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"Enriching 360-degree technologies through human-computer interaction: psychometric validation of two memory tasks"

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ABSTRACT

This doctoral dissertation explores the domain of neuropsychological assessment, with the objective of gaining a comprehensive understanding of an individual's cognitive functioning and detecting possible impairments. Traditional assessment tools, while possessing inherent value, frequently exhibit a deficiency in ecological validity when evaluating memory, as they predominantly concentrate on short-term, regulated tasks. To overcome this constraint, immersive technologies, specifically virtual reality and 360° videos, have surfaced as promising instruments for augmenting the ecological validity of cognitive assessments. This work examines the potential advantages of immersive technologies, particularly 360° videos, in enhancing memory evaluation. First, a comprehensive overview of contemporary virtual reality tools employed in the assessment of memory, as well as their convergence with conventional assessment measures has been provided. Then, the present study utilizes cluster and network analysis techniques to categorize 360° videos according to their content and applications, thereby offering significant insights into the potential of this nascent medium. The second study introduces a novel platform, Mindscape, that aims to address the existing technological disparity, thereby enhancing the accessibility of clinicians and researchers in developing cognitive tasks within immersive environments. The conclusion of the thesis encompasses the psychometric validation of two memory tasks, which have been specifically developed with Mindscape to assess episodic and spatial memory. The findings demonstrate disparities in cognitive performance between individuals diagnosed with Mild Cognitive Impairment and those without cognitive impairments, underscoring the interrelated nature of cognitive processes and the promising prospects of virtual reality technology in improving the authenticity of real-world experiences. Overall, this dissertation aims to respond to the demand for practical and ecologically valid neuropsychological assessments within the dynamic field of neuropsychology. It achieves this by integrating user-friendly platforms and immersive cognitive tasks into its methodology. By highlighting a shift in the field of neuropsychology towards prioritizing functional and practical assessments over theoretical frameworks, this work indicates a changing perspective within the discipline. This study highlights the potential of comprehensive and purpose-oriented assessment methods in cognitive evaluations, emphasizing the ongoing significance of research in fully comprehending the capabilities of immersive technologies.

RIASSUNTO IN ITALIANO

Questa tesi di dottorato esplora il campo della valutazione neuropsicologica con l'obiettivo di ottenere una completa comprensione del funzionamento cognitivo di un individuo e rilevare possibili disfunzioni. Gli strumenti di valutazione tradizionali, pur possedendo un intrinseco valore, spesso mostrano una carenza di validità ecologica nella valutazione della memoria, poiché si concentrano principalmente su compiti a breve termine e regolamentati. Al fine di superare questo limite, le tecnologie immersive, in particolare la realtà virtuale e i video a 360°, sono emerse come strumenti promettenti per migliorare la validità ecologica delle valutazioni cognitive. Questo lavoro esamina i potenziali vantaggi delle tecnologie immersive, in particolare dei video a 360°, nel migliorare la valutazione della memoria. Inizialmente, è stata fornita una panoramica completa degli strumenti di realtà virtuale contemporanei utilizzati nella valutazione della memoria, nonché della loro convergenza con le misure di valutazione convenzionali. Successivamente, il presente studio utilizza tecniche di cluster and network analysis per categorizzare i video a 360° in base al loro contenuto e

alle loro applicazioni, offrendo così significative intuizioni sul potenziale di questo nuovo medium. Lo studio introduce quindi una nuova piattaforma, Mindscape, che mira a affrontare la disparità tecnologica esistente, migliorando così l'accessibilità di clinici e ricercatori nello sviluppo di compiti cognitivi in ambienti immersivi. La conclusione della tesi include la validazione psicometrica di due compiti di memoria, specificamente sviluppati con Mindscape per valutare la memoria episodica e spaziale. I risultati dimostrano disparità nelle prestazioni cognitive tra individui diagnosticati con un lieve deterioramento cognitivo e quelli senza disturbi cognitivi, mettendo in evidenza la natura interconnessa dei processi cognitivi e le promettenti prospettive della tecnologia della realtà virtuale nel migliorare l'autenticità delle esperienze reali. In generale, questa tesi di dottorato mira a rispondere alla domanda di valutazioni neuropsicologiche pratiche ed ecologicamente valide all'interno del dinamico campo della neuropsicologia. Lo fa integrando piattaforme user-friendly e compiti cognitivi immersivi nella sua metodologia. Le discussioni sottolineano un cambiamento nel campo della neuropsicologia verso la priorità di valutazioni funzionali e pratiche rispetto a quadri teorici, indicando una prospettiva in evoluzione all'interno della disciplina. Questo studio evidenzia il potenziale di metodi di valutazione completi e orientati a uno scopo nelle valutazioni cognitive, sottolineando l'importanza continua della ricerca per comprendere appieno le capacità delle tecnologie immersive.

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1. Introduction

This doctoral dissertation explores the understanding of an individual's cognitive functioning, aiming to identify any potential impairments. This is accomplished by investigating the field of neuropsychological assessment. Although conventional assessment instruments have inherent value, they often do not meet the criteria for ecological validity when used to evaluate memory. This is mainly because they prioritize tasks that have restrictions and have short-term deadlines. Immersive technologies, like 360-degree videos and virtual reality (VR), have emerged as potentially valuable tools for improving the accuracy of cognitive assessments related to the environment, thus overcoming this limitation. The main aim of this research project is to investigate the potential benefits that immersive technologies, specifically 360-degree videos, may have on memory evaluation.

The first section of the dissertation introduces a comprehensive analysis of modern VR tools used for memory evaluation. This analysis is preceded by a description of memory processes and an exploration of immersive technologies and their suitability for neuropsychological assessment.

The primary focus is on the study of convergence of these technological tools with traditional evaluation methods. By utilizing techniques like cluster and network analysis, this contextualization forms the basis for the subsequent exploration of the potential of 360-degree video. The videos will be categorized according to the applications and content they utilize, following a thorough investigation. In the field of neuropsychological assessment, this classification offers valuable insights into the latent abilities of 360° technologies.

In the following phase of the research endeavor, a cutting-edge platform known as Mindscape is introduced. The main objective of this platform is to enhance its accessibility for researchers and clinicians by addressing the current technological limitations. Mindscape aims to enable professionals to promote the growth of cognitive tasks in immersive environments. Subsequently, the dissertation culminates with the psychometric validation of two memory tasks that were created using Mindscape. The tasks focus on enhancing spatial memory and episodic memory in individuals diagnosed with Mild Cognitive Impairment and older adults without cognitive impairment. This study emphasizes the interconnectedness of cognitive processes and the capacity of VR technology to accurately reproduce authentic experiences occurring in the real world.

This thesis concludes by highlighting the crucial significance of practical and ecologically valid neuropsychological evaluations in the dynamic field of neuropsychology, in response to the increasing need for assessments that accurately reflect real-world functionality. The wider implications of the results were carefully considered. This is accomplished by incorporating immersive cognitive tasks and user-friendly platforms into its methodology. A notable transformation in the field of neuropsychology has been the replacement of theoretical frameworks with functional and practical assessments. This transition represents a forward-thinking perspective in the field of neuropsychology.

2. Memory: definition, types and processes

Memory refers to the capacity to obtain, hold onto, and apply knowledge or information. According to neuroscientists and experimental psychologists, there are various types of memory, and each one is supported by a unique arrangement of brain regions (Alkon et al., 1991; Byrne et al., 2014). The two main categories described are 1) Explicit memory, which is the conscious recall of one's own past experiences; 2) Implicit memory, which is the influence of past experiences on present behavior, which is not conscious. The explicit memory, also known as just "memory" in everyday speech, can be further divided into memories containing factual information (like information from a basic science course) and memories of personally experienced events (like what you had for breakfast). Implicit memories refer to the "how to" elements of our behavior, such as motor skills and emotional associations to specific stimuli or events that shape what we like and dislike. Another aspect of implicit memories is priming, i.e., the capacity to recognize an object as a result of prior exposure to it, even if you are unaware of the prior exposure.

Explicit memories can also be categorized based on time. The information we receive from our senses is processed in fractions of a second, and if it is deemed significant enough, it is either consciously or unconsciously stored in short-term memory. The ability to recall five to nine items, like a phone number, falls under the category of short-term memory. Without practice, short-term memories are susceptible to loss, just like phone numbers. We can retain knowledge in working memory, a form of short-term memory, for minutes to hours if we practice and use it. The memory is either erased or stored in the long-term memory, depending on how much it has been practiced or used. Long-term memories are used for recalling particular events and facts, recognizing people and places, and recalling specific skills. These memories can be retained for a long time, especially if they are frequently reviewed. The deeply ingrained knowledge of language and music is part of remote memory, a special subset of long-term memory that is frequently the last to be lost in illnesses like Alzheimer's disease (AD).

There is evidence, however, that the brain does not store complete memories but rather bits of data that can be used to construct memories in the future. This explains why we frequently misremember facts, indicating that memory is not simply played back like a tape recorder. It is possible to think of memory as a place where we process and store information, where we update our knowledge as we learn new information, and where we contrast one experience with another.

The fact that encoding, storage, and retrieval of specific experiences, events, facts, and skills involve a variety of brain regions dates to the 19^{th} century. Hermann Ebbinghaus (1885) described in his monograph the quantitative outcomes of his meticulously controlled observations on learning and retention of verbal material, which marked the beginning of the experimental study of human memory as distinct from its philosophical analysis (Roediger, 1985). Soon after, Edward Lee Thorndik began the systematic experimental study of learning in lower animals, building on the groundbreaking work of comparative psychologists like George Romanes and Lloyd Morgan (Thorndike, 1898). The two great traditions that began with Ebbinghaus and Thorndike used a nearly entirely behavioral approach to study memory and learning in both humans and animals. Among other theories put forth by Rene Descartes and Franz Joseph Gall, the notion that the brain affects memory and learning was one of them. But it wasn't until the 19th century's end that it earned respect among scientists. Students of memory pathology like Theodule Ribot (1882) and Sergei Korsakoff (1889) who made careful clinical observations and reported them, served as an important source of inspiration for such a development (Korsakoff, 1889; Ribot, 1887). The work of the early pioneers of physiological psychology, a field now known by the name of behavioral neuroscience, served as another impetus for the study of brain/behavior relations in learning and memory. Ivan Pavlov (Pavlov, 1927) and Karl Lashley (Lashley, 2004), two of the first researchers in the field of behavioral neuroscience of learning, were among the most innovative and significant. As a result, the scientific study of learning and memory has developed over time along a number of broadly parallel tracks, in various fields of study, and in relative isolation from one another. Nowadays, the biological and psychological sciences, which are rapidly proliferating, are actively pursuing memory research, which is characterized by a wide range of orienting attitudes, methodological approaches, levels of analysis, and theoretical predilections (Tulving, 1987).

Human neuropsychology, a subfield of psychology that investigates the connection between brain activity and behavior (Kolb and Whishaw 1985), is one of these tracks. To understand memory, one must first understand how brain function and behavioral and experiential aspects of learning and memory relate to one another. This is what the neuropsychological study of human learning and memory entails. Clinical observations and laboratory studies examining the decrement in learning and memory in patients with brain damage provide a significant amount of pertinent evidence (Kinsbourne & Wood, 1975).

The study of amnesic patients with brain injuries provided some of the earliest understandings of how and where the brain processes memory (Scoviille & Milner, 1957). Clinical observations led to the controlled lesioning of experimental animals, a practice from which other approaches have developed (Izquierdo & Medina, 1998). Although experimental lesions may block circuits involved in the acquisition or retrieval of information and not actually affect the storage of information, the lesioning technique became more precise and targeted. The interpretation of subsequent behavioral studies may be impacted by the various types of reorganization that the undamaged neural tissue may experience following an experimentally induced lesion. As a result, scientists have created a variety of other methods to investigate the different memory-related processes.

Researchers have identified distinctive patterns of brain activity that change constantly as the brain responds to stimuli and executes learned responses by observing the activity of a single neuron or groups of neurons in animals during distinct phases of learning and memory. The coordinated actions of neural networks shed light on potential interactions between various brain regions for a variety of memory storage functions. The ability of the brain to change its structure and chemistry in response to environmental experiences has recently been explored by researchers using isolated cells in cultures and genetic engineering. They have also discovered that several biochemical steps are required to convert short-term memories into permanent memories.

However, using animal models or single-cell preparations to study memory has significant limitations. It is unclear, for instance, whether animals can encode personal events.

Therefore, knowledge about the fundamental mechanisms of memory has exploded in the last forty years thanks to new methods for brain imaging performed on healthy individuals while they perform learning and memory tasks. The metabolic activity of the brain and regional cerebral blood flow in particular brain regions can be observed by researchers using techniques like functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) scans as subjects perform various memory-related tasks. According to studies using fMRI and PET, certain cortical regions are active during particular tasks (like verbal processing), while other regions are active during different types of processing (like visuospatial processing).

Furthermore, whether short-term memory, working memory, and long-term memory are simply different stages of long-term memory, or whether they are distinct or sequential phenomena, has been a crucial question. Do different brain structures or cellular processes account for all memory or do these processes and structures evolve over time? The existence of patients with a disability that prevents the formation of only some types of memory as well as experimental studies showing memories are actively transferred from one phase to the next support the theory that different forms of explicit memory use unique analytic circuits.

One demonstration comes from a twenty-seven-year-old man, known as HM, with a history of epilepsy who underwent a neurosurgical procedure to bilaterally remove the medial temporal lobes, including the hippocampus and the amygdala that lie deep within the lobe, in 1957 (Scoviille & Milner, 1957). The procedure was successful in curing the seizures, but HM was left with severe amnesia about the circumstances leading up to his operation and was unable to learn or retain any new memories of details. Extensive psychological testing showed that HM's personality, perception, and intelligence did not alter. He also did not experience issues with short-term memory or the acquisition of new motor skills. However, following the operation, HM was totally unable to create any explicit memories. Even now, more than 40 years after his operation, HM has trouble remembering the time, his home address, what he ate for breakfast, or anyone he may have run into a short while ago. HM was even no able to recognize himself as he got older.

New theories of memory and learning have developed since the HM report. Models for the separation of the neuronal substrate for short-term and long-term memory, as well as for explicit and implicit memories, have been put forth.

To determine whether short-term and long-term memories develop sequentially or independently but concurrently, a number of experiments have been carried out. One widely held belief is that memories are somehow transformed from a fleeting, fragile state to one that is more durable (McGaugh, 2000). Numerous therapies can alter short-term memory while maintaining long-term memory. The surgical bilateral destruction of the temporal lobes did not have an impact on the majority of his presurgical long-term memories, as the example of HM showed. However, the parts of the brain that help short-term memories become long-term memories were damaged.

