos demostraron que esta intervención no solo mejora el rendimiento en funciones cognitivas, sino que también reduce significativamente los síntomas depresivos. Esto fortalece la perspectiva de que el entrenamiento combinado puede favorecer la independencia funcional de los participantes.

4.2. Impacto de la tesis y contribución al conocimiento

Los resultados obtenidos en esta tesis doctoral demostraron que las aplicaciones de RV basadas en una AIVD puede ser una herramienta eficaz para la detección y rehabilitación cognitiva en adultos mayores. Al implementar intervenciones que combinan el entrenamiento motor y cognitivo (en un entorno de RV), se refuerza la utilidad de un enfoque dual tanto para la práctica clínica como para la investigación académica en el ámbito de la geriatría y la neurorrehabilitación. A continuación, se detalla el impacto específico en distintos ámbitos.

4.2.1 Ámbito clínico

Uno de los impactos principales de esta tesis doctoral es su aplicación en el ámbito clínico, donde el deterioro cognitivo en adultos mayores plantea retos significativos para la atención y la rehabilitación. En el diagnóstico, las tareas de cribado diseñadas a partir de AVD en entornos virtuales permiten una evaluación más contextualizada del desempeño cognitivo. Los resultados obtenidos con la tarea de armarios físicos (primera publicación) y su adaptación al entorno virtual (segunda publicación) demostraron correlaciones significativas con herramientas estándar, validando su capacidad para detectar deterioro cognitivo en etapas tempranas. Este enfoque no solo evalúa dominios cognitivos, sino que también incorpora elementos funcionales que reflejan la capacidad de los adultos mayores para interactuar con su entorno, ofreciendo una base sólida para intervenciones tempranas y personalizadas.

Las intervenciones que combinan componentes cognitivos y motores, como las desarrolladas en esta investigación, destacan por su efectividad. La evidencia respalda que el aumento del flujo sanguíneo cerebral derivado de la actividad física mejora la neuroplasticidad y la capacidad de aprendizaje del cerebro, predisponiendo a los participantes a un mayor aprovechamiento de las tareas cognitivas. Esto se traduce en mejoras significativas en memoria, atención, planificación y autonomía funcional. Estos diseños basados en intervenciones cognitivo-motoras no solo mejoran el rendimiento mental, sino que también tiene un impacto emocional positivo al reducir síntomas de depresión y ansiedad, fomentando una mayor adherencia al tratamiento. Este modelo integrado de diagnóstico y rehabilitación refuerza el papel de la RV como una herramienta clave en la geriatría, proporcionando un puente entre la evaluación precisa y la intervención efectiva, con beneficios sostenibles en la calidad de vida de los adultos mayores.

4.2.2 Instituciones de cuidados y rehabilitación

Esta tesis doctoral presenta información relevante para instituciones de cuidados a largo plazo y centros de rehabilitación, donde el uso de tecnologías innovadoras puede mejorar las prácticas de atención. El enfoque propuesto combina evaluación, prevención y rehabilitación, adaptándose a las necesidades individuales de cada residente. La RV ofrece un entorno seguro y controlado que minimiza riesgos, como caídas o lesiones, durante las actividades terapéuticas. La simulación virtual de la gestión de medicamentos o la organización de tareas domésticas, pueden ajustarse para mantener un nivel de desafío adecuado, lo que incrementa la adherencia y motivación de los usuarios.

La integración de estas tecnologías en las rutinas diarias de cuidado tiene el potencial de reducir la dependencia de intervenciones farmacológicas. Al ofrecer una alternativa no invasiva y con efectos secundarios mínimos, las aplicaciones de RV contribuyen a un manejo más integral del deterioro cognitivo. Esta tecnología presenta la posibilidad de recopilar datos cuantitativos en tiempo real, lo que permite al personal de salud monitorear el progreso de los pacientes y ajustar el tratamiento de manera más precisa, mejorando las consideraciones terapéuticas y personalizando las intervenciones según las necesidades individuales.

4.2.3 Academia e investigación

Esta investigación amplía el conocimiento sobre la validez ecológica de las evaluaciones realizadas en entornos virtuales, siendo una alternativa más representativa en comparación con las metodologías tradicionales basadas en pruebas de laboratorio. Al integrar tareas simuladas con un alto nivel de realismo, se disminuyen las brechas en la evaluación clínica, al ofrecer una visión más contextualizada del desempeño cognitivo y funcional.

Además, se contribuye a la línea de investigación relacionada con el uso de la RV basada en AVD para la neurorrehabilitación, promoviendo el desarrollo de estudios experimentales y longitudinales que profundicen en los efectos a largo plazo. Este estudio plantea interdisciplinariedad que refuerce la colaboración entre ingenieros, terapeutas e investigadores, para generar soluciones innovadoras y accesibles.

4.3. Limitaciones de la tesis

Aunque se ha demostrado la viabilidad de estas aplicaciones en contextos controlados y se han obtenido resultados prometedores, existen algunas limitaciones inherentes que deben considerarse para futuras investigaciones y aplicaciones en entornos reales. Los ambientes virtuales que simulan AVD han mostrado alta validez ecológica en entornos controlados, pero aún se requiere su validación en ambientes no clínicos. Los resultados obtenidos en este estudio pueden variar al aplicarse en centros de cuidado de adulto mayor o en hogares.

Este estudio se enfocó en adultos mayores con deterioro cognitivo leve, lo que puede restringir la generalización de los hallazgos a individuos en etapas más avanzadas de deterioro, como la demencia moderada o severa. Para estos casos, las intervenciones podrían requerir adaptaciones significativas para atender sus necesidades específicas o estar restringidas. También se debe considerar que algunas personas no sienten familiaridad y comodidad con el uso de esta tecnología, afectando los resultados. Futuras investigaciones deberían considerar formas de adaptar la experiencia de RV para mejorar la accesibilidad y la aceptación en esta población.

La implementación de las intervenciones de RV requiere acceso a equipos especializados, lo cual puede representar una barrera en ciertas instituciones de salud o en hogares que carecen de la infraestructura necesaria y los recursos económicos. Además, dado que las pruebas de la aplicación desarrollada fueron realizadas en un período limitado, no se ha podido evaluar el impacto a largo plazo de estas intervenciones en la cognición y funcionalidad de los adultos mayores. Es posible que algunos efectos beneficiosos se disipen con el tiempo, por esto se motiva al desarrollo de estudios longitudinales que exploren la efectividad sostenida de estas intervenciones.

4.4. Trabajo futuro

Los hallazgos y perspectivas en esta investigación doctoral permiten establecer una serie de propuestas para futuras investigaciones. Desde el punto de vista tecnológico, los avances en la electrónica y la computación están permitiendo el desarrollo de aplicaciones funcionales. Los trabajos futuros deberían enfocarse en perfeccionar dispositivos de entrada y salida de RV, como HMD y controles hápticos, que posibiliten interacciones más naturales y fluidas con los entornos virtuales. Con el lanzamiento de nueva tecnología como el dispositivo Apple Vision Pro a inicios del 2024 se prevé que las aplicaciones de RV tengan un mayor alcance. Durante el desarrollo de esta tesis se utilizó la funcionalidad de seguimiento de manos, observándose que, aunque no se encontraron diferencias significativas en comparación con el uso de controles, esta línea de trabajo tiene el potencial de reducir barreras tecnológicas, especialmente en poblaciones que enfrentan limitaciones motoras.

Estas herramientas deben ajustarse a las necesidades específicas de los adultos mayores, integrando estrategias como las señales/pistas (cues en inglés). Estas señales actúan como guías durante la interacción con los entornos virtuales, ayudando a los usuarios a comprender y ejecutar las tareas de manera más eficiente [125]. Al reducir la carga cognitiva, las señales facilitan el aprendizaje, mejoran la ejecución y promueven la transferencia de habilidades adquiridas a contextos reales. Para maximizar la efectividad de estas herramientas, se debe optimizar la experiencia del usuario. Esto incluye considerar la inmersión sensorial mediante estímulos visuales, auditivos, táctiles e incluso olfativos y gustativos, creando entornos virtuales envolventes y convincentes. Como se menciona en una reciente revisión [126], existe poca información sobre los estímulos distintos a los audiovisuales hasta el momento, por lo que se abre una interesante línea en la simulación y evaluación de estos. Asimismo, elementos como la latencia, el realismo y la interactividad son determinantes para fortalecer la sensación de presencia del usuario en el entorno virtual. Estos factores, al integrarse adecuadamente, no solo harán que la experiencia sea más fluida y atractiva, sino que también mejoran el compromiso del usuario, aumentando la efectividad y adherencia a las intervenciones propuestas.