Memory loss of the events just before losing consciousness is another typical side effect of a concussion, such as one that might happen in a car accident. The temporary loss of consciousness may have prevented the consolidation of short-term memories into long-term memories, which is one explanation for this amnesia. Different medications that can impair either long-term or short-term memory also provide evidence that time-dependent stages of memory are processed independently.

Moreover, not all short-term memories are archived for later use. It is obvious that we do not want to permanently store all of the minutiae of daily life because doing so would make it difficult to concentrate on the important things. When consolidation is overly successful, the effects are disastrous. Savants, or people with "superhuman memories," can recall endless lists of facts and words and long streams of numbers, but they struggle horribly with abstract thought. A savant might, for instance, recite lengthy passages of a novel verbatim but have little comprehension of the plot.

Brain activity research suggests that while we sleep, we may consolidate our memories of the events of the day. A rat's sleep-induced brain activity follows a similar pattern to that of the activity sparked by the animal's recent exploration of novel environments (Sutherland & McNaughton, 2000). For human subjects, comparable outcomes have been discovered. Rapid eye movement (REM) sleep, which is a hallmark of dreaming, was detected during PET scans of human subjects while they were learning a task and revealed common brain regions that were more active in those who had learned the task compared to those who hadn't (Maquet et al., 2000). The increased brain activity during sleep suggests that the brain is using energy to consolidate previously learned material, which researchers hypothesize may be how memories are stored for the long term. Although the molecular processes underlying sleep are not fully understood, cholinergic activity increases and serotonin levels decrease in a variety of neuronal structures during REM, suggesting that cellular pathways are being modulated (Graves et al., 2001).

2.1. The neuroscience of memories

At the systems level, the various forms of memory have a wide range of distinctions. The prefrontal cortex and areas of the medial temporal gyrus are some of the brain areas that are noticeably active during short-term working memory, while the hippocampus and nearby cortical areas of the temporal lobe are active during the storage of information from short-term to long-term (Rolls, 2003). Considerable evidence now supports the idea that events and facts have different learning and memory systems for long-term memory (Byrne et al., 2014). It is unlikely that each type of memory is stored entirely in a separate neural structure. Instead, it's likely that the cooperative operation of these neural structures is crucial for memory. So, the question is: How do the various brain regions interact?

1.1.1. Short-Term and Working Memory

Tasks involving verbal and visuospatial working memory, or the capacity to "rehearse" or "keep in mind" things like a spatial location, provide evidence for a relationship between conscious experiences and sustained neural activity (Smith & Jonides, 1999). While working memory is responsible for the short-term storage and online manipulation of information required for higher cognitive functions, such as language, planning, and problem-solving, short-term memory may be used to temporarily hold some information. Working memory is typically split into two categories of processes: "executive control", which directs the encoding and retrieval of information in working memory, and "active maintenance", which keeps the information available (Fuster, 2000).

The two types of working memory appear to be handled by separate areas of the prefrontal lobe, with the cortex in the more dorsal and posterior areas of the lobe handling content-specific information (such as verbal versus visuospatial information) and the executive control processes being handled in anterior and ventral areas of the lobe. Human neuroimaging studies indicate that verbal, spatial, and object information consistently activates the prefrontal cortex, which is important for active maintenance (Smith & Jonides, 1999).

The amount and complexity of fact processing increase as do the activations in several areas of the left prefrontal cortex. According to Smith & Jonides, the left prefrontal cortex supports the advantageous effects of semantic processing on subsequent memory (Smith & Jonides, 1999). Wagner and colleagues provided evidence in favor of this theory (Wagner et al., 1998): neuroimaging studies have been conducted to demonstrate an increase in left prefrontal cortex activity when words were categorized according to their semantic properties rather than their physical characteristics. While tasks require analysis of the item's meaning, prefrontal neuron activity rises.

The parahippocampal gyrus and the entorhinal cortex, which are in the ventro-medial region of the temporal lobe, may also play a role in working memory. Lesion studies have shown that this area is necessary for the development of long-lasting memories. Additionally, information that has already been processed by other cortical regions, such as the visual or somatosensory regions, is sent to the ventromedial region of the temporal lobe.
Similar findings were observed in subjects who were scanned as they looked at pictures of commonplace situations and then attempted to recall them; the recalled images were linked to increased activity in both the left and right parahippocampal regions. In contrast, neuroimaging studies in elderly patients with non-Alzheimer dementia—which is characterized by a poor memory of facts—show that the ventromedial portions of the temporal lobe are undergoing neurodegeneration (Garrard & Hodges, 2000).

2.1.2. Storage of Information from Short Term into Long Term

The hippocampus and its surrounding tissue, collectively known as the hippocampal formation, are located deep within the temporal lobe. The cerebral cortex's permanent storage locations receive explicit information from this region in some manner (possibly while sleeping) (Squire, 1992). Only the creation of new long-term memories is affected by hippocampal formation damage, according to research by neuropsychologists who have studied patients with this condition. However, extensive damage to the hippocampal formation, the connecting fiber bundles, and nearby cortical tissue can result in the total loss of all new explicit memories (Henke et al., 1999). Furthermore, animal research and more recent human neuroimaging studies raise doubts about whether hippocampal formation is equally crucial for remembering events and facts. According to neuroimaging findings, the human hippocampal formation is more useful for storing events than specific facts (Vargha-Khadem et al., 1997), and the structure is especially crucial when learning spatial or novel information—defined as the binding of all elements of new pictorial scenes in memory. The hippocampus has the capacity to combine data from various sensory modalities and send connections widely to numerous regions of the cerebral cortex (Eichenbaum, 1999). As a result, hippocampal formation must play a key role in memory by connecting various sensory stimuli of an event (such as place, sounds, smells, and people), binding the stimuli together, and temporarily storing the information while forming connections with other brain regions. Recent neuroimaging studies have posed an important question regarding the nature of the relationship between the hippocampus and the prefrontal lobe's cortical areas, parahippocampal cortex, and the entorhinal cortex during information encoding (Lavenex & Amaral, 2000): Do these regions act independently, perhaps by supplying distinct inputs to a shared structure like the hippocampus, or do they act serially to support memory encoding? Research by Fernandes and colleagues (Fernández et al., 1999) examined the serial encoding of memories in the hippocampus and the cortical regions that surround it (the parahippocampal gyrus and the entorhinal cortex). These researchers used microelectrodes implanted in the brains of epileptic patients whose disease had not affected the hippocampus or the nearby cortex to record the electrical activity. The patients memorized words during the electrophysiological recordings and then tried to recall them after a brief break. The parahippocampal region was activated before the hippocampus, which the researchers ultimately discovered to be a case of temporally staggered encoding. This supports the idea that the parahippocampal cortex serves as the hippocampus's input pathway, whereas the cerebral cortex's larger regions serve as the hippocampus's outputs and potential memory storage sites. The prefrontal lobe, as well as significant portions of the temporal and parietal lobes, form extensive reciprocal connections with the hippocampus. The hippocampus' connections to the cortical regions associated with language have been proposed as a mechanism by which it consolidates memories of facts and concepts.

What takes place at the cellular and molecular level when the brain creates new memories and then transforms transient experiences that last for a short time into memories that can last for days, weeks, or years? One widely accepted theory holds that alternations take place at synapses, which are the places where neurons communicate with one another. Through repeated experience, the strength of the connection between neurons is enhanced in some way. The simultaneous and coordinated activation of a pattern of neuronal connections as a result of repetition of an event, idea, or fact makes it simpler for the same neuronal connections to reactivate in the future. It is believed that one fundamental mechanism underlying the encoding of memory traces is a change in the synapse's efficacy (Martin et al., 2003). The strengthening of synaptic connections takes place when neural pathways are electrically stimulated in coordination with other activity of neurons in laboratory experiments where the ionic currents are recorded through channels of individual cells (the patch-clamp method). Long-term potentiation (LTP) is the term for this increase in synaptic strength, which can last for hours or even days. The molecular changes that underlie LTP are essential components of memory storage (Martin et al., 2003). Numerous studies have looked at the synaptic plasticity in a hippocampal slice preparation (where a piece of hippocampal tissue is kept in a culture dish so that the ionic currents of individual hippocampal neurons can be studied), as the hippocampus is thought to play some role in the consolidation of short-term memories into long-term memories.

Because only the synapses involving the active pathway experience enhanced synaptic strength, while other synapse sites on the same cell that do not receive input are unaffected, these studies demonstrate that LTP has input specificity. LTP is also associative, though, because when two inputs are activated simultaneously, one set of synapses on a cell can strengthen nearby synapses with different inputs. The phenomenon of associative learning, in which pairing two stimuli can individually produce the same response, may be explained by causing an effect in nearby synapses. Whether or not food was provided, Pavlov's dogs learned to salivate in response to the sound of a bell.

A biochemical mechanism to increase synaptic efficacy is started by LTP, a type of molecular switch. The N-methyl-D-aspartate (NMDA) receptor, which is located on the postsynaptic cell membrane and binds to the neurotransmitter glutamate, is essential for LTP. The NMDA receptor, a tiny cell membrane pore regulates calcium ion entry into the neuron. The NMDA receptor responds to glutamate when one neuron uses it to communicate with another neuron, which sets off a series of chemical processes inside the postsynaptic neuron. However, the glutamate signal is not the only thing the NMDA receptor requires. Prior to allowing calcium ions to enter the postsynaptic cell, the NMDA channel must first receive an electrical discharge from its own cell by simultaneously activating an ion channel in nearby synapses (depolarization of the postsynaptic membrane causes the removal of a $Mg2+$ ion from the NMDA receptor's pore). This facilitates the cell's activation the following time it experiences the same synaptic input. As a result, the brain uses two distinct signals—the binding of glutamate and the depolarization of the membrane—as "coincidence detectors" to link the two events (Tsien, 2000). Hippocampal neurons receive inputs from a variety of sources, and although no single source may be sufficient to activate the neuron, when these inputs are presented simultaneously and repeatedly (i.e., through temporal and spatial summation), it is sufficient to do so. In addition to the hippocampus, synaptic plasticity also takes place in the amygdala (LeDoux, 2003) and throughout the cerebral cortex, where NMDA receptors support the creation of connections between various cortical inputs (Maren, 1999).

2.2. Age-related memory problems

A prevalent concern expressed by individuals in the elderly population pertains to a perceived decline in their cognitive abilities, particularly in relation to memory function.
The phenomenon of cognitive decline that accompanies the natural process of aging has been extensively studied and documented. The process of aging is associated with a decline in various cognitive domains. It is evident that while the cognitive ability known as "crystallized intelligence," which pertains to knowledge and skills acquired through learning and practice, remains relatively unaffected by the aging process, "fluid intelligence," which involves reasoning with unfamiliar concepts or information, tends to decline with age. One area of cognitive functioning that is negatively impacted is the process of encoding information into memory, i.e., the encoding of episodic memories. In a cross-sectional study, Price and colleagues investigated the relationship between recall and recognition ability in the domains of logical memory and visual reproduction. The study's findings indicated that the primary factor associated with learning impairments in older individuals was the process of encoding information into memory, rather than the retrieval of stored information (Price et al., 2010). This phenomenon becomes evident in various commonplace scenarios, such as instances where individuals fail to recall names or when they visit a supermarket and inadvertently neglect to bring along their shopping bag or the most up-to-date shopping list. Additionally, individuals may inadvertently leave behind personal belongings, such as a purse or purchased items, after completing a transaction. The investigation of age-related changes in memory performance has been a prominent area of interest in psychological research over the past few decades (Reuter-Lorenz & Park, 2010). Nevertheless, it is worth noting that there are notable disparities between the age-related variations in fundamental and intricate cognitive capabilities as observed in controlled experimental settings and the actual cognitive performance observed in everyday life (Blanchard-Fields, 2007; Hertzog et al., 2008).
As previously stated, the concept of memory has been classified by Atkinson and Shiffrin (1968) into two distinct categories based on the temporal dimension: short-term memory (STM) and long-term memory (LTM) (Hoyer & Verhaeghen, 2006). Upon conducting a comprehensive analysis of the existing literature pertaining to memory performance and the aging process, it becomes evident that a notable degree of variability exists in memory performance. The extent of this variability becomes particularly evident when the tasks are assumed to place demands on distinct memory components, such as STM and LTM. The impact of aging on these two components and their respective subcomponents varies, as noted by Hoyer & Verhaeghen (Hoyer & Verhaeghen, 2006). One perspective suggests that older adults exhibit consistent or even enhanced performance on tasks that depend on semantic memory, which is the component of LTM responsible for an individual's accumulated knowledge (Nyberg et al., 2012; Park et al., 1996, 2002). In contrast, it has been observed that older individuals exhibit notable changes in LTM tasks that require the retrieval of particular events with respect to their temporal and spatial location, as well as the contextual details associated with these events (Bäckman, Small, & Wahlin, 2001; Light et al., 2000; Zacks et al., 2000). Numerous studies have shown performance impairments in episodic-like memory tests in older people, even if there is no evidence of dementia or Mild Cognitive Impairment (MCI) (Harris et al.,

2010). The assessment of episodic memory predominantly involves the administration of explicit learning tasks, wherein individuals are required to acquire information through methods such as memorizing a list or comprehending a narrative, and subsequently demonstrate their ability to recall the learned material following a period of delay. Episodic memory encompasses three fundamental components, namely the encoding phase, the storage phase, and the retrieval process of the encoded and stored information. While the storage of information is generally considered to be relatively stable, the processes of encoding and retrieval are believed to be influenced by age, as suggested by Castel & Craik (Castel & Craik, 2003). When considering the instance of name recall, it is plausible that older individuals possess the name in their memory but encounter difficulties in retrieving it. Moreover, Kessels and colleagues (Kessels et al., 2009) demonstrated broad performance decrements in older adults on a visuo-spatial episodic memory task which were especially pronounced in conditions requiring contextual binding. Tasks requiring the learning and recall of word lists (e.g., Rey-Auditory or California Verbal Learning Tests; R-AVLT/CVLT) have been found to be impaired in aging (Lundervold et al., 2014), with particular deficits in temporal order indices (Blachstein et al., 2012). There is also some suggestion that the age-related decline in verbal episodic memory may be greater in males than females (Lundervold et al., 2014). Because of these changes, it is sometimes difficult to distinguish the early signs of dementia from natural declines in cognitive capacity with old age. However, it has been suggested that measures such as the R-AVLT may be useful in delineating different dementias (Ricci et al., 2012; Tierney et al., 1994).