En este contexto, los avances en computación e inteligencia artificial (IA) han abierto nuevas oportunidades para optimizar la interacción humano-máquina. Estas tecnologías permiten un análisis detallado del comportamiento del usuario, lo que facilita la creación de sistemas más intuitivos y adaptables. Los estudios futuros deberán estudiar la personalización y usabilidad que las aplicaciones de RV pueden brindar mediante el uso de algoritmos de IA. Estas tecnologías tienen el potencial de transformar la experiencia del usuario al permitir ajustes dinámicos en la complejidad de las tareas, adaptándose en tiempo real al progreso, las capacidades y las necesidades específicas de cada individuo. Por ejemplo, un algoritmo de IA podría identificar patrones en el desempeño del usuario y ajustar automáticamente parámetros como el nivel de dificultad, la duración de las sesiones o la frecuencia de las pistas. Como han indicado Oumaima et al. [127] se podrán personalizar los mundos virtuales, lo que podría mejorar los resultados terapéuticos al proporcionar desafíos adecuados para cada etapa del tratamiento, fomentando la adherencia. Sin embargo, para comprobar el verdadero impacto obtenido es necesario evaluar cómo los usuarios perciben y utilizan estas tecnologías.

La inclusión de elementos que conecten emocional y cognitivamente con el usuario puede mejorar los resultados terapéuticos. Una narrativa bien estructurada en las actividades simuladas dentro del entorno virtual permitirá que el usuario se involucre de manera significativa. La simulación de AVD, aunque prometedora, aún necesita explorarse para diversificar y personalizar las tareas. Futuros estudios podrían centrarse en simulaciones que integren varias AIVD con la planificación de actividades sociales, ya que la evidencia menciona que los problemas cognitivos pueden promover el aislamiento social [128]. La inclusión de escenarios culturalmente relevantes podría contribuir a la transferencia de habilidades al entorno real. Esto es particularmente importante en poblaciones mayores, donde las diferencias culturales pueden influir en la percepción y efectividad de las tareas simuladas. Esto fomenta un sentido de pertenencia y compromiso, incrementando la posibilidad de tener resultados sostenibles en el tiempo.

Por otro lado, la combinación de AVD con el análisis de biomarcadores muestra una línea de investigación poco explorada [129]. Al integrar tecnologías de monitorización en tiempo real, como sensores portátiles o dispositivos de RV habilitados para la recopilación de datos fisiológicos, se puede evaluar simultáneamente el impacto cognitivo y físico de las tareas realizadas. Esto permitiría identificar patrones relacionados con el esfuerzo mental, la atención y las respuestas emocionales, ofreciendo una visión más integral del efecto de las intervenciones. Además, este enfoque podría ayudar a personalizar aún más las aplicaciones, ajustando dinámicamente la dificultad de las tareas en función de las respuestas fisiológicas del usuario, contribuyendo a la efectividad terapéutica y minimizando riesgos asociados como la fatiga o el estrés [130].

Aunque hay evidencia que respalda los beneficios potenciales de la RV en el adulto mayor, pocos estudios abordan si estas herramientas son realmente accesibles, intuitivas y aceptadas. Para garantizar que los sistemas desarrollados generen la experiencia deseada, los trabajos futuros deben diseñar y aplicar pruebas específicas que midan aspectos como usabilidad, facilidad de interacción y percepción del usuario. La usabilidad incluye factores como la facilidad de uso, la claridad de las instrucciones y la adaptación de las interfaces a las capacidades cognitivas y motoras de los adultos mayores. Por ejemplo, pruebas como la escala de usabilidad del sistema (SUS) o el cuestionario de usabilidad del sistema posterior al estudio (PSSUQ) podrían ser adaptadas para evaluar la experiencia específica de esta población [131]. Además, la aceptación tecnológica, evaluada a través de modelos como el modelo de aceptación de tecnología (TAM), permitirá identificar barreras y facilitadores en la adopción de estas tecnologías. Esto incluye el análisis de factores como la percepción de utilidad, la facilidad percibida y la intención de uso continuo [132]. Por otro lado, instrumentos cualitativos como entrevistas y grupos focales podrían complementar estas evaluaciones, proporcionando información detallada sobre las expectativas, preocupaciones y preferencias de los usuarios.

Desde el punto de vista clínico, la mayoría de los estudios previos se centraron en entornos controlados, como laboratorios [105], [133], [134] o centros de cuidado [116], [120], [135]. Como mencionan Miller et al. [136], los sistemas de RV y juegos serios tienen viabilidad para trasladarse al entorno doméstico. Este enfoque podría beneficiarse del diseño de intervenciones basadas en RV que permitan la interacción del participante tanto de manera autónoma como con el apoyo de sus familiares. Al integrarse en la rutina diaria, estas tecnologías no solo amplían su accesibilidad, sino que también favorecen la continuidad del tratamiento, fomentando el auto entrenamiento y la independencia funcional. Para ello, se deben desarrollar interfaces intuitivas que faciliten su uso independiente, así como sistemas de monitorización remotos que permitan a los profesionales de la salud supervisar el progreso de forma efectiva y ajustar las intervenciones según sea necesario [137].

En paralelo, se debe atender a poblaciones con alta fragilidad, como los pacientes con demencia, quienes podrían beneficiarse significativamente de las aplicaciones tecnológicas. Aunque la evidencia actual respalda la seguridad y eficacia de estas herramientas para fomentar un estilo de vida activo en esta población, coincidimos con Sortino et al. [138], en que se requieren investigaciones adicionales para maximizar su utilidad y accesibilidad. Estas investigaciones deberían enfocarse en adaptar las tecnologías a personas con demencia moderada o avanzada, una población cuya prevalencia sigue en aumento a nivel mundial. Estas condiciones representan un desafío significativo, pero también una oportunidad para explorar la viabilidad de las intervenciones en etapas avanzadas del deterioro cognitivo.

Los futuros estudios deberán abordar la pertinencia de estas aplicaciones en dichas etapas, definiendo ajustes específicos para minimizar la carga cognitiva, adaptarse a las limitaciones motoras y sensoriales, y maximizar los beneficios terapéuticos. Las actividades podrían centrarse en objetivos emocionales y funcionales, priorizando tareas que promuevan la conexión social, la estimulación sensorial y la mejora del bienestar general. Por ejemplo, simular actividades sencillas de la vida diaria, como organizar objetos o identificar colores y formas, puede facilitar la interacción con el entorno virtual sin generar frustración. Además, se podría explorar el impacto de la RV en la reducción de síntomas conductuales y psicológicos asociados con la demencia, como la ansiedad.

En esta tesis se obtuvo una mejora en la escala de depresión por medio de una intervención cognitivo-motora, por lo que se contribuyó a la generación de herramientas basadas en RV para el manejo integral de estas condiciones.

REFERENCIAS

[1] E. Nichols *et al.*, «Estimation of the global prevalence of dementia in 2019 and forecasted prevalence in 2050: an analysis for the Global Burden of Disease Study 2019», *The Lancet Public Health*, vol. 7, n.º 2, pp. e105-e125, feb. 2022, doi: 10.1016/S2468-2667(21)00249-8.

[2] C. Iribarne, V. Renner, C. Pérez, y D. L. de Guevara, «Trastornos del Ánimo y Demencia. Aspectos clínicos y estudios complementarios en el diagnóstico diferencial», *Revista Médica Clínica Las Condes*, vol. 31, n.º 2, pp. 150-162, mar. 2020, doi: 10.1016/j.rmclc.2020.02.001.

[3] X.-X. Zhang, Y. Tian, Z.-T. Wang, Y.-H. Ma, L. Tan, y J.-T. Yu, «The Epidemiology of Alzheimer's Disease Modifiable Risk Factors and Prevention», *J Prev Alzheimers Dis*, vol. 8, n.º 3, pp. 313-321, jul. 2021, doi: 10.14283/jpad.2021.15.

[4] C. Iadecola *et al.*, «Vascular Cognitive Impairment and Dementia», *Journal of the American College of Cardiology*, vol. 73, n.º 25, pp. 3326-3344, jul. 2019, doi: 10.1016/j.jacc.2019.04.034.

[5] M. Jonson, S. Avramescu, D. Chen, y F. Alam, «The Role of Virtual Reality in Screening, Diagnosing, and Rehabilitating Spatial Memory Deficits», *Frontiers in Human Neuroscience*, vol. 15, p. 32, feb. 2021, doi: 10.3389/fnhum.2021.628818.

[6] J. Zhang, «Cognitive Functions of the Brain: Perception, Attention and Memory», 30 de mayo de 2019, *arXiv*: arXiv:1907.02863. doi: 10.48550/arXiv.1907.02863.

[7] K. Oberauer, «Working Memory and Attention – A Conceptual Analysis and Review», *J Cogn*, vol. 2, n.º 1, p. 36, 2019, doi: 10.5334/joc.58.

[8] K. Desmond y N. Mindo, «Neurodevelopmental and Executive Function and Dysfunction - ClinicalKey», en *Nelson Textbook of Pediatrics*, 2020. Accedido: 20 de noviembre de 2024. [En línea]. Disponible en: https://www.clinicalkey.es/#!/content/book/3-s2.0-B9780323529501000481

[9] N. Sato, «Memory Processing in the Nervous System», en *Understanding Information: From the Big Bang to Big Data*, A. J. Schuster, Ed., Cham: Springer International Publishing, 2017, pp. 83-98. doi: 10.1007/978-3-319-59090-5_5.

[10] D. Tromp, A. Dufour, S. Lithfous, T. Pebayle, y O. Després, «Episodic memory in normal aging and Alzheimer disease: Insights from imaging and behavioral studies», *Ageing Research Reviews*, vol. 24, pp. 232-262, nov. 2015, doi: 10.1016/j.arr.2015.08.006.

[11] S. Weintraub, A. H. Wicklund, y D. P. Salmon, «The Neuropsychological Profile of Alzheimer Disease», *Cold Spring Harb Perspect Med*, vol. 2, n.º 4, p. a006171, ene. 2012, doi: 10.1101/cshperspect.a006171.

[12] J. Jonides, T. D. Wager, y D. T. Badre, «Memory, neuroimaging», en *Encyclopedia of the Human Brain*, vol. 1, Elsevier, 2002.

[13] I. Cristofori, S. Cohen-Zimerman, y J. Grafman, «Chapter 11 - Executive functions», en *Handbook of Clinical Neurology*, vol. 163, M. D'Esposito y J. H. Grafman, Eds., en The Frontal Lobes, vol. 163. , Elsevier, 2019, pp. 197-219. doi: 10.1016/B978-0-12-804281-6.00011-2.

[14] A. D. Baddeley y G. Hitch, «Working Memory», en *Psychology of Learning and Motivation*, vol. 8, G. H. Bower, Ed., Academic Press, 1974, pp. 47-89. doi: 10.1016/S0079-7421(08)60452-1.

[15] I. Tarnanas, W. Schlee, M. Tsolaki, R. Müri, U. Mosimann, y T. Nef, «Ecological validity of virtual reality daily living activities screening for early dementia: Longitudinal study», *JMIR Serious Games*, vol. 1, n.º 1, p. e2778, ago. 2013, doi: 10.2196/games.2778.

[16] R. J. Perry y J. R. Hodges, «Fate of Patients with Questionable (Very Mild) Alzheimer's Disease: Longitudinal Profiles of Individual Subjects' Decline», *DEM*, vol. 11, n.º 6, pp. 342-349, 2000, doi: 10.1159/000017264.

[17] M. S. Bosma, T. C. W. Nijboer, M. A. A. Caljouw, y W. P. Achterberg, «Impact of visuospatial neglect post-stroke on daily activities, participation and informal caregiver burden: A systematic review», *Annals of Physical and Rehabilitation Medicine*, vol. 63, n.º 4, pp. 344-358, jul. 2020, doi: 10.1016/j.rehab.2019.05.006.

[18] Q. Oort, M. J. B. Taphoorn, S. A. M. Sikkes, B. M. J. Uitdehaag, J. C. Reijneveld, y L. Dirven, «Evaluation of the content coverage of questionnaires containing basic and instrumental activities of daily living (ADL) used in adult patients with brain tumors», *J Neurooncol*, vol. 143, n.º 1, pp. 1-13, may 2019, doi: 10.1007/s11060-019-03136-9.

[19] S. S. Roley *et al.*, «Occupational therapy practice framework: Domain & process 2nd edition», *American Journal of Occupational Therapy*, vol. 62, n.º 6, pp. 625-683, nov. 2008, doi: 10.5014/ajot.62.6.625.

[20] S. Joubert, L. Gardy, M. Didic, I. Rouleau, y E. J. Barbeau, «A Meta-Analysis of Semantic Memory in Mild Cognitive Impairment», *Neuropsychol Rev*, vol. 31, n.º 2, pp. 221-232, jun. 2021, doi: 10.1007/s11065-020-09453-5.

[21] H. Amieva *et al.*, «Prodromal Alzheimer's disease: Successive emergence of the clinical symptoms», *Annals of Neurology*, vol. 64, n.º 5, pp. 492-498, 2008, doi: 10.1002/ana.21509.

[22] M. Adolphe, M. Sawayama, D. Maurel, A. Delmas, P.-Y. Oudeyer, y H. Sauzéon, «An Open-Source Cognitive Test Battery to Assess Human Attention and Memory», *Front. Psychol.*, vol. 13, jun. 2022, doi: 10.3389/fpsyg.2022.880375.

[23] Z. S. Nasreddine *et al.*, «The Montreal Cognitive Assessment, MoCA: A Brief Screening Tool For Mild Cognitive Impairment», *Journal of the American Geriatrics Society*, vol. 53, n.º 4, pp. 695-699, 2005, doi: 10.1111/j.1532-5415.2005.53221.x.

[24] M. F. Folstein, S. E. Folstein, y P. R. McHugh, «"Mini-mental state": A practical method for grading the cognitive state of patients for the clinician», *Journal of Psychiatric Research*, vol. 12, n.º 3, pp. 189-198, nov. 1975, doi: 10.1016/0022-3956(75)90026-6.

[25] A. Smith, *Symbol digit modalities test: Manual*. Los Angeles, CA: Western Psychological Services, 1982. Accedido: 5 de enero de 2025. [En línea]. Disponible en: https://doi.apa.org/doi/10.1037/t27513-000

[26] A. Rey, «L'examen psychologique dans les cas d'encephalopathie traumatique», *Archives de Psychologie*, vol. 28, pp. 286-340, 1941, doi: 10.2466/PMS.8.7.271-276.

[27] A. K. Troyer y J. B. Rich, «Psychometric Properties of a New Metamemory Questionnaire for Older Adults», *The Journals of Gerontology: Series B*, vol. 57, n.º 1, pp. P19-P27, ene. 2002, doi: 10.1093/geronb/57.1.P19.

[28] R. M. Reitan, «Validity of the Trail Making Test as an indicator of organic brain damage», *Perceptual and Motor Skills*, vol. 8, pp. 271-276, 1958, doi: 10.2466/PMS.8.7.271-276.

[29] E. E. De Roeck, P. P. De Deyn, E. Dierckx, y S. Engelborghs, «Brief cognitive screening instruments for early detection of Alzheimer's disease: a systematic review», *Alzheimer's Research & Therapy*, vol. 11, n.º 1, p. 21, feb. 2019, doi: 10.1186/s13195-019-0474-3.

[30] A. Lobo, V. Escobar, J. Ezquerra, y A. Seva Díaz, «"El Mini-Examen Cognoscitivo" (Un test sencillo, práctico, para detectar alteraciones intelectuales en pacientes psiquiátricos)», *Revista de Psiquiatría y Psicología Médica*, vol. 14, n.º 5, pp. 39-57, 1980.

[31] J. A. Yesavage *et al.*, «Development and validation of a geriatric depression screening scale: A preliminary report», *Journal of Psychiatric Research*, vol. 17, n.º 1, pp. 37-49, ene. 1982, doi: 10.1016/0022-3956(82)90033-4.

[32] M. P. Lawton y E. M. Brody, «Assessment of older people: Self-maintaining and instrumental activities of daily living», *The Gerontologist*, vol. 9, n.º 3, Pt 1, pp. 179-186, 1969, doi: 10.1093/geront/9.3_Part_1.179.

[33] S. Na, E.-S. Lee, y T.-K. Lee, «Diagnostic Performance of a Tablet Computer-Based Cognitive Screening Test for Identification of Amnestic Mild Cognitive Impairment», *Journal of Korean Medical Science*, vol. 38, n.º 17, p. e131, abr. 2023, doi: 10.3346/jkms.2023.38.e131.

[34] M. J. Begemann, B. A. Brand, B. Ćurčić-Blake, A. Aleman, y I. E. Sommer, «Efficacy of non-invasive brain stimulation on cognitive functioning in brain disorders: a meta-analysis», *Psychological Medicine*, vol. 50, n.º 15, pp. 2465-2486, nov. 2020, doi: 10.1017/S0033291720003670.

[35] I. Tarnanas, W. Schlee, M. Tsolaki, R. Müri, U. Mosimann, y T. Nef, «Ecological validity of virtual reality daily living activities screening for early dementia: Longitudinal study», *JMIR Serious Games*, vol. 1, n.º 1, p. e2778, ago. 2013, doi: 10.2196/games.2778.