Nevertheless, a prominent issue pertaining to memory performance in older adults appears to be the process of transferring the necessary information from LTM to STM for the current task (Verhaeghen et al., 2012). Additionally, this encompasses alterations in STM capacity that are associated with age. The decline in cognitive performance among older adults is particularly noticeable in STM tasks that require the manipulation or retention of information while processing additional information (Elliott et al., 2011; S. Hale et al., 2011). Working memory (WM) is a cognitive function that involves the simultaneous storage and active manipulation of information (Baddeley, 2000). Laboratory assessments of WM, such as the reading span, listening span, or operation span, have consistently demonstrated significant and substantial age-related impairments (Bopp & Verhaeghen, 2005). On the other hand, it has been observed that basic STM tasks, such as digit span tasks or recalling the final items of lengthier lists, which do not require additional cognitive processing, exhibit minimal or negligible age-related effects (Zacks et al., 2000).

Verhaeghen, Martin, and Sedek (2012) offer circumstantial evidence to support this perspective. They conducted a comparative analysis of two meta-analyses, one focusing on cognitive abilities assessed through conventional laboratory tests, and the other examining indicators of job performance (Verhaeghen et al., 2012). This study revealed a notable disparity in cognitive functions, including perceptual speed, working memory, spatial ability, episodic memory, and reasoning, among individuals of different age groups. Additionally, the research also identified a consistent level of performance in everyday life activities, specifically job-related tasks, across various age cohorts. One potential reason for the consistent or improved cognitive performance observed in older individuals may be attributed to the utilization of acquired knowledge, strategies, or a personally developed framework for retrieving information from long-term memory (Ericsson & Kintsch, 1995). This could potentially serve as a compensatory mechanism for age-related declines in short-term memory (Elliott et al., 2011; Hale et al., 2011). The research conducted by Kempe and colleagues (Kempe et al., 2015) aims to examine the relationship between age and memory performance within a naturalistic setting.

Furthermore, a second objective was to assess the memory performance of elderly individuals in an episodic memory task and assess the extent to which this performance aligns with conventional laboratory-based memory performance. Consequently, they replicated a shopping scenario to investigate three specific inquiries: 1) Is there an age-related disparity in everyday memory performance between younger and older adults? 2) Does the memory performance of older adults in everyday life vary from fundamental laboratory measures? 3) Do older and younger adults exhibit divergent performance levels based on whether the item recall is sequential or necessitates manipulation? In accordance with existing research on cognitive aging, the performance of older adults was found to be inferior to that of younger adults across all administered tasks. The age-related discrepancy observed in laboratory memory tasks aligns with previous research on short-term memory measures (Elliott et al., 2011; S. Hale et al., 2011). The results of the EDL tasks also demonstrated a notable disparity in performance based on age, as observed in both scoring methods. The impact of age was most prominent in the EDL tasks when comparing the various tasks. This finding is in opposition to the initial hypothesis, which posited that older individuals would experience advantages in the shopping task due to their accumulated knowledge and strategic abilities, as suggested by the expert performance approach (Miller, 2009; Sohn & Doane, 2003).

The following sections will provide a more comprehensive analysis of two specific areas of memory that have frequently been observed to experience changes as a result of the aging process: episodic memory and spatial memory. Episodic memory pertains to the cognitive capacity to recall distinct personal experiences and events, situated within a temporal and contextual framework. This particular aspect of memory is distinguished by the recollection of specific details pertaining to the temporal and spatial context of an event, frequently accompanied by vivid sensory and emotional elements. In contrast, spatial memory refers to the cognitive ability to process, retain, and recall spatial details pertaining to the surrounding environment, including the arrangement of elements, positions of objects, and cues for navigation. The decline of both episodic and spatial memory functions is commonly observed during the aging process, making them important areas of study in the field of memory assessment. The examination of these specific subtypes of memory is of great importance in comprehending the cognitive aging process and its potential ramifications for the emergence of neurodegenerative disorders such as dementia.

2.1.1. Episodic memory

The issue of normal and pathological memory in the context of aging has become a prominent focus of neuropsychological research, given the prevalent phenomenon of an aging population in many developed nations. The decline in the quality of cognitive functions with advancing age is widely recognized. Episodic memory is commonly observed by clinicians to be the initial cognitive function to deteriorate in both normal older adults and individuals in the early stages of AD (Bäckman, Small, & Fratiglioni, 2001; Chételat et al., 2006; Perri et al., 2007; Spaan et al., 2010). The aforementioned form of memory facilitates the retrieval of individual experiences within their specific spatial and temporal framework, thereby playing a role in the development of a sense of self-identity (Tulving, 2002).

The model of episodic-like memory is a simplified representation of memory for episodes, which is characterized by three key conditions: the specific details of 'what' occurred during an episode, the location or 'where' it took place, and the temporal aspect of 'when' it happened (Allen & Fortin, 2013).

In the context of our everyday experiences, the ability to remember objects or the detail of an event is closely tied to the surrounding circumstances, such as the location and timing of when an object was observed or utilized in a significant daily activity. This integration of contextual information is an integral component of episodic memory, as described by Tulving (Tulving, 2002). Therefore, it can be observed that contexts serve as retrieval cues for objects. During an episodic retrieval, individuals can fully recollect both the contexts (such as where and when) and the objects, accompanied by specific details (Buckner et al., 1998). For example, in the context of retrieving information from a particular meeting, possessing knowledge of the meeting's location and time can prove advantageous. To retrieve past events, it is essential to establish accurate associations between the contextual characteristics of these events through a cognitive process referred to as binding (Kessels et al., 2009; Lekeu et al., 2002). The hippocampus is widely recognized for its role in facilitating episodic memory and is commonly regarded as the primary neural substrate for the process of binding (Eichenbaum, 2000). Furthermore, it has been found that the frontal cortex is linked to the strategic components of encoding and retrieval processes in relation to episodic memories (Hayes et al., 2004; Isingrini & Taconnat, 2008).

The effective performance of various activities of daily living is crucial and facilitates the spatial and temporal recall of prior learning (Tulving, 2002). Both normal aging (Cansino, 2009; Folville et al., 2020; D. C. Park & Reuter-Lorenz, 2008) and neuropathology (Dikmen et al., 2014) have been observed to have a negative impact on episodic memory. Furthermore, it should be noted that the impairment of episodic memory serves as an initial clinical indicator of typical AD (Epelbaum et al., 2018), occurring before the decline in other cognitive areas (Derby et al., 2013; Grober et al., 2008). The preservation of item memory is a well-established finding (Craik & McDowd, 1987a). Age-related disparities in object memory are primarily attributed to deficiencies in strategic processing, which refers to the ability to independently initiate and implement strategies during the encoding and retrieval processes. Additionally, the associative deficit hypothesis, supported by a meta-analysis conducted by Old and Naveh-Benjamin (Old & Naveh-Benjamin, 2008), posits that age-related differences in object memory can be attributed to difficulties in binding contextual elements together to form a cohesive episode. These difficulties are likely a result of alterations in the functional connectivity between the prefrontal and medio-temporal cortices (Dennis et al., 2008). Episodic memory deficits frequently manifest as reliable markers of brain injury or pathological conditions.

Research on object memory provides valuable insights into the mechanisms of everyday memory. However, the current scope of these studies is limited as they often overlook crucial elements of everyday memory, such as contextual richness. This includes the ability to select and remember objects within complex scenes. The presence of contextual richness in real-life situations, as opposed to controlled laboratory experiments, enhances the selectivity of both learning and retrieval processes (Neisser et al., 1997). Moreover, the process of selecting objects within everyday life scenes is an ongoing endeavor, as individuals frequently engage in visual exploration to navigate their surroundings (Pylyshyn, 2001). The fundamental elements of everyday episodic memory formation revolve around contextual features and dynamic aspects of events, which heavily rely on visual perception in the physical environment (Hollingworth, 2007). VR-based memory assessments appear to effectively address these real-world dimensions.

Deluca and Chiaravalloti propose that neuropsychological evaluations of episodic memory typically follow a two-step framework. The first step, known as the study phase, involves presenting participants with information to be learned, such as a shopping list, and instructing them to intentionally commit the material to memory. The second step, referred to as the test phase, requires participants to retrieve previously learned information through various tasks, including free recall, cued recall, and recognition tasks (Chiaravalloti & DeLuca, 2008).

2.1.2. Spatial memory

Spatial memory is the cognitive capacity of organisms to encode, retain, and retrieve information pertaining to the attributes and features of their surroundings (Postma et al., 2004). Spatial memory, like other forms of memory, involves the processes of acquisition, consolidation, and retrieval of spatial information, with the hippocampus playing a significant role (Florian et al., 2004).

The cognitive map theory, as proposed by O'Keefe and Nadel in 1979 (O’keefe & Nadel, 1979), posits that spatial memory is elucidated through the formation of a cognitive representation of the surrounding environment, encompassing all constituent elements within it. The present representation is derived from the neural activity of place cells situated in the hippocampus, as demonstrated by O'Keefe and Dostrovsky in 1971 (O’Keefe & Dostrovsky, 1971). It should be noted that the involvement of associative learning processes has been deliberately omitted in this analysis. On the other hand, a theoretical framework known as the associative approach posits that spatial memory is governed by associative processes when individuals navigate towards a desired destination. According to Leising and Blaisdell (2009), when a connection is formed between a prominent feature in the surrounding environment and a specific objective, the former can serve as a dependable indicator of the latter (Leising & Blaisdell, 2009).

Spatial memories serve as the foundation for various crucial cognitive abilities, including spatial orientation and navigation. In essence, the capacity of an individual to perceive and adapt its bodily orientation with respect to a prior position within the surrounding context, thereby discerning its comparative spatial placement in relation to other entities or environmental stimuli (Pietropaolo & Crusio, 2012). Spatial navigation encompasses a variety of cognitive processes, such as the understanding of environmental characteristics, decision-making guided by current objectives, the integration of path information, and the recognition of one's own position within the surrounding space. To investigate spatial orientation, researchers have developed a range of spatial tasks, including map learning, distance estimation, and spatial key recognition (Coluccia, 2008; Foreman et al., 2005; Hegarty et al., 2006; Marchette et al., 2017).

As individuals navigate their surroundings, the nature of their relationship with the environment undergoes a continuous evolution. When an individual undergoes or perceives motion, it is necessary for them to readjust their orientation by relying on consistent static cues in relation to their prior position. The phenomenon of reorientation is commonly known as spatial updating (Rieser, 1989). As an illustration, consider a scenario where an individual is positioned in front of a computer and subsequently rotates their body towards the right to respond to a doorbell. Consequently, the computer's location is now situated on the left side of the individual. Multiple studies have provided evidence indicating that spatial updating is a cognitive process that occurs automatically (Farrell & Robertson, 1998; Rieser, 1989). This process serves the purpose of maintaining congruence between an individual's egocentric reference and their present alignment. In their study, Wan, Wang, and Crowell demonstrated that stimuli presented through a VR headset were displayed with a resolution of 800 pixels horizontally and 600 pixels vertically for each eye (Wan et al., 2009). The participants in the study demonstrated the ability to update their spatial position within the VR environment, even when their optical field of view for each eye was limited to 26 degrees diagonally and they physically moved. Spatial updating is a cognitive process that operates in conventional physical settings, serving the purpose of maintaining individuals' awareness of their immediate surroundings, preventing collisions with nearby objects during movement, and facilitating the monitoring of distant targets. However, it is worth noting that visual cues are not necessary for automatic spatial updating, as blindfolded participants have demonstrated high levels of accuracy in spatial updating tasks (Farrell & Robertson, 1998). The available evidence indicates that the integration of vestibular and proprioceptive information plays a crucial role in facilitating accurate spatial updating processes (Lackner & DiZio, 2004). According to Lackner and DiZio (2005), in scenarios where visual cues are present, they serve to enhance and corroborate vestibular information, which is derived from multiple sources such as body position and ocular muscle positioning, rather than serving as the primary determinant of this information.

The ability to navigate, which involves finding one's way from one location to another, has been demonstrated to be a crucial but intricate spatial cognitive skill for effective daily life functioning (Van der Ham et al., 2010). The act of navigation encompasses various cognitive processes, including perception, attention, memory, and executive control functions (Wolbers & Hegarty, 2010). When individuals traverse a given setting, they utilize various cognitive processes to effectively reach their desired endpoint. In the realm of spatial navigation behavior, individuals commonly rely on landmarks as a means of guidance (Blades & Medlicott, 1992; Chan et al., 2012; Janzen & Van Turennout, 2004). Additionally, they engage in the creation of mental maps to represent their surroundings (Iaria et al., 2007; H. A. Taylor & Tversky, 1992; Thorndyke & Hayes-Roth, 1982; Tolman, 1948).

Numerous cognitive abilities that contribute to navigation behavior predominantly depend on spatial characteristics, while others involve features that are primarily temporal in essence. A frequently employed task in navigation research involves requesting participants to determine whether various scenes or landmarks were included in a specific route (referred to as a scene or landmark recognition task). This task does not explicitly require participants to make spatial judgments (Janzen & Van Turennout, 2004). However, it is likely that engaging in such a task activates (visuo)spatial processing. In other words, scenes possess inherent information regarding the spatial arrangement of multiple buildings or objects.

The complex nature of scene and landmark recognition has been demonstrated to be distinct from general memory performance. A number of scholarly investigations have documented cases of individuals experiencing a distinct deficit in utilizing salient features of their surroundings for the purposes of navigation and orientation, commonly referred to as "landmark agnosia" (Hirayama et al., 2003; Mendez & Cherrier, 2003; Rosenbaum et al., 2005). Nevertheless, it should be noted that deficits in scene recognition do not necessarily coincide with impaired performance in other navigation-related tasks (Aguirre & D'Esposito, 1999; Rosenbaum et al., 2005; Van der Ham et al., 2010). The aforementioned discovery unequivocally demonstrates that the capacity for navigation is not inherently contingent upon explicit scene recognition.

In contrast, the recollection of the sequential arrangement of various locations or landmarks encountered during a journey distinctly involves a different category of cognitive data. The topic of order memory in relation to navigation has received limited attention despite its classification as a component of route knowledge (Montello, 1998; Siegel & White, 1975). According to a recent study conducted by van der Ham et al. (2010), it has been demonstrated that order memory of this nature significantly influences navigation behavior, particularly within a neuropsychological framework (Van der Ham et al., 2010). However, the specific cognitive characteristics associated with order memory in the context of navigation remain uncertain. Most studies examining the role of order memory in navigation commonly define order memory as "temporal order" (Barker et al., 2007; Ekstrom et al., 2011; Van der Ham et al., 2010). Nevertheless, it is important to acknowledge that traversing a path inherently entails spatial displacements. Furthermore, if the velocity of travel remains consistent, the concepts of space and time advance in a congruent fashion. The process of memorizing the order of landmarks may be influenced by the distinct temporal and spatial locations at which these landmarks are encountered. Hence, the study in question labels the temporal aspects of navigation behavior as "spatiotemporal" due to this rationale.

There are two distinct types of navigational strategies that have been identified in the literature, supported by evidence of separate underlying brain structures. These strategies are known as egocentric and allocentric navigation (Chersi & Burgess, 2015; R. G. M. Morris et al., 1982). Egocentric navigation refers to a form of navigation that is centered around the self and is dependent on one's own viewpoint. It is commonly associated with response learning, which involves acquiring knowledge and making decisions based on one's own position. The method in question utilizes measurements of distances or angles between specific landmarks and is commonly employed for navigating familiar routes. This approach is believed to depend on the involvement of parietal-cortical and striatal brain regions (Wolbers et al., 2004). Allocentric navigation is a form of navigation that is not influenced by an individual's viewpoint, but rather relies on distal cues. The concept pertains to the spatial arrangement of a given environment, as observed through a survey or a top-down perspective, wherein one acquires knowledge about the positioning of landmarks in relation to one another. The process of allocentric navigation is dependent on the medial temporal lobe, specifically the hippocampus. Recent research has indicated a connection between the volume of the basal forebrain and spatial accuracy in allocentric navigation, but not in egocentric navigation (Kerbler et al., 2015).

Spatial memory problems

Spatial memory problems are frequently observed as a consequence of hippocampal damage (Astur et al., 2002; Holdstock et al., 2000). Spatial memories are known to be particularly reliant on the right hippocampus. Spatial orientation deficits are among the initial symptoms that serve as indicators of Alzheimer's disease, and these deficits have been linked to damage in the hippocampus (Moodley et al., 2015). The importance of precise early diagnosis lies in its ability to enable timely intervention prior to significant neuronal loss (Coughlan et al., 2018). Hence, the assessment of navigational skills has the potential to serve as a valuable instrument for the early detection of not only this particular neurodegenerative condition, but also other disorders characterized by cognitive decline. To gain a comprehensive understanding of human spatial memory and its impairments, it is imperative to construct assessments that effectively measure these abilities within ecological spatial contexts (Allison et al., 2016; Bird & Burgess, 2008).

The characteristics of spatial representations in relation to aging, particularly their adaptability in transitioning between different perspectives, have become increasingly intriguing to scholars due to the decline in our spatial learning capacity as we age. This phenomenon is observed not only in individuals experiencing pathological aging, as demonstrated by (Gazova et al., 2013), but also in typically aging individuals, as indicated by (Klencklen et al., 2012; Lithfous et al., 2013). Previous studies have provided evidence that the cognitive process of switching perspectives becomes increasingly challenging as individuals age. This difficulty is particularly pronounced when individuals are required to navigate and switch from an egocentric (self-centered) to an allocentric (external reference point) mode while performing a spatial recall task. For instance, research conducted by (Devlin & Wilson, 2010) as well as (M. A. Harris & Wolbers, 2014) has supported this finding. The identification of age-related challenges in spatial representation can be accomplished through an examination of the specific forms of input, such as map reading and navigation, in relation to the spatial recall modalities employed. This analysis primarily focuses on the extent to which individuals rely on egocentric or allocentric knowledge. Regarding the acquisition of knowledge from a map, certain researchers have observed minimal or nonexistent disparities related to age when evaluating the resultant cognitive representation through tasks that maintain consistent configurational properties, such as sketch map tasks (Muffato et al., 2017; Yamamoto & DeGirolamo, 2012). This phenomenon can likely be attributed to the alignment between the modalities of input and recall. The manifestation of age-related disparities subsequent to map-based learning became more evident when the spatial recall tasks necessitated adapting to a distinct form of inquiry that placed greater emphasis on one's own perspective, such as mentally adopting hypothetical viewpoints (Borella et al., 2015), or selecting the most expeditious route to achieve a specific objective (Salthouse & Siedlecki, 2007). Several studies have indicated that the process of aging has an impact on the capacity to acquire spatial knowledge through navigation, utilizing both real-world and visual media (Klencklen et al., 2012; Moffat, 2009). Specifically, older individuals, particularly those in their seventies, tend to encounter greater challenges when it comes to re-tracing a previously learned path (repetition task involving a specific route) (Muffato et al., 2016; Wilkniss et al., 1997). Nevertheless, it is important to note that certain exceptions were observed in the study. Specifically, no discernible variations based on age were identified in relation to the participants' aptitude for navigating through a maze after they had acquired a complete understanding of the route (Jansen et al., 2009). Age-related disparities become evident in tasks that require the management of spatial knowledge (Duffy et al., 2008), such as the recollection of information in an allocentric manner (through map drawing tasks; Muffato et al., 2016), subsequent to learning it through navigation. There have been documented instances of diminished performance among older individuals in an allocentric-based location task, both following navigation within an environment (Muffato et al., 2016) and after route learning in general, including spatial descriptions (Meneghetti et al., 2012). The aforementioned studies have identified notable age-related differences that can be attributed to the transition between the learning format, which emphasizes a route perspective, and the test format, which emphasizes an allocentric focus.

The challenges experienced by older adults in managing multiple spatial demands following a route-based learning perspective, as opposed to a survey-based learning perspective, are apparent when comparing two learning inputs directly. In their study, Yamamoto and DeGirolamo (2012) employed a methodology wherein participants were instructed to acquire knowledge of landmark locations through two distinct approaches: examining an aerial view (i.e., a map) and physically navigating the environment (Yamamoto & DeGirolamo, 2012). Subsequently, participants were tasked with identifying and marking the respective landmarks on a sketch map. The researchers discovered that older individuals exhibited lower accuracy in sketching the environment compared to younger individuals following navigation. However, both age groups performed equally well in sketching after studying the aerial view. This implies that the capacity to acquire knowledge from a map is better maintained with age than the skills related to exploratory navigation. The researchers examined the implications of their findings regarding the neuroimaging evidence of the medial temporal lobe. This particular brain region has been associated with navigation abilities, but not with map reading skills. The authors also noted that the medial temporal lobe is susceptible to age-related decline, which can make it more challenging for individuals to acquire information from an egocentric perspective compared to an allocentric perspective (Yamamoto & DeGirolamo, 2012). The findings of their study are subject to certain limitations, primarily due to the use of the sketch map task as the sole measure of participants' recall of the environment. This task maintained the same format as learning from an aerial view. The aforementioned study neglected to consider the scenario in which learning occurs through navigation and subsequent completion of a task that evaluates knowledge specific to routes. The influence of aging on the relationship between learning inputs and spatial recall tasks is still a topic of ongoing investigation.

In summary, research on the process of aging has yielded initial findings indicating variations in older individuals' capacity to acquire knowledge from maps in comparison to their navigation skills. These differences appear to be influenced by the alignment between the mode of recall and the mode of learning. The severity of age-related decline is heightened when there is a need for individuals to shift their perspective between the learning and testing stages. The current body of research is inadequate due to the limited number of studies that have examined the differences in learning outcomes between map-based learning and navigation-based learning in older adults (Yamamoto & DeGirolamo, 2012). Further research is required to investigate the interaction between learning conditions and recall tasks in relation to the spatial mental representations of both young and older individuals. This exploration aims to gain a deeper understanding of the characteristics and adaptability of cognitive maps in older adults. Specifically, the examination of perspective switching, where individuals learn from one viewpoint and are tested from another, can provide valuable insights into the accuracy and effectiveness of mental maps. Previous studies, such as those conducted by (Iglói et al., 2009) and Wiener & Mallot (2003), have demonstrated the potential of this approach.

Spatial navigation is a fundamental cognitive capacity that holds significant importance in facilitating mobility and fostering independence. Nevertheless, an increasing body of empirical research has provided evidence for the decline of orientation and navigational abilities associated with aging. These abilities include tasks such as route learning and repetition (Head & Isom, 2010; Zhong & Moffat, 2016), route retracing (Wiener et al., 2012), cognitive mapping (Moffat & Resnick, 2002), and wayfinding (Iaria, Palermo, Committeri, & Barton, 2009).

The documented literature has extensively explored the decline in spatial orientation and navigation abilities in both typical and atypical aging (Lester et al., 2017). The effectiveness of navigation relies on various strategies and mechanisms that exhibit varying rates of decline. In the context of healthy older individuals, it is commonly observed that egocentric navigation strategies, alternatively known as route learning or response strategies, tend to remain intact for a longer duration compared to allocentric strategies. Allocentric strategies involve the cognitive processing and encoding of the spatial relationship between landmarks and/or places (Moffat, 2009). Moreover, it should be noted that spatial disorientation has been identified as an early indicator of AD (M. C. Pai & Jacobs, 2004; Serino et al., 2015). For instance, individuals in the middle-aged adult population who are at a heightened susceptibility to AD exhibit diminished spatial abilities, as indicated by research conducted by Ritchie et al. (2017). Furthermore, Kunz et al. (2015) have observed impaired spatial computations within the entorhinal cortex among this high-risk group. Additionally, (Wood et al., 2016) have found that performance on spatial memory tasks can serve as a predictive factor for the progression from mild cognitive impairment to AD. One plausible rationale for the heightened susceptibility of spatial tasks and navigational tasks to deviations from typical aging can be attributed to the presence of pathological changes associated with AD in brain regions implicated in navigation, specifically the entorhinal cortex and the precuneus (Weston et al., 2016). The evaluation of navigation skills possesses the potential to serve as a robust diagnostic instrument in aiding the early and distinct identification of atypical aging. However, in order to accomplish this objective, it is crucial to obtain normative data for a range of well-established navigational tasks that depend on various navigation mechanisms.

3. Neuropsychological assessment

The complexity of diagnosing major neurocognitive disorders is compounded by the lack of reliable biomarkers for the underlying causes and the blurred distinction between normal age-related decline and significant cognitive impairment. Although the utilization of technologies such as magnetic resonance imaging (MRI) and other neuroimaging methods can effectively detect notable abnormalities in brain health, it is important to acknowledge that their implementation is not a simple or flawless process.

Cognitive assessments serve as a crucial tool in addressing the diagnostic discrepancy by providing a relatively convenient and non-intrusive method for evaluating an individual's cognitive condition. Nevertheless, in practical application, the knowledge obtained from MRI data is insufficient to replace the valuable insights that can be obtained through cognitive assessments. Lebedeva and colleagues conducted a study that provided illustrative evidence for the effectiveness of integrating Mini-Mental State Examination (MMSE) data into a random-forest classifier (Lebedeva et al., 2017). The results of the study showed that this integration led to enhanced test accuracy, sensitivity, and specificity, surpassing the performance achieved by relying exclusively on MRI data (Lebedeva et al., 2017).

The utilization of assessments specifically designed to evaluate the cognitive symptoms associated with major NCDs is an important strategy in the screening of patients and in providing guidance for subsequent comprehensive analyses. The significance of this matter is heightened by the lack of a universally applicable physiological indicator that encompasses all variations of both major and minor NCDs. The Diagnostic and Statistical Manual of Mental Disorders (DSM)-5 provides criteria for minor NCDs that characterize these conditions as exhibiting a discernible decrease in cognitive functioning. This decline can be observed by an informant or detected through a cognitive assessment, but it does not significantly impair the individual's ability to carry out their daily activities. Significantly, it is crucial to note that this decline in cognitive function cannot be ascribed to the presence of delirium or an underlying mental disorder (American Psychiatric Association, 2013).

The prioritization of a methodical evaluation of cognitive disorders associated with aging becomes crucial in the endeavor to implement timely intervention and treatment for NCDs. Through the implementation of comprehensive and standardized assessment protocols, it becomes possible to proactively detect and manage cognitive impairments that have the potential to progress into more severe neurocognitive disorders. By implementing timely identification and control measures, the detrimental effects of NCDs on an individual's overall well-being can be alleviated. This allows for the prompt implementation of appropriate interventions aimed at improving cognitive health.

3.1. The history of neuropsychology

The field of clinical neuropsychology is experiencing rapid growth and is considered to be one of the most rapidly expanding specialty areas within the broader field of psychology. Clinical neuropsychologists investigate the associations between brain function and behavior in individuals who possess typical cognitive abilities, as well as those who have experienced brain damage or are afflicted with neurological disorders. In recent decades, the field of clinical neuropsychology has experienced a growing acknowledgment as a discipline that holds significance in various practice areas such as neurology, neurosurgery, psychiatry, and family medicine. Additionally, it has been recognized for its relevance in specific research areas within neuroscience, including behavior, learning, and individual differences. Consequently, neuropsychologists are required to possess a comprehensive comprehension of psychology, physiology, and neurology in order to evaluate, diagnose, and provide treatment for individuals suffering from neurological, medical, neurodevelopmental, psychiatric, and cognitive disorders.

Clinical neuropsychologists employ a comprehensive battery of assessments to evaluate various cognitive domains, encompassing attention and information encoding capabilities, receptive and expressive language skills, problem-solving aptitude, reasoning and conceptualization abilities, learning and memory capacities, perceptual-motor proficiencies (such as visuospatial organization and visual-motor coordination), processing speed, intelligence, academic and vocational competencies, behavioral patterns, emotional functioning, and personality traits. Neuropsychological assessments encompass a variety of cognitive functions, as evident from the available evidence. This aspect holds significance as the majority of neuropsychological assessments lack purity, as they do not exclusively evaluate a single skill. In the context of a timed task involving the replication of figures, multiple domains are being evaluated, namely motor skills, visual perception, attention, and processing speed. For instance, consider the outcomes of an individual who exhibited challenges in a quantitative aptitude assessment. The observed outcomes may indicate constraints in various areas, such as comprehension of numerical principles, retention of mathematical information, comprehension of mathematical terminology, recall of appropriate mathematical operations, visualization of mathematical concepts, execution of sequential processes, and attention to visual elements like operational symbols, place value, and numerical columns. Consequently, neuropsychological assessments are designed in a manner that aims to examine various facets or subcomponents of an individual's performance, thereby elucidating the specific strengths and weaknesses they possess across multiple domains within the field of neuropsychology. In addition to employing neuropsychological assessments, which encompass tests evaluating neurocognitive, behavioral, and emotional capabilities, neuropsychologists conscientiously analyze the interplay between these factors and the individual's psychosocial context in order to generate hypotheses about their neurological functioning. The neuropsychological assessments provide data that can be used to make inferences about the individual's daily functioning.
The neuropsychological assessment has traditionally been described as a process that refines and expands upon the neurological examination (A. Benton, 1985).The origins of contemporary

neuropsychological assessment can be traced back to the efforts of physicians in the late 19th and early 20th centuries to enhance the evaluation of cognitive abilities in individuals with brain disorders, such as Broca and Wernicke aphasics (Broca, 1865). A contributing factor to this phenomenon is the construction of numerous widely utilized neuropsychological tests prior to the development of neuroimaging techniques and the accumulation of contemporary knowledge regarding the association between abnormal behavior and brain dysfunction. One significant challenge encountered in the field of neurological examination pertains to the absence of a universally accepted protocol for administering and evaluating the procedures involved in the examination. The depiction of administrative procedures often lacks clarity in numerous instances. Furthermore, it is not uncommon for neurologists to modify procedures on a case-by-case basis for individual patients. Despite the clarity of administrative procedures, scoring procedures remain unclear. The scoring process relies on the subjective evaluation of the neurologist, drawing upon their expertise and understanding, rather than being guided by any standardized or normative data. Notwithstanding these significant challenges, it is evident that the neurological examination exhibits a considerable level of face validity and is firmly grounded in theory. Significant progress has been achieved by neuropsychologists in the areas of appropriate standardization, scoring, and validation. Consequently, the modified neurological examination, also known as the neuropsychological assessment, has emerged as a significant instrument in both clinical and experimental fields of neuropsychology. The scholarly contributions of A. R. Luria, a prominent Russian neuropsychologist, exemplify a commendable instance of a neuropsychological assessment rooted in a neurological framework. Luria posits that the results obtained from a neuropsychological evaluation can elucidate the interconnected neurological regions, referred to as "functional systems," that underlie specific behaviors. Each neurological region within the brain actively engages in multiple functional systems. Luria's objective was to demonstrate that the cognitive consequences resulting from a brain injury are indicative of a disruption in the implementation of any functional system that encompasses the affected area(s). One notable limitation of the original Luria battery is the absence of standardized administration and scoring procedures, which has hindered the ability to evaluate its validity. Nevertheless, efforts have been made to address these limitations through the creation of an impartial framework that integrates Luria's methodologies with the benefits of a conventional test battery, commonly referred to as the Luria-Nebraska Neuropsychological Battery (LNNB).