[36] N. Chaytor y M. Schmitter-Edgecombe, «The ecological validity of neuropsychological tests: A review of the literature on everyday cognitive skills», *Neuropsychology Review*, vol. 13, n.º 4, pp. 181-197, dic. 2003, doi: 10.1023/B:NERV.0000009483.91468.fb.

[37] C. L. Thompson, J. D. Henry, A. Withall, P. G. Rendell, y H. Brodaty, «A naturalistic study of prospective memory function in MCI and dementia», *British Journal of Clinical Psychology*, vol. 50, n.º 4, pp. 425-434, nov. 2011, doi: 10.1111/j.2044-8260.2010.02004.x.

[38] M. F. Schwartz, M. Segal, T. Veramonti, M. Ferraro, y L. J. Buxbaum, «The Naturalistic Action Test: A standardised assessment for everyday action impairment», *Neuropsychological Rehabilitation*, vol. 12, n.º 4, pp. 311-339, sep. 2002, doi: 10.1080/09602010244000084.

[39] T. Giovannetti, K. S. Schmidt, J. L. Gallo, N. Sestito, y D. J. Libon, «Everyday action in dementia: Evidence for differential deficits in Alzheimer's disease versus subcortical vascular dementia», *Journal of the International Neuropsychological Society*, vol. 12, n.º 1, pp. 45-53, ene. 2006, doi: 10.1017/S1355617706060012.

[40] J. D. O'Leary, O. F. O'Leary, J. F. Cryan, y Y. M. Nolan, «A low-cost touchscreen operant chamber using a Raspberry Pi^{TM}», *Behav Res*, vol. 50, n.º 6, pp. 2523-2530, dic. 2018, doi: 10.3758/s13428-018-1030-y.

[41] M. Pitteri, C. Dapor, S. Ziccardi, M. Guandalini, R. Meggiato, y M. Calabrese, «Visual-Attentional Load Unveils Slowed Processing Speed in Multiple Sclerosis Patients: A Pilot

Study with a Tablet-Based Videogame», *Brain Sciences*, vol. 10, n.º 11, Art. n.º 11, nov. 2020, doi: 10.3390/brainsci10110871.

[42] S.-M. Khaligh-Razavi *et al.*, «Integrated Cognitive Assessment: Speed and Accuracy of Visual Processing as a Reliable Proxy to Cognitive Performance», *Sci Rep*, vol. 9, n.º 1, p. 1102, ene. 2019, doi: 10.1038/s41598-018-37709-x.

[43] R. Burman, «Virtual Reality's Evolution From Science Fiction to Mainstream Technology», NextGen Invent Corporation. Accedido: 11 de noviembre de 2024. [En línea]. Disponible en: https://nextgeninvent.com/blogs/the-evolution-of-virtual-reality/

[44] D. A. Foloppe, P. Richard, T. Yamaguchi, F. Etcharry-Bouyx, y P. Allain, «The potential of virtual reality-based training to enhance the functional autonomy of Alzheimer's disease patients in cooking activities: A single case study», *Neuropsychological Rehabilitation*, vol. 28, n.º 5, pp. 709-733, jul. 2018, doi: 10.1080/09602011.2015.1094394.

[45] J. Vindenes, A. O. de Gortari, y B. Wasson, «Mnemosyne: Adapting the method of loci to immersive virtual reality», *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 10850 LNCS, pp. 205-213, 2018, doi: 10.1007/978-3-319-95270-3_16.

[46] J. B. Caplan, E. L. G. Legge, B. Cheng, y C. R. Madan, «Effectiveness of the method of loci is only minimally related to factors that should influence imagined navigation», *Quarterly Journal of Experimental Psychology*, vol. 72, n.º 10, pp. 2541-2553, oct. 2019, doi: 10.1177/1747021819858041.

[47] S. M. C. Davison, C. Deeprose, y S. Terbeck, «A comparison of immersive virtual reality with traditional neuropsychological measures in the assessment of executive functions», *Acta Neuropsychiatrica*, vol. 30, n.º 2, pp. 79-89, abr. 2018, doi: 10.1017/neu.2017.14.

[48] M. D. Barnett, L. G. Childers, y T. D. Parsons, «A Virtual Kitchen Protocol to Measure Everyday Memory Functioning for Meal Preparation», *Brain Sciences*, vol. 11, n.º 5, Art. n.º 5, may 2021, doi: 10.3390/brainsci11050571.

[49] P. Allain *et al.*, «Detecting Everyday Action Deficits in Alzheimer's Disease Using a Nonimmersive Virtual Reality Kitchen», *Journal of the International Neuropsychological Society*, vol. 20, n.º 5, pp. 468-477, may 2014, doi: 10.1017/S1355617714000344.

[50] É. Ouellet, B. Boller, N. Corriveau-Lecavalier, S. Cloutier, y S. Belleville, «The Virtual Shop: A new immersive virtual reality environment and scenario for the assessment of everyday memory», *Journal of Neuroscience Methods*, vol. 303, pp. 126-135, jun. 2018, doi: 10.1016/j.jneumeth.2018.03.010.

[51] A. E. Martis, C. Bassano, F. Solari, y M. Chessa, «Going to a Virtual Supermarket: Comparison of Different Techniques for Interacting in a Serious Game for the Assessment of the Cognitive Status», en *New Trends in Image Analysis and Processing – ICIAP 2017*, S. Battiato, G. M. Farinella, M. Leo, y G. Gallo, Eds., Cham: Springer International Publishing, 2017, pp. 281-289. doi: 10.1007/978-3-319-70742-6_26.

[52] C. Zucchella *et al.*, «The Multidisciplinary Approach to Alzheimer's Disease and Dementia. A Narrative Review of Non-Pharmacological Treatment», *Front. Neurol.*, vol. 9, dic. 2018, doi: 10.3389/fneur.2018.01058.

[53] A. T. C. Chan, R. T. F. Ip, J. Y. S. Tran, J. Y. C. Chan, y K. K. F. Tsoi, «Computerized cognitive training for memory functions in mild cognitive impairment or dementia: a systematic

review and meta-analysis», *npj Digit. Med.*, vol. 7, n.º 1, pp. 1-11, ene. 2024, doi: 10.1038/s41746-023-00987-5.

[54] J. Carroll, L. Hopper, A. M. Farrelly, R. Lombard-Vance, P. D. Bamidis, y E. I. Konstantinidis, «A Scoping Review of Augmented/Virtual Reality Health and Wellbeing Interventions for Older Adults: Redefining Immersive Virtual Reality», *Front. Virtual Real.*, vol. 2, jun. 2021, doi: 10.3389/frvir.2021.655338.

[55] R. De Luca *et al.*, «Cognitive rehabilitation using immersive virtual reality at young age: A case report on traumatic brain injury», *Applied Neuropsychology: Child*, vol. 9, n.º 3, pp. 282-287, jul. 2020, doi: 10.1080/21622965.2019.1576525.

[56] P. Grewe *et al.*, «Learning real-life cognitive abilities in a novel 360°-virtual reality supermarket: a neuropsychological study of healthy participants and patients with epilepsy», *J NeuroEngineering Rehabil*, vol. 10, n.º 1, p. 42, abr. 2013, doi: 10.1186/1743-0003-10-42.

[57] T. D. Parsons y T. McMahan, «An initial validation of the Virtual Environment Grocery Store», *Journal of Neuroscience Methods*, vol. 291, pp. 13-19, nov. 2017, doi: 10.1016/j.jneumeth.2017.07.027.

[58] K. Chatterjee, A. Buchanan, K. Cottrell, S. Hughes, T. W. Day, y N. W. John, «Immersive Virtual Reality for the Cognitive Rehabilitation of Stroke Survivors», *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 30, pp. 719-728, 2022, doi: 10.1109/TNSRE.2022.3158731.

[59] S. Mohapatra y S. T. Kulnik, «Kitchen-related tasks used in occupational therapy during rehabilitation of adults with acquired brain injury: A systematic review», *British Journal of Occupational Therapy*, vol. 84, n.º 1, pp. 22-41, ene. 2021, doi: 10.1177/0308022620950975.

[60] S. Sharples, S. Cobb, A. Moody, y J. R. Wilson, «Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems», *Displays*, vol. 29, n.º 2, pp. 58-69, mar. 2008, doi: 10.1016/j.displa.2007.09.005.

[61] F. Marson, S. Lasaponara, y M. Cavallo, «A Scoping Review of Neuromodulation Techniques in Neurodegenerative Diseases: A Useful Tool for Clinical Practice?», *Medicina*, vol. 57, n.º 3, Art. n.º 3, mar. 2021, doi: 10.3390/medicina57030215.

[62] F. Mora, «Successful brain aging: plasticity, environmental enrichment, and lifestyle», *Dialogues in Clinical Neuroscience*, vol. 15, n.º 1, pp. 45-52, mar. 2013, doi: 10.31887/DCNS.2013.15.1/fmora.

[63] S. Zhu *et al.*, «Effects of virtual reality-based intervention on cognition, motor function, Mood, and activities of Daily living in pat», *Front. Aging Neurosci.*, vol. 13, may 2021, doi: 10.3389/fnagi.2021.586999.

[64] Y. Gao *et al.*, «Effects of Virtual Reality-Based Intervention on Cognition, Motor Function, Mood, and Activities of Daily Living in Patients With Chronic Stroke: A Systematic Review and Meta-Analysis of Randomized Controlled Trials», *Front. Aging Neurosci.*, vol. 13, dic. 2021, doi: 10.3389/fnagi.2021.766525.

[65] R. J. Adams *et al.*, «Virtual Activities of Daily Living for Recovery of Upper Extremity Motor Function», *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, n.º 1, pp. 252-260, ene. 2018, doi: 10.1109/TNSRE.2017.2771272.

[66] M. Guidali, A. Duschau-Wicke, S. Broggi, V. Klamroth-Marganska, T. Nef, y R. Riener, «A robotic system to train activities of daily living in a virtual environment», *Med Biol Eng Comput*, vol. 49, n.º 10, pp. 1213-1223, oct. 2011, doi: 10.1007/s11517-011-0809-0.

[67] J.-S. Park, Y.-J. Jung, y G. Lee, «Virtual Reality-Based Cognitive-Motor Rehabilitation in Older Adults with Mild Cognitive Impairment: A Randomized Controlled Study on Motivation and Cognitive Function», *Healthcare (Basel)*, vol. 8, n.º 3, p. 335, sep. 2020, doi: 10.3390/healthcare8030335.

[68] K. Laver, S. George, J. Ratcliffe, y M. Crotty, «Virtual reality stroke rehabilitation – hype or hope?», *Australian Occupational Therapy Journal*, vol. 3, n.º 58, pp. 215-219, may 2011, doi: 10.1111/j.1440-1630.2010.00897.x.

[69] F. González-Landero, I. García-Magariño, R. Amariglio, y R. Lacuesta, «Smart Cupboard for Assessing Memory in Home Environment», *Sensors*, vol. 19, n.º 11, Art. n.º 11, ene. 2019, doi: 10.3390/s19112552.

[70] J.-A. Gil-Gómez, P. Manzano-Hernández, S. Albiol-Pérez, C. Aula-Valero, H. Gil-Gómez, y J.-A. Lozano-Quilis, «USEQ: A Short Questionnaire for Satisfaction Evaluation of Virtual Rehabilitation Systems», *Sensors*, vol. 17, n.º 7, Art. n.º 7, jul. 2017, doi: 10.3390/s17071589.

[71] M. Z. Nakhla, D. Banuelos, C. Pagán, A. Gavarrete Olvera, y J. Razani, «Differences between episodic and semantic memory in predicting observation-based activities of daily living in mild cognitive impairment and Alzheimer's disease», *Applied Neuropsychology: Adult*, vol. 29, n.º 6, pp. 1499-1510, nov. 2022, doi: 10.1080/23279095.2021.1893172.

[72] M. O. Pflueger, R.-D. Stieglitz, P. Lemoine, y T. Leyhe, «Ecologically relevant episodic memory assessment indicates an attenuated age-related memory loss – A virtual reality study», *Neuropsychology*, vol. 32, n.º 6, pp. 680-689, 2018, doi: 10.1037/neu0000454.

[73] G. Ward, C. Jagger, y W. Harper, «A review of instrumental ADL assessments for use with elderly people», *Reviews in Clinical Gerontology*, vol. 8, n.º 1, pp. 65-71, feb. 1998, doi: 10.1017/S0959259898008089.

[74] J. Robin, B. R. Buchsbaum, y M. Moscovitch, «The Primacy of Spatial Context in the Neural Representation of Events», *J. Neurosci.*, vol. 38, n.º 11, pp. 2755-2765, mar. 2018, doi: 10.1523/JNEUROSCI.1638-17.2018.

[75] N. Reggente, J. K. Y. Essoe, H. Y. Baek, y J. Rissman, «The Method of Loci in Virtual Reality: Explicit Binding of Objects to Spatial Contexts Enhances Subsequent Memory Recall», *J Cogn Enhanc*, vol. 4, n.º 1, pp. 12-30, mar. 2020, doi: 10.1007/s41465-019-00141-8.

[76] C. Kalafatis *et al.*, «Validity and Cultural Generalisability of a 5-Minute AI-Based, Computerised Cognitive Assessment in Mild Cognitive Impairment and Alzheimer's Dementia», *Front. Psychiatry*, vol. 12, jul. 2021, doi: 10.3389/fpsyt.2021.706695.

[77] J. E. Baker *et al.*, «Episodic Memory and Learning Dysfunction Over an 18-Month Period in Preclinical and Prodromal Alzheimer's Disease», *Journal of Alzheimer's Disease*, vol. 65, n.º 3, pp. 977-988, ene. 2018, doi: 10.3233/JAD-180344.

[78] J. M. Poos, I. J. M. van der Ham, A. E. Leeuwis, Y. A. L. Pijnenburg, W. M. van der Flier, y A. Postma, «Short Digital Spatial Memory Test Detects Impairment in Alzheimer's Disease and Mild Cognitive Impairment», *Brain Sciences*, vol. 11, n.º 10, Art. n.º 10, oct. 2021, doi: 10.3390/brainsci11101350.

[79] V. Drolet *et al.*, «Comparaison des performances à l'épreuve des 15 mots de Rey et au RL/RI 16 dans le vieillissement normal et la démence de type Alzheimer», *Gériatrie et Psychologie Neuropsychiatrie du Vieillissement*, vol. 12, n.º 2, pp. 218-226, jun. 2014, doi: 10.1684/pnv.2014.0469.

[80] P. De Vriendt, E. Cornelis, W. Cools, y E. Gorus, «The Usefulness of Evaluating Performance of Activities in Daily Living in the Diagnosis of Mild Cognitive Disorders», *International Journal of Environmental Research and Public Health*, vol. 18, n.º 21, Art. n.º 21, ene. 2021, doi: 10.3390/ijerph182111623.

[81] D. V. Cicchetti, «Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology», *Psychological Assessment*, vol. 6, n.º 4, pp. 284-290, 1994, doi: 10.1037/1040-3590.6.4.284.

[82] S. D. Moffat, A. B. Zonderman, y S. M. Resnick, «Age differences in spatial memory in a virtual environment navigation task», *Neurobiology of Aging*, vol. 22, n.º 5, pp. 787-796, sep. 2001, doi: 10.1016/S0197-4580(01)00251-2.

[83] A. K. Troyer, L. Leach, y E. Strauss, «Aging and Response Inhibition: Normative Data for the Victoria Stroop Test», *Aging, Neuropsychology, and Cognition*, vol. 13, n.º 1, pp. 20-35, ene. 2006, doi: 10.1080/138255890968187.

[84] F. I. M. Craik, «A functional account of age differences in memory», en *Human Memory and Cognitive Capabilities, Mechanisms and Performances*, F. Klix y H. Hagendorf, Eds., Amsterdam: Elsevier, 1986, pp. 409-422.

[85] C. M. Armstrong, G. M. Reger, J. Edwards, A. A. Rizzo, C. G. Courtney, y T. D. Parsons, «Validity of the Virtual Reality Stroop Task (VRST) in active duty military», *Journal of Clinical and Experimental Neuropsychology*, vol. 35, n.º 2, pp. 113-123, feb. 2013, doi: 10.1080/13803395.2012.740002.

[86] I. García-Magariño, J. T. Fox-Fuller, G. Palacios-Navarro, A. Baena, y Y. T. Quiroz, «Visual working memory for semantically related objects in healthy adults», *Rev Neurol*, vol. 71, n.º 8, pp. 277-284, oct. 2020, doi: 10.33588/rn.7108.2019479.

[87] S. Ventura, E. Brivio, G. Riva, y R. M. Baños, «Immersive Versus Non-immersive Experience: Exploring the Feasibility of Memory Assessment Through 360° Technology», *Front. Psychol.*, vol. 10, nov. 2019, doi: 10.3389/fpsyg.2019.02509.

[88] E. Krokos, C. Plaisant, y A. Varshney, «Virtual memory palaces: immersion aids recall», *Virtual Real.*, vol. 23, n.º 1, pp. 1-15, mar. 2019, doi: 10.1007/s10055-018-0346-3.

[89] M. Hassandra *et al.*, «A Virtual Reality App for Physical and Cognitive Training of Older People With Mild Cognitive Impairment: Mixed Methods Feasibility Study», *JMIR Serious Games*, vol. 9, n.º 1, p. e24170, mar. 2021, doi: 10.2196/24170.