The Halstead-Reitan Battery was designed with the specific purpose of identifying and distinguishing individuals with brain damage, particularly those with "organic" dysfunction, from those without such impairment. Its primary objective is to differentiate between patients with brain damage and those with "functional" disorders. Throughout the years, there has been a collaborative effort to develop tests that align with the advancing knowledge about how behavior is influenced by particular brain structures or circuits. These tests aim to provide a deeper understanding of the overall functioning or impairment of neurological processes. A substantial amount of prior experience with these instruments serves as a foundation for interpreting the tests from a neurologic perspective. The Wechsler Scales are a frequently employed battery of tests. Although frequently employed by neuropsychologists, it is crucial to acknowledge that the Wechsler Adult Intelligence Scale (WAIS) and the Wechsler Memory Scale (WMS) were not originally designed with the explicit purpose of evaluating brain functionality or identifying brain disorders. However, through extensive utilization of these measures, professionals have gained valuable insights into interpreting the test results within a neurologic framework. Contemporary neuropsychological assessment methodologies typically employ a combination of conventional tests alongside novel techniques tailored to assess neurocognitive functions and elucidate brain functionality across various pathological conditions. Therefore, there has been a significant increase in the scope of domains evaluated by clinical neuropsychologists in recent years. This expansion encompasses domains that go beyond behavioral neurology and the conventional distinction between organic and functional disorders in psychiatry. While there are certain similarities between neuropsychological assessment and the conventional evaluation conducted by behavioral neurologists, it is worth noting that neuropsychological measures possess certain advantages in terms of standardization and psychometric rigor.

2.1.1. Standardized Neuropsychological Measures

The establishment of standardized assessment measures capable of identifying the neurocognitive effects of brain dysfunction is a crucial element in the advancement of clinical neuropsychology. The origins of standardized assessment in neuropsychology can be primarily attributed to its historical evolution from Alfred Binet's intelligence tests (Binet & Henri, 1895; Binet & Simon, 1904, 1907) and the United States' involvement in World War I in 1917 (Anastasi & Urbina, 1997). During this period, Robert Yerkes, Arthur Otis, and the American Psychological Association collaborated to create a group-administered variant of the Stanford-Binet intelligence test, known as the Army Alpha. Additionally, they devised a unique group-administered assessment called the Army Beta, which consisted of nonverbal tasks. Yerkes (Yerkes, 1917) expressed a preference for utilizing a point-scale methodology, which involves selecting tests based on specific functions, as opposed to Binet's age-scale approach, where tasks vary according to age and developmental level. In the end, the Army group implemented measures that combined elements of Yerkes's point-scale approach and Binet's task-specific approach in order to assess cognitive performance. Additionally, it is worth noting that an Army battery incorporated a performance scale devised by David Wechsler, which consisted of subtests primarily developed by Binet and psychologists during World War I (Yoakum & Yerkes, 1920).

A significant transformation in the field of testing took place when Wechsler adapted testing protocols (specifically, group and individual procedures) originally designed for individuals with typical cognitive abilities to the development of a comprehensive clinical test battery. After the conclusion of World War I, Wechsler organized the Wechsler-Bellevue battery, a comprehensive assessment tool that incorporated Verbal and Performance Scales. During the 1940s, clinicians had access to a variety of specialized neurocognitive tests for evaluating the cognitive abilities of individuals with brain disorders (Conkey, n.d.; Goldstein & Scheerer, 1941; Hunt, 1943; Shipley, 2010). The cumulative impact of these tests laid the groundwork for contemporary neuropsychological evaluation protocols (A. L. Benton, 1994; Bishop, 1999; Reitan, 1955; Strauss et al., 2010).

Neuropsychologists commonly prioritize the psychometric rigor of neuropsychological assessments by placing significant emphasis on the concepts of reliability and validity. The term "reliability" in the field of neuropsychology pertains to the degree of consistency in obtaining identical information from a specific neuropsychological test or a collection of such tests. In order for scores to possess reliability, it is imperative that they exhibit stability, provided that no intervening variables such as illness, injury, or new learning are present. There are several instances that exemplify reliability, such as: 1) Inter-rater reliability refers to the extent to which test scores remain consistent when administered by different examiners. 2) Intra-rater reliability pertains to the consistency of test scores when the same examiner administers the test on multiple occasions. 3) Test-retest reliability examines the consistency of test scores when administered to the same patient on different occasions. Therefore, the concept of test reliability pertains to the degree of consistency in the information obtained when the test is administered by different examiners (inter-rater reliability), by the same examiner on multiple occasions (intra-rater reliability), or to the same patient on different days (test-retest reliability). It is imperative to acknowledge that the reliability of neuropsychological tests pertaining to memory consistently exhibits lower levels compared to other categories of neuropsychological tests. In instances of this nature, it is imperative for the clinician to be cognizant of the fact that the inferences derived from the tests may exhibit a higher degree of variability than is deemed optimal.

The term "validity" in the field of neuropsychology pertains to the extent to which a test accurately assesses the specific construct it claims to measure. Several specific types of validity that may be subject to questioning include the following: 1) Construct validity refers to the extent to which a test accurately measures the specific construct it is intended to assess. 2) Concurrent validity pertains to the degree of correlation between a newly developed test and established tests or independent measures that evaluate the same construct under consideration. 3) Face validity refers to the visual perception or external appearance of a test, indicating its ability to measure the intended construct. 4) The assessment's localization validity pertains to its ability to accurately identify the specific location of focal lesions. 5) Ecological validity refers to the assessment's ability to accurately predict an individual's real-life functional abilities and performance in activities of daily living. Therefore, the neuropsychologist can utilize validity data to address inquiries regarding the psychometric soundness of various aspects. These include *construct validity*, which examines whether memory tests effectively assess memory; *concurrent validity,* which investigates whether new tests yield similar conclusions to established tests; *localization validity*, which explores whether test results accurately identify focal lesions; *diagnostic validity*, which assesses the accuracy of tests in diagnosing diseases; and *ecologic validity*, which examines whether test results can predict real-life performance. It is imperative to acknowledge that the neuropsychologist exercises caution in employing the concepts of reliability and validity. When discussing reliability, neuropsychologists typically refer to the consistency of scores rather than the tests themselves. On the other hand, when referring to validity, neuropsychologists focus on the interpretation of test performance rather than the tests per se. The question regarding the validity of a specific neuropsychological test is not easily resolvable. In contrast, the neuropsychologist inquiries about the interpretation of one's performance. Consequently, a significant portion of the discourse surrounding validity pertains to the concept of ecological validity.

As previously indicated, a significant portion of contemporary neuropsychological assessment practices can be traced back to the endeavors of physicians in the late 19th and early 20th centuries. These medical professionals sought to enhance the evaluation of cognitive abilities in individuals afflicted with brain disorders. During a phase characterized by an emphasis on localization, neuropsychologists were referred to by neurosurgeons in order to conduct psychometric assessments to determine the specific location of brain damage. Consequently, the implemented measures were grounded in a localization paradigm that emphasized double dissociation. This paradigm entails the functional dissociation of two neocortical areas using two behavioral measures. Specifically, each measure is influenced by a lesion in one neocortical area while remaining unaffected by a lesion in the other (Friederici et al., 2017; Teuber, 1955). Due to the significance of lesion localization in neuropsychological assessment, there has been a growing emphasis on improving the psychometric rigor of such assessments. In addition to the aforementioned concerns regarding reliability and validity, the matter at hand also encompasses considerations of sensitivity and specificity. The term "sensitivity" as used by neuropsychologists pertains to the capacity of a test to identify even the most subtle indications of irregularities in neurological function, particularly within the central nervous system. Sensitivity is conceptualized as a measure of the neuropsychological test's capacity to accurately detect individuals who exhibit symptoms of a particular disorder. This metric is commonly known as the true positive rate. The term "specificity" in the field of neuropsychology pertains to the capacity of a neuropsychological test to distinguish individuals with a particular abnormality from those with different abnormalities or without any abnormality. This is commonly known as the true negative rate. The results of any given test can be classified into four categories: true positive, false positive, true negative, or false negative. In order for a score to be classified as a true positive, it is imperative that it exhibits a high level of sensitivity towards dysfunction, thereby enabling the detection of dysfunctions. If a test score yields a false positive result, it suggests a general sensitivity to dysfunction but does not possess specificity towards a specific dysfunction. A test score can be classified as a true negative when it exhibits a high level of specificity, enabling the accurate differentiation of negative results from other outcomes. If a test produces a false negative score, it signifies a deficiency in its sensitivity, irrespective of the test's specificity. To conduct a comprehensive evaluation, it is imperative to possess a thorough comprehension of the rates pertaining to each of the four distinct categories of outcomes. The capacity to detect brain dysfunction varies significantly across different neuropsychological tests and is influenced by two main factors: the accuracy with which the test can differentiate between normal and abnormal brain function, and the specific type of cognitive impairment displayed by the patient. For instance, the Wechsler Adult Intelligence Scale (WAIS) lacks memory subtests, rendering it inherently incapable of detecting impairments related to memory. However, it has exhibited the ability to identify deficiencies in visuospatial, calculation, and attentional capacities caused by various disorders. Typically, timed tests that necessitate patients to complete them within a predetermined timeframe exhibit higher sensitivity towards diffuse or multifocal cerebral changes compared to untimed tests.

In essence, clinical neuropsychology can be regarded as an integration of neurological, psychiatric, and psychological assessment methods, wherein a comprehensive evaluation of cortical and subcortical systems is conducted alongside precise psychometric measurement. The utilization of neuropsychological assessment serves to mitigate the inherent subjectivity present in conventional neurological examinations. This is achieved through the administration of assessments that yield quantifiable standardized scores, thereby enhancing the reliability of the evaluation process. Additionally, this approach facilitates the establishment of a more discerning baseline for comparisons over time. Moreover, the inclusion of normative data and adherence to standardized administration procedures enhance the sensitivity of neuropsychological evaluation in detecting mild cognitive disturbances, surpassing the efficacy of unstructured mental status testing.

3.2. Towards an integration with technologies

It is noteworthy to acknowledge, nevertheless, that the utilization of neuroimaging has significantly diminished the necessity for neuropsychologists to ascertain the specific location of brain injury. Regrettably, a significant number of neuropsychologists persist in employing "localization" as the primary criterion for validating neuropsychological assessments. According to Ronald Ruff's argument, the advent of neuroimaging has led to a change in the focus of neuropsychology from localizing brain functions to documenting neuropsychological deficits in order to predict real-world functioning. However, clinical neuropsychologists often neglect to develop assessments that are ecologically oriented and instead rely on test batteries that were originally designed with a localizationist perspective (Ruff, 2003). Despite the widespread utilization of contemporary neuropsychological assessment procedures, professionals in the field of neuropsychology have exhibited a sluggish response in adapting to the influence of technology on their discipline. The refusal to adapt to technology has led to two significant limitations. The existing procedures for neuropsychological assessment are a technology that has undergone minimal changes since the initial development of scales in the early 1900s. These scales include the first scale by Binet and Simon in 1905 and Wechsler's initial test in 1939. For neuropsychologists to wholeheartedly adopt the advancement of novel batteries that prioritize ecological validity, it is imperative for them to transcend superficial modifications to standardized tests and instead shift towards utilizing computerized measures. Nevertheless, there has been a historical reluctance among neuropsychologists to fully adopt and incorporate technological advancements in the field of computation. While neuropsychology places significant emphasis on its scientific nature, its technological advancements are not keeping up with those of other scientific disciplines. Furthermore, the original objective of clinical neuropsychology was to differentiate between various brain pathologies. However, with advancements in other clinical neurosciences, such as the emergence of neuroimaging techniques, the role of the neuropsychologist has evolved. Presently, their primary responsibility is to make predictions that are ecologically valid regarding the influence of a patient's neurocognitive strengths and weaknesses on their day-to-day functioning.

Computer-based neuropsychological assessments provide several benefits compared to traditional paper-and-pencil testing. These advantages include enhanced standardization of administration, improved accuracy in timing presentation and response latencies, simplified administration and data collection processes, and consistent and randomized presentation of stimuli for repeated administrations (Schatz & Browndyke, 2002). During the 1980s, there was a notable inclination towards computerizing different assessment measures. Neuropsychologists undertook the task of adapting several paper-and-pencil measures to be compatible with personal computer systems. The researchers initially made efforts to evaluate the comparability of these measures with conventional tests (Eckerman et al., 1985). Several computerized adaptations of traditional paper-and-pencil neuropsychological tests can be identified, such as the Raven's Colored Progressive Matrices; the Pea-body Picture Vocabulary Test (Space, 1975); Category Test subtest of the Halstead Reitan Battery; and the Wisconsin Card Sorting Test (Waterfall, 2009). In the past decade, a number of computerized tests on neurocognitive function have been developed: CogSport (Brooks, 2006), ImPACT, Automated Neuropsychological Assessment Metrics (ANAM) (Johnson et al., 2008), and HeadMinder are some examples.

The ANAM battery is one of the most extensively utilized computerized neuropsychological assessment batteries. It has been administered to both civilian and military populations on a large scale. Indeed, the ANAM battery has been distributed to a total of more than 400,000 soldiers who were deployed in advance. This battery is a product of three decades of computerized psychological test development, primarily funded by the U.S. Military. It can be traced back to its origins as a descendant of the joint services. At present, there is still a significant emphasis on the utilization of the ANAM battery in the evaluation of cognitive functioning among Military Service Members. A significant portion of this emphasis stems from injuries incurred during conflicts, wherein Service Members may sustain injuries due to explosions, leading to concussions, also known as mild traumatic brain injuries. The ANAM is a scientifically validated computerized assessment tool that has been specifically developed to measure the speed and accuracy of cognitive functions such as attention, memory, and overall cognitive ability. The system documents the performance of a Service Member by capturing their responses on a computer. This activity is carried out before implementation and serves the purpose of identifying and monitoring alterations in functionality. A specialized neuropsychological assessment tool has been developed specifically for the purpose of evaluating individuals affected by blast injuries. The ANAM Traumatic Brain Injury (TBI) Battery comprises a collection of tests sourced from the ANAM library, specifically developed to assist in the evaluation of overall cognitive abilities subsequent to a cranial trauma. The Defense and Veterans Brain Injury Center has undertaken a continuous project that has yielded valuable research on ANAM and TBI. The Defense and Veterans Brain Injury Center possesses comprehensive databases pertaining to specific ANAM tests. A normative study was conducted on the ANAM TBI Battery test modules, involving a sample size of more than 2,000 paratrooper recruits. Additionally, another study was conducted with a sample size of over 5,000 recruits. Both studies yielded consistent findings. These studies have contributed to the creation of extensive and high-quality neuropsychological assessment databases specifically for military personnel. They demonstrate the cost-effectiveness and value of the Department of Defense -sponsored development and implementation of the ANAM test. In spite of the existence of computerized adaptations of conventional paper-and-pencil neuropsychological tests, the overwhelming majority of contemporary neuropsychological assessment methods continue to rely on technology that has remained largely unchanged since the inception of the initial scales in the early 1900s (such as Binet and Simon's first scale in 1905 and Wechsler's scale in 1939). The Wechsler scales, such as the WAIS-R and WAIS III, have been extensively utilized as neuropsychological assessments over the past few decades (Guilmette et al., 1990; Hartlage, 1980; Lees-Haley et al., 1996). Automated iterations of the original WAIS were introduced in 1969 and subsequently in 1980 (Elwood & Griffin, 1972; Vincent, 1980). However, these automated versions offered only basic stimulus presentation and restricted data recording capabilities. Since the 1980s, there has been a significant decline in the use of automated versions, with the current emphasis being on making minor modifications to the traditional paper-and-pencil versions while incorporating computerized scoring. The most recent iterations of the Wechsler scales, such as the Wechsler Adult Intelligence Scale—Third Edition (Wechsler, 1997) and the Wechsler Intelligence Scale for Children—Fourth Edition (D Wechsler, 2003) provide minimal substantive modifications and enhanced standardization. The significance of the limited technological progress of the Wechsler scales is underscored by a study conducted in 2005, which examined assessment practices and test usage patterns among 747 clinical neuropsychologists with doctorate-level qualifications in North America. This study revealed that the Wechsler Scales were the most employed tests in their neuropsychological assessments (Rabin et al., 2005).

The Cambridge Neuropsychological Test Automated Battery (CANTAB), a computerized neuropsychological assessment tool, has garnered increasing interest from researchers in the field of dementia (Morris et al., 1987; Sahakian et al., 1988, 1990, 1992; Talebi et al., 2020). Prior studies have demonstrated that two subtests of the CANTAB, namely paired associate learning and delayed matching to sample, exhibit sensitivity in detecting early stages of Alzheimer's disease dementia. According to Fowler and colleagues (Fowler et al., 2010), the subtests accurately classified 88% of early dementia patients during the initial assessment which revealed that performance on delayed matching to sample and paired associate learning tasks did not exhibit discriminatory ability between

subjects with questionable dementia and control participants, similar to other conventional neuropsychological measures.
Overall, computerized neuropsychological tests typically exhibit a notable degree of objectivity with respect to both their administration and scoring procedures (Witt et al., 2013). The presence of a high degree of test objectivity is a necessary but not solely determinative factor for achieving high test-reliability. The aforementioned statement holds true for the correlation between test reliability and test validity. In comparison to traditional paper-pencil testing, computer-based tests offer the advantage of precise measurement of reaction times in milliseconds. This is especially beneficial when assessing attention processes, such as alertness and speed of information processing. In addition, computerized assessments have the capability to incorporate advanced interactive and multimedia-based question formats, as well as virtual reality components. Stationary hardware is not necessary for their operation, as they have the potential to be utilized on mobile phones or handheld computers. The potential for a seamless and immediate recording of cognitive performance can be harnessed for adaptive testing, which involves customizing the level of task difficulty or demands to match an individual's performance level. The utilization of random selection from a stimulus pool, as opposed to employing fixed parallel versions, presents a notable benefit in scenarios where multiple reassessments are necessary. Additionally, computerized assessments are typically straightforward to administer, and in some cases, individuals can even administer them to themselves. While the current application may not explicitly demand specialized knowledge in neuropsychology, conducting computerized testing without the guidance of a neuropsychologist carries the potential for inaccurate interpretations. It is essential to distinguish between fully computerized tests and computer-guided or -aided tests. While the term "fully computerized" denotes the utilization of computer technology for both task presentation and automated response registration, computer-guided or -aided testing involves the use of a computer either for presenting stimuli or as an electronic log sheet for the examiner to record the patient's reactions or answers. Hence, the administration of computer-guided or computer-aided testing inherently necessitates the presence of an examiner, rendering it non-self-administrable.
When the process of recording outcomes is digitized, computerized assessments have the capability to automatically compute and present the results. This includes both the raw data and standardized values that are compared to normative data. These findings can be seamlessly incorporated into printed reports or electronic patient records without manual intervention. This approach is characterized by its efficiency in terms of time allocation, enabling clinicians to promptly deliver feedback to the patient under investigation. In the realm of scientific research, the potential for electronic data export greatly facilitates the process of importing data into statistical software packages. One significant benefit of computerized testing, particularly in the context of epilepsy, is the potential for time-locked co-registration of cognitive processes and physiological measures. Through the utilization of this method, it becomes possible to examine the effects of interictal epileptiform discharges on cognitive performance, as an illustrative example. In addition to concurrent EEG analyses, computerized tests can also be utilized in functional brain imaging studies, such as fMRI. Ultimately, despite the initial higher investment in computerized testing procedures, potential long-term savings may be realized due to the elimination of ongoing expenses associated with replenishing log sheets for paper-pencil tests (Witt et al., 2013).

Computerized neuropsychological tests may also possess certain drawbacks. The utilization of self-administered computerized tests significantly diminishes the level of interaction between the examiner and the patient. Consequently, a potentially significant reservoir of information becomes inaccessible. One additional drawback can be observed in the context of interface issues, where behavioral responses are limited to reactions facilitated by input devices such as the mouse, keyboard, or joystick. For instance, the precise placement of the index finger, such as the distance between the finger and the key, may hold significance in the assessment of reaction times measured in milliseconds. The growing accessibility of touchscreens that are more user-friendly may alleviate these concerns. The potential for future advancements in video-monitoring, language recognition, and movement registration techniques holds promise for expanding the range of behavioral expressions. The familiarity with computer devices can have a significant impact on individuals' affinity towards and performance in computerized tests. An additional concern pertains to certain established paper-and-pencil tests that have undergone rigorous validation. These tests necessitate written or spoken answers, such as free verbal memory recall, as well as patient drawings or manual constructions involving the use of blocks. The conversion of this task into a computerized test poses significant challenges, primarily due to the need for thorough validation of novel patient-test interaction methods (Witt et al., 2013). Finally, some computer test batteries require extra hardware (e.g. push-button, touchscreen) or have special software requirements (e.g., in terms of the operating system used). Variations in screen dimensions and disparities in contrast and clarity have the potential to influence outcomes, while the management of audio volume during the delivery of sounds or speech can pose challenges.

3.3. Limitation of traditional neuropsychological tests

Classical tests, despite their utility, possess certain limitations that should be acknowledged. One such limitation is the perception of intrusiveness associated with these tests (Chaytor & Schmitter-Edgecombe, 2003). Additionally, the white-coat effect has been found to influence the results of these tests (Mario et al., 2009). Another drawback is the delayed nature of the diagnosis (Holtzman, Morris & Goate, 2011). Moreover, these tests are heavily reliant on confounding factors, including age and educational level (Cordell et al., 2013), as well as the practice effect (Hawkins et al., 2004), which can introduce biases. Furthermore, the manual processing of these tests can lead to processing errors (Farias et al., 2003; Knight & Titov, 2009). Given the intricate nature of memory, which is dependent on a multitude of interconnected processes and systems, researchers have developed various experimental and clinical tests to assess memory and disentangle its distinct components. Various tasks and testing conditions have been devised to differentiate between familiarity and recollection, item, and associative memory, as well as memory for verbal, visual, or spatial material. Memory tasks commonly employed in clinical practice or experimental studies on aging are designed in a manner that enables precise manipulation of task parameters and testing conditions, thereby capturing the intricate processes involved. However, it is important to note that these tasks may lack ecological validity, as they may not accurately represent the complexity and diversity of memory situations that older adults encounter in their everyday lives (Bowman, 1996; Chaytor & Schmitter-Edgecombe, 2003a; Farias et al., 2003; Piolino et al., 2009; Schultheis et al., 2002). In practical settings, the process of memorization frequently takes place amidst environments characterized by high levels of noise and the presence of complex information. Moreover, this cognitive activity is often carried out concurrently with the execution of other tasks, such as engaging in conversation, walking, or engaging in problem-solving activities. This stands in stark contrast to the testing conditions observed in

experimental and clinical settings, where participants typically engage in their tasks under quiet circumstances, receive explicit instructions regarding the tasks, primarily process unidimensional material, and direct their attention towards the task at hand.
One possible critique of numerous clinical assessments of episodic memory is their limited ecological validity (Pause et al., 2013). The characteristics of everyday episodic memory, which are often not adequately assessed by most clinical tests, encompass the recollection of long-term memories pertaining to distinct events within their spatiotemporal framework. These memories encompass the details of what occurred, where it transpired, and when it took place. According to (Vakil & Blachstein, 1994), the encoding of information typically occurs incidentally, and its retrieval is often spontaneous, without the presence of any cues associated with the initial event. Laboratory tests typically exhibit certain characteristics, although it is uncommon for them to encompass all of these attributes. For instance, certain assessments, such as the R-AVLT, focus on the retrieval of information from long-term memory over a period of 30 minutes. In this particular test, participants are required to recall a list of words without the need to remember any spatial or temporal context. However, it is worth noting that an optional temporal-order trial can be included in the administration of the test, as suggested by (Vakil & Blachstein, 1994). Additionally, the learning process for this test involves intentional acquisition of the information and subsequent rehearsal of the material. Additional assessments, such as the Object Relocation task as described by (Kessels et al., 1999), aim to assess the association between objects and their respective spatial locations. These assessments typically involve brief periods of retention and employ recognition processes for the objects, while not employing such processes for the spatial locations. Furthermore, intentional encoding of the information is incorporated in these assessments. One notable benefit of employing these tests is that the experimenter or clinician possesses precise knowledge regarding the correct and incorrect answers, as they exercise control over the information that needs to be retained.
When employing ecologically valid measures of episodic memory, such as the unrestricted recollection of genuine personal experiences, the evaluation of these memories must necessarily depend on the level of detail recalled, rather than the accuracy of the memories. This is due to the absence of an objective record of the original event in most cases (Irish et al., 2011). Furthermore, it is worth noting that the episodes that are remembered tending to be those that have been repeatedly recounted in the past, potentially resulting in a greater presence of semantic information rather than actual episodic recall (Pause et al., 2013). Notwithstanding these critiques, it is evident that current assessments of episodic memory have proven to be valuable (e.g., (Bäckman et al., 2001). However, it is possible that these tests fail to capture certain dimensions of episodic memory as it occurs in real-life scenarios.
Similar to the CVLT-II (Delis, Kramer, Kaplan, & Ober, 1987), numerous conventional clinical and experimental cognitive tests currently employed were designed to assess abstract cognitive constructs while maximizing task purity, thereby ensuring experimental control. One challenge encountered in the development of these memory tests is the inherent tradeoff between maintaining ecological validity and ensuring experimental control (Kvavilashvilil & Ellis, 2004). The significance of experimental control in memory assessments is frequently emphasized by neuropsychologists due to its crucial role in the targeted and standardized manipulation of construct variables, such as episodic memory. Regrettably, the prioritization of experimental control leads to a reduction in ecological validity and a narrower depiction of the patient's episodic memory performance in real-life situations. Therefore, it is possible that traditional neuropsychological assessments, which prioritize

experimental control, may possess restricted ecological validity (P. W. Burgess et al., 2006; Chaytor & Schmitter-Edgecombe, 2003a). Although the CVLT, a construct-driven task, can provide insights into certain aspects of a patient's episodic memory, it may not accurately reflect their performance in everyday memory tasks.
Burgess and colleagues have advocated for the advancement of neuropsychological assessments that accurately capture everyday "functions" (P. W. Burgess et al., 2006). The "function-led" approach commences by examining readily observable behaviors in everyday life and subsequently traces back a predetermined sequence of actions that contribute to the manifestation of that behavior in everyday functioning. Transitioning from construct-driven assessments to function-led evaluations will enable a more accurate depiction of functional proficiency.

But what is ecological validity?