[90] N. Jamalian, M. Gillies, F. F. Leymarie, y X. Pan, «The Effects of Hand Tracking on User Performance: an experimental study of an object selection based memory game», en *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, oct. 2022, pp. 768-776. doi: 10.1109/ISMAR55827.2022.00095.

[91] B. G. Witmer y M. J. Singer, «Measuring Presence in Virtual Environments: A Presence Questionnaire», *Presence: Teleoperators and Virtual Environments*, vol. 7, n.º 3, pp. 225-240, jun. 1998, doi: 10.1162/105474698565686.

[92] K. Finstad, «The Usability Metric for User Experience», *Interacting with Computers*, vol. 22, n.º 5, pp. 323-327, sep. 2010, doi: 10.1016/j.intcom.2010.04.004.

[93] M. Schreiber, «Potential of an Interactive Computer-based Training in the Rehabilitation of Dementia: An Initial Study», *Neuropsychological Rehabilitation*, vol. 9, n.º 2, pp. 155-167, abr. 1999, doi: 10.1080/713755596.

[94] P. Gamito, J. Oliveira, C. Alves, N. Santos, C. Coelho, y R. Brito, «Virtual Reality-Based Cognitive Stimulation to Improve Cognitive Functioning in Community Elderly: A Controlled Study», *Cyberpsychology, Behavior, and Social Networking*, vol. 23, n.º 3, pp. 150-156, mar. 2020, doi: 10.1089/cyber.2019.0271.

[95] K. Zhu, Q. Zhang, B. He, M. Huang, R. Lin, y H. Li, «Immersive Virtual Reality–Based Cognitive Intervention for the Improvement of Cognitive Function, Depression, and Perceived Stress in Older Adults With Mild Cognitive Impairment and Mild Dementia: Pilot Pre-Post Study», *JMIR Serious Games*, vol. 10, n.º 1, p. e32117, feb. 2022, doi: 10.2196/32117.

[96] E. Park *et al.*, «Effects of a Mixed Reality-based Cognitive Training System Compared to a Conventional Computer-assisted Cognitive Training System on Mild Cognitive Impairment: A Pilot Study», *Cognitive and Behavioral Neurology*, vol. 32, n.º 3, p. 172, sep. 2019, doi: 10.1097/WNN.0000000000000197.

[97] S. Masoumzadeh y Z. Moussavi, «Does Practicing with a Virtual Reality Driving Simulator Improve Spatial Cognition in Older Adults? A Pilot Study», *Neurosci Insights*, vol. 15, p. 2633105520967930, 2020, doi: 10.1177/2633105520967930.

[98] S. Maeng *et al.*, «Effects of Virtual Reality-Based Cognitive Training in the Elderly with and without Mild Cognitive Impairment», *Psychiatry Investig*, vol. 18, n.º 7, pp. 619-627, jul. 2021, doi: 10.30773/pi.2020.0446.

[99] D. W. K. Man, J. C. C. Chung, y G. Y. Y. Lee, «Evaluation of a virtual reality-based memory training programme for Hong Kong Chinese older adults with questionable dementia: a pilot study», *Int J Geriatr Psychiatry*, vol. 27, n.º 5, pp. 513-520, may 2012, doi: 10.1002/gps.2746.

[100] T. Yamaguchi, D. A. Foloppe, P. Richard, E. Richard, y P. Allain, «A Dual-Modal Virtual Reality Kitchen for (Re)Learning of Everyday Cooking Activities in Alzheimer's Disease», *Presence: Teleoperators and Virtual Environments*, vol. 21, n.º 1, pp. 43-57, feb. 2012, doi: 10.1162/PRES_a_00080.

[101] S. Mondini *et al.*, «Cognitive Reserve in Dementia: Implications for Cognitive Training», *Front. Aging Neurosci.*, vol. 8, abr. 2016, doi: 10.3389/fnagi.2016.00084.

[102] C. da S. Langoni *et al.*, «The effect of group exercises on balance, mobility, and depressive symptoms in older adults with mild cognitive impairment: a randomized controlled trial», *Clin Rehabil*, vol. 33, n.º 3, pp. 439-449, mar. 2019, doi: 10.1177/0269215518815218.

[103] S. Fjordside y A. Morville, «Factors influencing older people's experiences of participation in autonomous decisions concerning their daily care in their own homes: a review of the literature», *International Journal of Older People Nursing*, vol. 11, n.º 4, pp. 284-297, 2016, doi: 10.1111/opn.12116.

[104] D.-R. Kim, E. Moon, M.-J. Shin, Y.-A. Yang, y J.-H. Park, «Effect of Individual Virtual Reality Cognitive Training Programs on Cognitive Function and Depression in Middle-Aged

Women: Randomized Controlled Trial», *JMIR Mental Health*, vol. 10, n.º 1, p. e48912, oct. 2023, doi: 10.2196/48912.

[105] M. A. McDaniel *et al.*, «Effects of cognitive training with and without aerobic exercise on cognitively demanding everyday activities», *Psychology and Aging*, vol. 29, n.º 3, pp. 717-730, 2014, doi: 10.1037/a0037363.

[106] L. Nguyen, K. Murphy, y G. Andrews, «Immediate and long-term efficacy of executive functions cognitive training in older adults: A systematic review and meta-analysis», *Psychological Bulletin*, vol. 145, n.º 7, pp. 698-733, 2019, doi: 10.1037/bul0000196.

[107] S. Panerai *et al.*, «Functional Living Skills: A Non-Immersive Virtual Reality Training for Individuals with Major Neurocognitive Disorders», *Sensors*, vol. 21, n.º 17, Art. n.º 17, ene. 2021, doi: 10.3390/s21175751.

[108] Y. Wei y X. Guo, «Impact of smart device use on objective and subjective health of older adults: findings from four provinces in China», *Front. Public Health*, vol. 11, jul. 2023, doi: 10.3389/fpubh.2023.1118207.

[109] H. Liu *et al.*, «Process evaluations of primary care interventions addressing chronic disease: a systematic review», *BMJ Open*, vol. 9, n.º 8, p. e025127, ago. 2019, doi: 10.1136/bmjopen-2018-025127.

[110] P. Kourtesis, S. Collina, L. A. A. Doumas, y S. E. MacPherson, «Validation of the Virtual Reality Neuroscience Questionnaire: Maximum Duration of Immersive Virtual Reality Sessions Without the Presence of Pertinent Adverse Symptomatology», *Front. Hum. Neurosci.*, vol. 13, nov. 2019, doi: 10.3389/fnhum.2019.00417.

[111] J. Buele, F. Avilés-Castillo, C. Del-Valle-Soto, J. Varela-Aldás, y G. Palacios-Navarro, «Effects of a dual intervention (motor and virtual reality-based cognitive) on cognition in patients with mild cognitive impairment: a single-blind, randomized controlled trial», *Journal of NeuroEngineering and Rehabilitation*, vol. 21, n.º 1, p. 130, ago. 2024, doi: 10.1186/s12984-024-01422-w.

[112] K. Laver, C. Hamilton, y A. McCluskey, «Computerised cognitive training programs improved the cognitive performance of healthy older adults on some cognitive tests including memory, speed of information processing and visuospatial skills», *Australian Occupational Therapy Journal*, vol. 62, n.º 3, pp. 223-224, 2015, doi: 10.1111/1440-1630.12209.

[113] M. E. Kelly, D. Loughrey, B. A. Lawlor, I. H. Robertson, C. Walsh, y S. Brennan, «The impact of cognitive training and mental stimulation on cognitive and everyday functioning of healthy older adults: a systematic review and meta-analysis», *Ageing Res Rev*, vol. 15, pp. 28-43, may 2014, doi: 10.1016/j.arr.2014.02.004.

[114] M. C. Howard, «A meta-analysis and systematic literature review of virtual reality rehabilitation programs», *Computers in Human Behavior*, vol. 70, pp. 317-327, may 2017, doi: 10.1016/j.chb.2017.01.013.

[115] D. Romero-Ayuso *et al.*, «Assessment of cognitive instrumental activities of daily living: a systematic review», *Disability and Rehabilitation*, vol. 43, n.º 10, pp. 1342-1358, may 2021, doi: 10.1080/09638288.2019.1665720.

[116] Y.-Y. Liao, H.-Y. Tseng, Y.-J. Lin, C.-J. Wang, y W.-C. Hsu, «Using virtual reality-based training to improve cognitive function, instrumental activities of daily living and neural efficiency in

older adults with mild cognitive impairment», *Eur J Phys Rehabil Med*, vol. 56, n.º 1, pp. 47-57, feb. 2020, doi: 10.23736/S1973-9087.19.05899-4.

[117] D. A. Raichlen *et al.*, «Effects of simultaneous cognitive and aerobic exercise training on dual-task walking performance in healthy older adults: results from a pilot randomized controlled trial», *BMC Geriatr*, vol. 20, n.º 1, p. 83, mar. 2020, doi: 10.1186/s12877-020-1484-5.

[118] S. A. Galle *et al.*, «The effects of a moderate physical activity intervention on physical fitness and cognition in healthy elderly with low levels of physical activity: a randomized controlled trial», *Alzheimers Res Ther*, vol. 15, n.º 1, p. 12, ene. 2023, doi: 10.1186/s13195-022-01123-3.

[119] S. B. Chapman *et al.*, «Neural mechanisms of brain plasticity with complex cognitive training in healthy seniors», *Cereb Cortex*, vol. 25, n.º 2, pp. 396-405, feb. 2015, doi: 10.1093/cercor/bht234.

[120] R. Y. C. Kwan *et al.*, «Feasibility and Effects of Virtual Reality Motor-Cognitive Training in Community-Dwelling Older People With Cognitive Frailty: Pilot Randomized Controlled Trial», *JMIR Serious Games*, vol. 9, n.º 3, p. e28400, ago. 2021, doi: 10.2196/28400.

[121] P. Gamito *et al.*, «Cognitive Stimulation of Elderly Individuals with Instrumental Virtual Reality-Based Activities of Daily Life: Pre-Post Treatment Study», *Cyberpsychology, Behavior, and Social Networking*, vol. 22, n.º 1, pp. 69-75, ene. 2019, doi: 10.1089/cyber.2017.0679.

[122] J. D. Edwards, H. Xu, D. Clark, L. A. Ross, y F. W. Unverzagt, «S2-01-02: The Active Study: what we Have Learned and what is Next? Cognitive Training Reduces Incident Dementia Across Ten Years», *Alzheimer's & Dementia*, vol. 12, n.º 7S_Part_4, pp. P212-P212, 2016, doi: 10.1016/j.jalz.2016.06.373.

[123] N. Dużmańska, P. Strojny, y A. Strojny, «Can Simulator Sickness Be Avoided? A Review on Temporal Aspects of Simulator Sickness», *Front. Psychol.*, vol. 9, nov. 2018, doi: 10.3389/fpsyg.2018.02132.

[124] N. Kawano *et al.*, «Slower adaptation to driving simulator and simulator sickness in older adults», *Aging Clin Exp Res*, vol. 24, n.º 3, pp. 285-289, jun. 2012, doi: 10.1007/BF03325260.

[125] W. Li, Q. Feng, X. Zhu, Q. Yu, y Q. Wang, «Effect of summarizing scaffolding and textual cues on learning performance, mental model, and cognitive load in a virtual reality environment: An experimental study», *Computers & Education*, vol. 200, p. 104793, jul. 2023, doi: 10.1016/j.compedu.2023.104793.

[126] M. Magalhães, A. Coelho, M. Melo, y M. Bessa, «Measuring users' emotional responses in multisensory virtual reality: a systematic literature review», *Multimed Tools Appl*, vol. 83, n.º 14, pp. 43377-43417, abr. 2024, doi: 10.1007/s11042-023-16918-1.

[127] D. Oumaima, L. Mohamed, H. Hamid, y H. Mohamed, «Application of Artificial Intelligence in Virtual Reality», en *Trends in Sustainable Computing and Machine Intelligence*, S. Lanka, A. Sarasa-Cabezuelo, y A. Tugui, Eds., Singapore: Springer Nature, 2024, pp. 67-85. doi: 10.1007/978-981-99-9436-6_6.

[128] A. R. Huang *et al.*, «Social isolation and 9-year dementia risk in community-dwelling Medicare beneficiaries in the United States», *Journal of the American Geriatrics Society*, vol. 71, n.º 3, pp. 765-773, 2023, doi: 10.1111/jgs.18140.

[129] B. Park *et al.*, «Integrating Biomarkers From Virtual Reality and Magnetic Resonance Imaging for the Early Detection of Mild Cognitive Impairment Using a Multimodal Learning Approach: Validation Study», *Journal of Medical Internet Research*, vol. 26, n.º 1, p. e54538, abr. 2024, doi: 10.2196/54538.

[130] E. Kruijff, A. Marquardt, C. Trepkowski, J. Schild, y A. Hinkenjann, «Designed emotions: challenges and potential methodologies for improving multisensory cues to enhance user engagement in immersive systems», *Vis Comput*, vol. 33, n.º 4, pp. 471-488, abr. 2017, doi: 10.1007/s00371-016-1294-0.

[131] E. Takano *et al.*, «User Experience of Older People While Using Digital Health Technologies: A Systematic Review», *Applied Sciences*, vol. 13, n.º 23, Art. n.º 23, ene. 2023, doi: 10.3390/app132312815.

[132] S. S. Man, Y. Guo, A. H. S. Chan, y H. Zhuang, «Acceptance of Online Mapping Technology among Older Adults: Technology Acceptance Model with Facilitating Condition, Compatibility, and Self-Satisfaction», *ISPRS International Journal of Geo-Information*, vol. 11, n.º 11, Art. n.º 11, nov. 2022, doi: 10.3390/ijgi11110558.

[133] S. Mrakic-Sposta *et al.*, «Effects of Combined Physical and Cognitive Virtual Reality-Based Training on Cognitive Impairment and Oxidative Stress in MCI Patients: A Pilot Study», *Front Aging Neurosci*, vol. 10, p. 282, 2018, doi: 10.3389/fnagi.2018.00282.

[134] G. M. Doniger *et al.*, «Virtual reality-based cognitive-motor training for middle-aged adults at high Alzheimer's disease risk: A randomized controlled trial», *Alzheimers Dement (N Y)*, vol. 4, pp. 118-129, 2018, doi: 10.1016/j.trci.2018.02.005.

[135] Y.-Y. Liao, I.-H. Chen, Y.-J. Lin, Y. Chen, y W.-C. Hsu, «Effects of Virtual Reality-Based Physical and Cognitive Training on Executive Function and Dual-Task Gait Performance in Older Adults With Mild Cognitive Impairment: A Randomized Control Trial», *Front Aging Neurosci*, vol. 11, p. 162, 2019, doi: 10.3389/fnagi.2019.00162.

[136] K. J. Miller, B. S. Adair, A. J. Pearce, C. M. Said, E. Ozanne, y M. M. Morris, «Effectiveness and feasibility of virtual reality and gaming system use at home by older adults for enabling physical activity to improve health-related domains: a systematic review», *Age and Ageing*, vol. 43, n.º 2, pp. 188-195, mar. 2014, doi: 10.1093/ageing/aft194.

[137] J. P. Salisbury, «Using Medical Device Standards for Design and Risk Management of Immersive Virtual Reality for At-Home Therapy and Remote Patient Monitoring», *JMIR Biomedical Engineering*, vol. 6, n.º 2, p. e26942, jun. 2021, doi: 10.2196/26942.

[138] M. Sortino, A. Amato, y G. Musumeci, «Advanced technologies applied to physical exercise for dementia and Alzheimer's disease management: a narrative review», *Advanced Technology in Neuroscience*, vol. 1, n.º 1, p. 72, sep. 2024, doi: 10.4103/ATN.ATN-D-23-00002.

APÉNDICES

Apéndice 1: Factor de impacto y área temática de las revistas

Publicación	Revista	Año de publicación	Factor de Impacto	Área Temática	Cuartil	Citaciones WoS	Citaciones Scopus	Citaciones G. Scholar
Cognitive Decline Detection for Alzheimer's Disease Patients Through an Activity of Daily Living (ADL)	IEEE Transactions on Neural Systems and Rehabilitation Engineering	2022	4,8	Engineering, Biomedical	Q2	8	13	18
				Rehabilitation	Q1			
The Cupboard Task: An Immersive Virtual Reality-Based System for Everyday Memory Assessment	International Journal of Human-Computer Studies	2022	5,3	Computer Science, Cybernetics	Q1	14	19	24
				Ergonomics	Q1			
				Psychology, Multidisciplinary	Q1			
Influence of Hand Tracking in Immersive Virtual Reality for Memory Assessment	International Journal of Environmental Research and Public Health	2023	0,81*	Health, Toxicology and Mutagenesis	Q2	No aplica	4	12
				Pollution	Q2			
				Public Health, Environmental and Occupational Health	Q2			
Virtual Reality Applications Based on Instrumental Activities of Daily Living	Journal of Neuroengineering and Rehabilitation	2023	5,2	Engineering, Biomedical	Q1	5	7	13

(iADLs) for Cognitive Intervention in Older Adults: A Systematic Review				Neurosciences	Q1			
				Rehabilitation	Q1			
Cognitive-Motor Interventions Based on Virtual Reality and Instrumental Activities of Daily Living (iADL): An Overview	Frontiers in Aging Neuroscience	2023	4,1	Geriatrics & Gerontology	Q2	3	5	7
				Neurosciences	Q2			
Effects of a Dual Intervention (Motor and Virtual Reality-Based Cognitive) on Cognition in Patients with Mild Cognitive Impairment: A Single-Blind, Randomized Controlled Trial	Journal of Neuroengineering and Rehabilitation	2024	5,2	Engineering, Biomedical	Q1	3	3	4
				Neurosciences	Q1			
				Rehabilitation	Q1			

Nota: El factor de impacto y el cuartil corresponden al indicador Journal Citation Reports (JCR) 2023, ya que los datos del año 2024 todavía no han sido publicados. Los datos sobre número de citas están actualizados a diciembre de 2024.