3.4. Ecological validity

The historical progression of clinical neuropsychology demonstrates that its original objective was to diagnose individuals with brain injury or disease and subsequently elucidate the relationships between the brain and behavior. However, contemporary clinical neuropsychologists are now frequently tasked with providing prescriptive evaluations regarding everyday functioning. The emergence of this novel position for neuropsychologists has led to a heightened focus on the ecological validity of neuropsychological measures. The concept of ecological validity refers to the extent to which the conditions of an experiment accurately reflect real-world environments (Tupper & Cicerone, 1990) or the degree to which the findings of a study can be applied to real-life situations (Franzen & Wilhelm. K.L., 1996). In other terms, it can be denoted as the correlation between test performance and performance in daily activities (Chaytor et al., 2006). While it has been previously believed that traditional neuropsychological tests effectively assess the cognitive functions utilized in daily activities, there exists evidence suggesting that this assumption may not always hold true. Several studies (Bottari et al., 2009; Manchester et al., 2009; Sbordone, 1996; B. A. Wilson, 1993) have demonstrated that subpar performance on these tests does not necessarily correlate with impaired performance in real-world situations. The aforementioned circumstance hinders the feasibility of utilizing conventional assessments to effectively intervene and provide suitable assistance to individuals with cognitive impairments.
In order to ensure ecological validity of neuropsychological measures, researchers in the field of neuropsychology place emphasis on demonstrating either verisimilitude or veridicality, or both (Chaytor & Schmitter-Edgecombe, 2003b; Franzen & Wilhelm. K.L., 1996; Spooner & Pachana, 2006).
Verisimilitude places emphasis on the necessity for data collection methods to closely resemble real-life tasks conducted in an open environment. In other words, it refers to the extent to which neuropsychological tests accurately reflect the complexity and cognitive demands of everyday tasks (Chaytor & Schmitter-Edgecombe, 2003b; Franzen & Wilhelm. K.L., 1996; Spooner & Pachana, 2006). The implementation of this approach often necessitates the abandonment of current tests and the development of new assessments that prioritize ecological objectives. These assessments are often considered to possess greater face validity compared to conventional tests, as they strive to replicate essential cognitive tasks encountered in real-life situations. The primary objective of these tests is not to assess the ability to differentiate individuals with brain injuries from those without, but rather to

evaluate the extent to which the test accurately measures fundamental cognitive abilities relevant to everyday life. The main objective of these tasks is to ascertain individuals who encounter challenges in executing real-world tasks, irrespective of the underlying cause of the issue. Therefore, these tests may exhibit limitations in identifying brain impairment in individuals who possess the capability to execute routine tasks. There has been a significant departure from the conventional emphasis on diagnosis, given that diagnostic tests are specifically formulated to yield consistent indicators of brain impairment for as long as it persists. It can be anticipated that performance on tests that closely resemble real-life situations would improve as functional abilities increase, for instance, through rehabilitation, even in cases where brain damage persists.

In contrast, the term "veridicality" pertains to the degree of correlation between the results obtained from neuropsychological assessments and measures of everyday functioning. These measures may include relevant questionnaires that assess one's ability to function independently in daily life. This concept has been explored in various studies conducted by (Chaytor & Schmitter-Edgecombe, 2003b; Franzen & Wilhelm. K.L., 1996; Spooner & Pachana, 2006). In order for the neuropsychological measure to exhibit veridicality, it is imperative that the outcomes of the test accurately reflect and have the ability to forecast real-world phenomena. This form of research typically entails employing statistical methodologies to establish a correlation between performance on conventional neuropsychological assessments and indicators of real-world functioning, such as employment status, questionnaires, or evaluations conducted by clinicians. Hence, despite the lack of explicit consideration for ecological validity during the development of traditional tests, there remains the potential for these assessments to offer predictive insights into individuals' cognitive abilities in real-world contexts.

While both the verisimilitude and veridicality approaches have their respective merits, existing literature suggests that the verisimilitude approach may offer superior predictive capabilities in relation to real-world memory and attention (Higginson et al., 2000), executive functioning (e.g., multitasking, planning, and mental flexibility (Burgess et al., 1998), and prospective memory abilities (e.g., the ability to remember and initiate planned actions in the future (Phillips et al., 2008); compared to the veridicality approach (Chaytor & Schmitter-Edgecombe, 2003b; Franzen & Wilhelm. K.L., 1996; Spooner & Pachana, 2006). Certain neuropsychologists have a preference for employing a veridicality approach. This approach involves integrating findings obtained from neuropsychological measures with behavioral observations, rating scales, and self-report measures, such as the Everyday Memory Questionnaire (Royle & Lincoln, 2009).One limitation of this approach, however, is that although rating scales generally exhibit acceptable reliability, they demonstrate weak associations with performance measures, indicating relatively low validity. Several other neuropsychologists adopt the verisimilitude approach, wherein they create entirely new measures that closely resemble everyday activities and behaviors. Examples of such measures include the Rivermead Behavioral Memory Test (Wilson et al., 1985), the Behavioral Assessment of the Dysexecutive Syndrome(B. Wilson et al., 1996), and the Test of Everyday Attention (Robertson et al., 1996). A critical examination of the ecological validity of neuropsychological tests has yielded evidence in favor of verisimilitude tests, as these measures have shown a more consistent relationship with outcome measures compared to traditional paper-and-pencil tests. Nevertheless, a challenge for the verisimilitude approach lies in the limited adoption of these instruments from research laboratories to the practical contexts of clinical neuropsychologists. One further limitation of this approach is the failure of neuropsychologists to incorporate advancements in computer technology, despite their development of instruments that better simulate the skills necessary for everyday functioning. Consequently, there is a risk of perpetuating the adverse pattern that undermines the scientific standing of psychology.

Irrespective of the choice between the veridicality, verisimilitude, or a combination of both approaches, it is necessary to make determinations regarding which everyday behaviors should be linked to the neuropsychological tests in order to establish ecological validity. For example, within the broader category of memory, the desired outcomes may vary from the capacity to perform tasks or handle domestic responsibilities to the assessment of common memory lapses in various contexts. The researcher is required to choose from a multitude of potential forms of commonplace behavior. Furthermore, after the identification of the specific behaviors under investigation, the researcher is required to establish the appropriate method of measuring said behaviors. Possible methods for gathering data in this context may involve the utilization of self or informant questionnaires, clinician ratings, or interviews. In certain instances, such as the reintegration into the workforce, the process may be straightforward, while in other cases, such as instances of everyday memory lapses, the selection of an appropriate measurement method becomes significantly more crucial. The prevailing assumption frequently holds that the chosen outcome measure provides a more precise depiction of real-world behaviors in comparison to neuropsychological tests. The utilization of inappropriate outcome measures may potentially result in the identification of inaccurate associations with neuropsychological tests.

The neuropsychological literature includes various laboratory-based test batteries that aim to replicate real-life tasks. These batteries assess different cognitive functions such as attention (e.g., Test of Everyday Attention, TEA; Robertson et al., 1996), memory (e.g., Rivermead Behavioral Memory Test-III, RBMT-III; (B. A. , Wilson et al., 1985), executive abilities (e.g., Behavioral Assessment of Dysexecutive Syndrome, BADS; Wilson et al., 1996), and prospective memory (e.g., Cambridge Prospective Memory Test, CAMPROMPT; (B. Wilson, 2005). However, it is important to note that neuropsychological test batteries often include basic, unchanging stimuli in a tightly regulated setting, which does not fully replicate the intricacies of real-world scenarios (Parsons, 2015; Rand, Rukan, et al., 2009a). Efforts to enhance the evaluation of individuals' everyday capabilities have incorporated assessments conducted in authentic environments, such as the completion of errands within a shopping center or a pedestrianized street (Garden et al., 2001; Shallice & Burgess, 1991). Nevertheless, it should be noted that these standardized procedures may not be universally applicable to other clinical settings or laboratories. Additionally, they may present challenges for certain individuals within specific populations, such as psychiatric patients or stroke patients experiencing paresis or paralysis. Furthermore, these procedures are known to be time-consuming and costly, requiring the transportation of participants and obtaining consent from local businesses. Lastly, it is important to acknowledge that these procedures lack experimental control over external variables. These limitations have been discussed in previous studies conducted (Elkind et al., 2004a; Logie et al., 2011; Parsons, 2015; Rand, Rukan, et al., 2009a).

Several tests have been developed by redefining the concept of episodic memory, initially designed for application in non-human animals. In the absence of linguistic communication, the tests rely on animals undergoing two distinct episodes and subsequently exhibiting behavioral responses that indicate their recollection of these episodes. These assessments prioritize the enduring preservation of distinct information regarding events within their spatial and temporal framework. The present investigation represents the inaugural study to examine the food-hoarding behavior of California scrub jays (Aphelocoma californica), wherein the avian subjects concealed two distinct categories of sustenance during two distinct instances. After receiving training regarding the perishability of the preferred food type over time, as opposed to the non-preferred food type which remains stable, the participants were subsequently assessed shortly following the second instance of concealing the food. The researchers observed that the subjects were able to retrieve the specific food items that they had concealed in particular locations during the second hiding episode. This finding suggests that the subjects possessed the ability to recall both the type of food and the corresponding hiding spot, as well as the timing of the concealment event (Clayton & Dickinson, 1998). Subsequently, numerous adaptations of this task have been devised for different animal species, encompassing additional avian species (Feeney et al., 2009; Gould et al., 2012; Zinkivskay et al., 2009), as well as rodents such as rats and mice (Babb & Crystal, n.d.; Dere et al., 2005; Eacott et al., 2005; Kart-Teke et al., 2006; Roberts et al., 2008). In recent times, there have been advancements in the development of tasks that are specifically designed for human beings. In a typical experimental task, participants are exposed to one or two distinct events and subsequently required to recall the details of what transpired, including the location and timing of these events (Cheke & Clayton, 2013; Eacott et al., 2005; Hayne & Imuta, 2011; Pause et al., 2010; Plancher et al., 2010; Russell et al., 2011) The inquiry pertains to the chronological order of events, specifically inquiring about either the specific episodes in which they occurred or the specific timing within a given episode. Certain methodologies necessitate a direct reaction from the individuals involved, while others aim to evaluate memory solely through behavioral indicators, such as exploration behavior (Pause et al., 2010; Weber et al., 2014). All of the aforementioned novel methodologies, excluding the study conducted by Holland and Smulders in 2011, employ computer-based displays as the stimuli to be retained in memory. Nevertheless, it is our contention that this particular approach exhibits a dearth of the intricacy and multifaceted nature inherent in real-life scenarios, which constitute integral components of individuals' episodic memories. Consequently, it is plausible to suggest that this approach may be less conducive to older individuals' engagement due to its diminished naturalness. A real-world task may also possess enhanced predictive value in real-world scenarios.

Nevertheless, despite the extensive discourse on the matter of ecological validity within the existing body of literature, there has been a notable dearth of efforts to address and rectify this predicament. In contrast, efforts have been made to solely augment the external validity of neuropsychological assessments. The concepts of external validity and ecological validity are interconnected, yet they should not be used interchangeably. External validity refers to the degree to which the results obtained from research studies can be applied to a diverse range of individuals, temporal contexts, and environments. It also encompasses the ability to make specific generalizations to particular individuals, temporal contexts, and environments. Considering the historical development of traditional paper- and-pencil neuropsychological measures, it is evident that their primary purpose was to identify specific brain regions and their functions, with an emphasis on demonstrating double dissociation. However, recent improvements in these measures have been aimed at enhancing their external validity. Therefore, experimental conditions are not typically necessary to replicate real-life conditions. Neuropsychological measures are presented in a rather rudimentary manner and do not seem to prioritize the level of fidelity. On the contrary, their objective is to achieve external validity, which entails maintaining a consistent ability to predict behavior observed in real-world settings. One could posit that the primary task for neuropsychologists lies in the development of methodologies that effectively address the requirements of internal validity, external validity, and ecological validity

in a simultaneous manner. Therefore, the construction of a test that accurately reflects real-world conditions should incorporate rigorous psychometric principles, such as internal and external validity, along with the concepts of verisimilitude and veridicality, which pertain to ecological validity. Attaining such standards necessitates the careful examination of various factors: 1) The tasks undertaken should align with the relevant elements of real-world activities and environments; 2) The tasks created should accurately represent individuals who are engaged in performing said tasks; 3) Research problems should have practical implications on real-world functioning in order to contribute to the authenticity and accuracy of the study; 4) Outcome measures must be pertinent to the practical problem under investigation (Parsons, 2011a).
Moreover, according to Sternberg's argument, advancements in neurocognitive testing should focus on the development of novel ideas rather than simply introducing new measures to enhance the efficacy of existing technologies. However, despite the widespread utilization of contemporary neuropsychological assessment procedures, professionals in the field of neuropsychology have been relatively sluggish in adapting to the influence of technology on their discipline.

4. Virtual reality technologies: definition and main features

Virtual Reality (VR) is a sophisticated computer interface that facilitates the complete immersion of individuals in a computer-generated simulation. The increasing availability of these advanced technologies has the potential to enhance our ability to assess various cognitive areas, identify particular shortcomings, and tackle everyday tasks. The recognition of the integration between VR technology resources and the requirements of different clinical fields has been acknowledged by multiple researchers (Parsons, Rizzo, et al., 2009; Rose et al., 2005). Furthermore, a growing body of research is emerging in this area (Lange et al., 2012; A. A. Rizzo et al., 2008). The continuous progress in VR technology, along with simultaneous decreases in the expenses associated with these systems, has facilitated the creation of VR systems that are more user-friendly, practical, and readily available. These systems possess the distinct ability to efficiently address a wide range of physical, psychological, and cognitive clinical goals and research inquiries. The distinguishing factor of VR application development in the fields of assessment, therapy, and rehabilitation sciences lies in its deviation from being a simple linear extension of preexisting computer technology designed for human utilization.
The VR environment can vary in terms of its graphical representation (2D or 3D, mixed or augmented VR), the devices used for display (such as screens, Head Mounted Display [HDM], Cave Automatic Virtual Environment [CAVE]), the tools employed for tracking and sensing (such as eye-tracking, Kinect, LEAP), and additional features (including resolution, display size, and field of view)(Anthes et al., 2016). In addition to the subjective experience of physical space and engagement, VR technologies can also be categorized based on their level of immersion, which refers to the extent of sensory fidelity offered by a VR system (Castronovo & Messner, 2013; Cipresso et al., 2018; Slater, 2003; Slater & Wilbur, 1997). The level of immersion refers to the extent to which a virtual environment can create a sense of presence or spatial presence, which is the illusion of actually being in that environment. This level has the ability to evoke intense emotional reactions as well, as supported by previous studies (Chirico et al., 2017; Ventura et al., 2019). The phenomenon of achieving a heightened sense of presence can be facilitated through the utilization of various technologies and their integration (Ijsselsteijn & Riva, 2003).

There are three types of immersive experiences: non-immersive, semi-immersive and fully-immersive. In a non-immersive experience, the user interacts with 3D environments using a conventional workstation's keyboard and mouse. On the other hand, in a semi-immersive experience, participants are instructed to stand on a force platform while observing a 3D virtual representation displayed on a large screen. These systems may also utilize gesture or location recognition systems to facilitate more organic interactions. Additionally, fully immersive experiences involve the complete engagement of users' vision through the use of a HMD or CAVE, which is a four-walled room that projects the virtual environment and encompasses the entirety of users' visual field (Riva et al., 2020).