*El factor de impacto corresponde al indicador indicador SCImago Journal Rank (SJR) 2023.

Apéndice 2: Justificación de la contribución del doctorando

I. Título: Cognitive Decline Detection for Alzheimer's Disease Patients Through an Activity of Daily Living (ADL)

El doctorando participó en la conceptualización de la investigación, el desarrollo de la metodología y la construcción del armario físico equipado con componentes tecnológicos avanzados, integrando microcontroladores como Raspberry Pi para capturar y procesar datos en tiempo real. Esta infraestructura permitió monitorizar y registrar las interacciones de los usuarios con el sistema. Asimismo, el doctorando contribuyó en la recolección de datos, análisis estadístico y redacción del artículo original, contribuyendo en las revisiones solicitadas por los evaluadores para su aceptación final.

II. Título: The Cupboard Task: An Immersive Virtual Reality-Based System for Everyday Memory Assessment

En este artículo, el doctorando participó en el del desarrollo de la aplicación de RVI "Cupboard Task," desde la fase inicial hasta su implementación final. Colaboró en la validación de la aplicación mediante pruebas empíricas y la recolección de datos experimentales. La contribución incluyó la redacción del manuscrito, además de realizar las revisiones solicitadas por los revisores para su aceptación final.

III. Título: Influence of Hand Tracking in Immersive Virtual Reality for Memory Assessment

El doctorando participó en el desarrollo de la aplicación de RVI para la evaluación de la memoria, investigando el impacto del seguimiento de manos frente a los controles tradicionales. La contribución incluyó el diseño experimental, la implementación del sistema, y la configuración de los parámetros de dificultad. Además, participó en la recolección de datos de precisión y tiempos de respuesta, así como en la evaluación de la percepción de presencia, usabilidad y satisfacción con otro autor. El doctorando también participó en la redacción del manuscrito y en las revisiones necesarias hasta su aceptación final.

IV. Título: Virtual Reality Applications Based on Instrumental Activities of Daily Living (iADLs) for Cognitive Intervention in Older Adults: A Systematic Review

El doctorando participó en la búsqueda, selección y análisis crítico de estudios sobre aplicaciones de RV basadas en AIVD para intervención cognitiva. Contribuyó al desarrollo metodológico y al análisis formal de los datos, organizando y sintetizando los hallazgos, destacando los beneficios y limitaciones de dichas intervenciones en el contexto de los adultos mayores. Además, colaboró en la redacción del artículo y en las revisiones solicitadas por los revisores para su publicación.

V. Título: Cognitive-Motor Interventions Based on Virtual Reality and Instrumental Activities of Daily Living (iADL): An Overview

En este artículo de revisión, el doctorando contribuyó a la concepción y diseño del estudio, recopilando y analizando literatura relevante sobre intervenciones cognitivo-motoras en RV basadas en AIVD. Además, organizó la base de datos de estudios seleccionados y evaluó la viabilidad de estas intervenciones para mejorar la independencia funcional en esta población. También colaboró en la redacción del primer borrador del manuscrito y en las revisiones necesarias para responder a los comentarios de los evaluadores.

VI. Título: Effects of a Dual Intervention (Motor and Virtual Reality-Based Cognitive) on Cognition in Patients with Mild Cognitive Impairment

El doctorando participó en la conceptualización y diseño de la intervención dual basada en RV basado en los aprendizajes previos de la revisión de la literatura. Se encargó de la organización y visualización de los datos, implementó el protocolo de intervención, recolectó y realizó análisis estadísticos, y contribuyó a la interpretación de los resultados. Además, participó en la redacción del borrador original del manuscrito y en las revisiones y ediciones necesarias para su aceptación final.

Apéndice 3: Artículos adicionales en revistas y conferencias

Además de los artículos publicados en revistas de alto impacto, se presentaron hallazgos complementarios del estudio en revistas y congresos internacionales.

Artículo de revista 1

Título: Memory rehabilitation during the COVID-19 pandemic

Autores: José Luis Varela-Aldás, Jorge Buele, Doris Pérez y Guillermo Palacios-Navarro

DOI: 10.1186/s12911-023-02294-1

Revista: BMC Medical Informatics and Decision Making

Año: 2023

Base de Datos: JCR

Editor: BMC

Resumen: Background: Loss of cognitive and executive functions is a problem that affects people of all ages. That is why it is important to perform exercises for memory training and prevent early cognitive deterioration. The aim of this work was to compare the cognitive performance of the participants after an intervention by using two mnemonic techniques to exercise memory functions (paired-associate learning and method of loci). Methods: A longitudinal study was conducted with 21 healthy participants aged 18 to 55 years over a 2-month period. To assess the impact of this proposal, the NEUROPSI brief battery cognitive assessment test was applied before and after the intervention. In each session, a previous cognitive training was carried out using the paired-associate learning technique, to later perform a task based on the loci method, all from a smart device-based application. The accuracy response and reaction times were automatically collected in the app. Results: After the intervention, a statistically significant improvement was obtained in the neuropsychological assessment (NEUROPSI neuropsychological battery) reflected by the Wilcoxon paired signed-rank test ($P < .05$). Conclusion: The task based on the method of loci also reflected the well-known age-related effects common to memory assessment tasks. Episodic memory training using the method of loci can be successfully implemented using a smart device app. A stage-based methodological design allows to acquire mnemic skills gradually, obtaining a significant cognitive improvement in a short period of time.

Artículo de conferencia internacional 1

Título: Virtual Reality applications based on activities of daily living (ADL) for cognitive diagnosis and rehabilitation

Autores: Jorge Buele; José Varela-Aldás; Guillermo Palacios-Navarro

DOI: 10.1109/TAEE54169.2022.9840591

Congreso: XV Technologies Applied to Electronics Teaching Conference

Lugar: Teruel, España

Año: 2022

Editor: IEEE

Resumen: Traditionally, screening tools are available to help diagnose a person's cognitive problem. Therefore, rehabilitation techniques are lab exercises that lack adequate ecological validity. In this paper, we propose to establish the projection of a methodology for the development of serious games based on activities of daily living (ADL). Both for real and immersive environments, to assess what provides better results when applied in healthy patients at first, but with a focus on those suffering from Alzheimer's disease. It is expected that when this research is completed, precedents will be established for the development of new proposals based on virtual environments.

Artículo de conferencia internacional 2

Título: Advancements in Virtual Reality for Elderly Care: A Two-Decade Journey

Autores: Jorge Buele; Verónica Elizabeth Labre-Tarco; Mónica Anahí López-Albuja; Valentina Tapia-Ramos; Guillermo Palacios-Navarro

DOI: 10.1109/ETCM58927.2023.10309039

Congreso: 2023 IEEE Seventh Ecuador Technical Chapters Meeting (ECTM)

Lugar: Ambato, Ecuador

Año: 2023

Editor: IEEE

Resumen: In the context of the global aging population, there is a critical need for effective and innovative care strategies for older adults. Virtual reality (VR) has emerged as a promising tool for improving the lives of older adults. However, the scope and direction of research in this field have not been fully explored. This bibliometric study aims to analyze the development and current trends in research on the use of VR in elderly care over the past 20 years. A systematic search was conducted in Scopus, applying inclusion and exclusion criteria, resulting in the selection of 1622 articles. Using VOSViewer software, these articles were analyzed, revealing significant patterns in keywords, authors, citations, and publication venues. The findings indicate a growing interest in this topic, with a notable focus on aging, cognition, therapeutic exercise, and randomized controlled trials. Future directions for VR research include spatial navigation, neuropsychological testing, and physical exercises. Notably, the journals Frontiers in Aging Neuroscience and Journal of NeuroEngineering and Rehabilitation have high citation rates for their VR-related articles. This study provides a comprehensive overview of VR research in elderly care, identifying emerging trends and highlighting areas that warrant further attention.