Immersive technologies possess the capability to elicit a sense of immersion within the virtual environment, while non-immersive devices merely exhibit content based on their positioning and utilization (Ventura et al., 2019). It is worth noting that VR has the capability to replicate real-life situations and offer immediate adjustments and multisensory responses based on the user's actions (Riva et al., 2019). This mechanism bears resemblance to the brain's ability to construct an internal representation or framework of the body and its environment, as described by the "predictive coding" paradigm (Clark, 2013; Friston, 2010, 2012). The prevailing notion that the perception of the body primarily arises from sensory signals originating from the bottom-up, afferent pathway is currently being questioned by predictive brain theories grounded in Bayesian Inference. From this perspective, it can be argued that our future is influenced by our past experiences. This is because our experiences are the result of a cognitive process in which the brain generates predictions, known as priors in the context of the predictive brain theory, regarding the state of the body.

One of the primary characteristics of VR is the synchronization between an individual's real body movements and the corresponding actions of a virtual avatar, resulting in a coherent first-person perspective (Vogeley et al., 2004). The correlation between the virtual and physical body establishes a sense of possession and "presence" in the virtual body, resulting in observable motor, physiological, and cognitive responses in the physical body. For instance, individuals modify their real-life actions based on the observed movements of their virtual avatar, influenced by the sensation of "presence" they perceive within it (Burin et al., 2019). Furthermore, the observation of an avatar engaging in aerobic exercise has been found to have positive effects on cognitive components and their associated neural substrates, even in the absence of physical movement (Burin et al., 2020). In conclusion, the utilization of VR to simulate the presence of a renowned intellectual figure, such as Albert Einstein, has been found to enhance the cognitive abilities of individuals engaged in such an experience (Banakou et al., 2018).

These examples indicate that VR has the potential to generate a profound sense of immersion and presence. This is achieved by leveraging a cognitive process called embodied simulation, which facilitates users' active engagement and participation. Through the digital medium, VR enables individuals to interact with the environment both physically and emotionally.

The concept of embodied cognition posits that numerous aspects of cognition are causally or even fundamentally connected to the physical body and the bodily actions performed by an individual. The theoretical foundation of this concept can be traced back to embodied simulation theories, which emphasize the significance of body parts, actions, and representations in cognitive processes (Gallese & Sinigaglia, 2011). Furthermore, it has been suggested that these characteristics have the potential to improve patients' cognitive abilities after undergoing neurorehabilitation using VR (Riva, 2008;

Riva et al., 2018), which cannot be achieved through conventional methods such as paper-and-pencil rehabilitation.

4.1. Virtual reality for neuropsychological assessment

Thanks to all these features, the utilization of VR is in fact increasingly being recognized as a potent instrument in the fields of cognitive psychology and neuropsychology. This trend can be attributed, at least in part, to the significant advancements in computer technology and the expansion of the video game industry. Virtual environments have been specifically created to replicate a wide range of real-life activities in various settings, including driving, shopping, and pedestrian navigation. These environments provide a valuable tool for objectively evaluating behavioral performance, while also offering a higher level of ecological validity. Furthermore, these settings function as instrumental resources for the rehabilitation of individuals who are contending with functional limitations, such as acquired brain injuries accompanied by cognitive impairments. Moreover, this recognition stems from its capacity to generate lifelike situations while maintaining precise experimental control. The fundamental aim of VR is to enable individuals to effectively participate in cognitive and sensorimotor endeavors within a synthetically generated environment. The virtual environment utilized in this context is dependent upon computer-generated imagery and has the capacity to adopt diverse manifestations, including those that are imaginary, symbolic, or representative of real-world elements. The concept of "sensorimotor activity" emphasizes that individuals who are immersed in the virtual environment actively participate using sensory and motor interfaces. As individuals engage in the virtual environment, they exert control over their movements within the simulated space, resulting in a profound sense of immersion (Mestre & Fuchs, 2006).
Within the field of neuropsychology, the incorporation of VR serves as an attempt to mitigate the inherent biases present in conventional assessments. The utilization of an immersive virtual environment presents a beneficial compromise as it enables the replication of intricate naturalistic scenarios while simultaneously upholding a rigorous level of experimental control (Steinicke et al., 2009). The aforementioned methodology has demonstrated efficacy in the assessment of memory, executive functions, attention, and practical activities of daily living such as cooking and driving (Campbell & Fiske, 1959; Riva et al., 2020). The emergence of this phenomenon aligns with an increasing acknowledgement among neuropsychologists regarding the constraints of traditional neuropsychological assessments, prompting the investigation of alternative approaches for assessing functional deficits. In fact, virtual environments provide a notable benefit through their ability to offer precise manipulation of dynamic perceptual stimuli across multiple sensory modalities, such as visual, auditory, olfactory, gustatory, ambulatory, and haptic conditions. This feature facilitates the development of ecologically valid assessments that integrate the methodological rigor of laboratory measures with the authenticity of real-life situations. Moreover, the increased computational capabilities of VR systems enable precise capturing of neurobehavioral reactions within perceptual environments that systematically present intricate stimuli. These distinctive characteristics render it highly suitable for the creation of ecologically valid environments. In such environments, three-dimensional objects can be consistently and accurately displayed, enabling individuals to interact with and manipulate these objects, while also accommodating a variety of task requirements.
Moreover, VR technology demonstrates exceptional capabilities in the surveillance of users' movements and interactions, both within the virtual environment and among themselves. The

technology effortlessly might incorporate various physiological measures, including electromyography, heart rate, skin conductance, eye tracking, electroencephalography (EEG), and functional Magnetic Resonance Imaging (fMRI), to capture bodily responses. VR environments have undergone significant advancements, resulting in the creation of immersive experiences that allow users to engage in a wide range of motions, such as walking, running, and other physical activities, within simulated spaces. Recent technological advancements have resulted in heightened haptic experiences and the incorporation of supplementary sensory modalities, such as olfaction. Furthermore, there has been a notable decrease in the cost, increased portability, and reduced weight, accompanied by advancements in headset design that have resulted in more compact and high-performance devices.

Overall, the integration of VR techniques holds significant potential for yielding numerous benefits to the field of neuropsychology. It provides an exceptional level of flexibility, allowing for the development of a wide range of environments and experimental tasks. Additionally, VR enables the development of multimodal environments that effectively engage all sensory modalities, thereby resulting in immersive experiences that closely resemble real-life situations by accurately reproducing sensory characteristics and simulating the cognitive demands of real-world situations. This technology functions as a secure and regulated substitute for evaluating and rehabilitating functional capabilities in real-world situations that could otherwise pose risks or incur high expenses. The utilization of well-constructed VR tasks has demonstrated the ability to more effectively measure cognitive abilities that mirror those observed in real-life scenarios, surpassing the capabilities of traditional neuropsychological tests. Moreover, VR tasks exhibit potential in evaluating the extent to which neuropsychological interventions can be applied to real-world situations. The participants actively engage in the tasks at hand and can concentrate on them, while simultaneously minimizing their awareness of being evaluated. Virtual environments provide a higher level of task transparency and functional tasks, which in turn improve the ecological validity when compared to abstract traditional assessments. Moreover, they have been specifically created to augment the process of functional assessment and rehabilitation. These virtual environments encompass a range of settings, including virtual cities, school classrooms, and supermarkets. This technological advancement facilitates a more precise evaluation of functional behaviors within authentic environments, offering valuable insights for individuals experiencing cognitive impairments. The utilization of VR technology can thus present numerous benefits in the evaluation and rehabilitation of cognitive processes. These advantages encompass improved ecological validity and multimodal engagement, as well as precise measurement and immersive experiences across diverse settings. The potential of this technology lies in its ability to fundamentally transform the field of cognitive assessment and intervention, facilitating a more comprehensive and accurate comprehension of human cognition and its practical consequences.

VR technology has the capacity to effectively track and analyze the actions and engagements of users, both on an individual level and as part of a collective, within a specific setting. This capability enables the acquisition of significant knowledge regarding user behavior and the dynamics that occur during VR experiences (Schroeder, 2002). The integration of VR with physiological responses encompasses a wide array of bodily indicators, showcasing the versatility of this technology. An example of this is the utilization of electromyography (EMG) measurements, which allows for the evaluation of muscular activity and responses (Pons et al., 2005). Similarly, the utilization of heart rate monitoring (Pugnetti et al., 1995) and skin conductance measurements (Bordnick et al., 2005) in VR scenarios provides an opportunity to observe autonomic responses, thereby facilitating an understanding of emotional states and cognitive involvement.

The trajectory of VR evolution involves a transition towards increased immersion, enabling users to not only interact with virtual environments but also actively navigate through them. The authors Perusquía-Hernández et al. (2017) demonstrate the immersive nature of these experiences through the ability of users to engage in activities such as walking, running, and performing movements that would otherwise be considered impossible within virtual environments (Perusquía-Hernández et al., 2017). The incorporation of haptic technology represents a significant progression, as it provides tactile feedback that enhances the perception of physical engagement within the virtual environment (De Boer et al., 2017). In addition to the involvement of the sense of touch, the incorporation of other sensory modalities, such as the sense of smell, enhances the level of immersion, thereby facilitating a more comprehensive engagement that encompasses multiple senses (Aiken & Berry, 2015). Environmental factors such as temperature and airflow can be effectively replicated within VR environments, thereby enhancing the overall immersive and multisensory nature of the experience. These advancements collectively enhance the potential of VR technology as a robust tool for comprehending human behavior, cognition, and experiences within intricate virtual environments.

In recent years, there have been significant advancements in the accessibility of VR technology. The costs associated with the development and utilization of VR technology have experienced a notable reduction, thereby making it more accessible and feasible for implementation in diverse fields. Concurrently, there has been a notable increase in industry standards, specifically pertaining to the level of immersion and processing speed, thereby expanding the limits of what can be accomplished within virtual environments. Significantly, VR technology has experienced notable advancements in terms of mobility, characterized by the development of lighter and more compact headsets, along with streamlined supporting hardware. The enhanced mobility provided by this technology enables users to actively participate in virtual reality experiences across various environments and situations, surpassing the constraints imposed by stationary configurations.

The utilization of VR offers a range of unique benefits in evaluating cognitive functions. This technology facilitates the creation of controlled and immersive testing, training, and treatment environments that provide precise manipulation of complex, dynamic three-dimensional (3-D) stimuli presentations. In these particular settings, there is the potential for seamless integration of intricate interactions, behavioral tracking, and performance recording. This integration allows for a comprehensive assessment of human functional performance in various stimulus conditions that may not be easily achievable or controllable in real-world environments.

The potential applications of VR encompass the assessment of a range of cognitive processes, including attention (Parsons, 2011b; Parsons, Cosand, et al., 2009; Parsons et al., 2007), spatial abilities (Hardiess et al., 2015; Tuena et al., 2021), memory (Bruni et al., 2022; Parsons & Rizzo, 2008), and executive functions (Elkind et al., 2004b). The current trend of integrating VR scenarios into neurocognitive batteries represents a significant shift in the field. This shift holds the potential to enhance the ecological validity of assessments, thereby facilitating more accurate differential diagnosis and improved treatment planning. Virtual environments provide a distinct opportunity to systematically introduce cognitive tasks that specifically target neuropsychological performance, surpassing the limitations of conventional methods. The meticulous control of the perceptual environment, consistent stimulus presentation, and precise scoring mechanisms contribute to the enhancement of reliability in neuropsychological assessment.

Moreover, the intrinsic functionalities of virtual environments allow for improved measurement of distinct behavioral reactions, thus aiding in the identification of more precise cognitive areas. The utilization of VR enhances the credibility of neurocognitive measurements by incorporating them into scenarios that closely resemble real-world situations. Experiential evaluation in simulated real-world contexts offers a departure from traditional contrived testing environments, enabling participants to undergo assessment within immersive settings that replicate everyday life situations (K. S. Hale & Stanney, 2014).

The potential for VR to revolutionize psychological assessment is not a mere conjecture. High-fidelity virtual environments provide the opportunity to accurately recreate real-life scenarios, while also granting researchers a greater level of control. This enhanced control helps to address the difficulties associated with unpredictable factors that may affect the experiment. This encompasses a wide range of situations, including the alteration of traffic patterns in a driving task, as well as the replication of infrequent or unique events such as malfunctions or emergency scenarios. VR is of particular importance in the field of clinical psychology, as it offers valuable applications for both short-term and long-term psychological rehabilitation. VR interventions have shown effectiveness in the management of pain for individuals with chronic conditions. Additionally, VR has been employed as a means of clinical assessment for post-stroke patients, individuals with Attention Deficit Hyperactivity Disorder (ADHD, Bioulac et al., 2012), and those diagnosed with schizophrenia (Ku et al., 2004) Systematic reviews are recognized for their potential to establish themselves as the preferred method for clinical assessment (D. Freeman et al., 2017).

In brief, the incorporation of VR technology into cognitive assessment represents a significant departure from traditional methods, as it enables the administration of ecologically valid evaluations, meticulous regulation of stimulus presentations, and improved quantification of responses. The potential of this technology to recreate real-world situations, its utilization in psychological rehabilitation, and its effectiveness in the treatment of anxiety disorders collectively establish VR as a revolutionary instrument in the domain of cognitive assessment and intervention.

3.1.1. Advantages of VR assessment

Within the field of psychological assessment, the incorporation of VR technology has brought about a significant and profound change in the comprehension of cognitive processes. VR is a highly advanced technology that presents numerous benefits, enabling the field to surpass the constraints of conventional assessment methods. An in-depth examination of these benefits elucidates the unparalleled opportunities that VR presents in the realm of cognitive assessment (Hardiess et al., 2015). Through the utilization of controlled environments, precise manipulation techniques, and advanced physiological measurements, VR serves as a means to connect theoretical constructs with real-world behaviors. In addition, the ability to customize and personalize virtual reality scenarios enables researchers to conduct more detailed investigations into the complex intricacies of cognitive functioning. This discussion explores the fundamental benefits that characterize the impact VR on cognitive assessment, offering a comprehensive perspective on its potential to transform our comprehension of the human mind:

(i) Enhanced Controllability of the Environment: Virtual reality offers a setting in which researchers can exert meticulous control over multiple variables. The experimenter has the ability to carefully control various factors, including lighting conditions, spatial arrangement, and the presence of objects, in order to maintain uniformity throughout the experimental trials. The implementation of this control mechanism serves to enhance the reliability of experiments by mitigating the potential influence of confounding variables on cognitive performance. The utilization of a controlled environment is particularly beneficial when examining specific cognitive functions that may be influenced by external variables in real-life contexts.

(ii) Real-Time Environmental Manipulation: VR technology enables researchers to actively manipulate the environment in real time. The ability to quickly modify stimulus parameters, task demands, and environmental conditions allows for the immediate adjustment of experimental conditions, enabling the examination of different cognitive scenarios within a single session. This particular characteristic facilitates the comprehension of participants' reactions to various cognitive challenges and dynamic surroundings, thereby enhancing the overall evaluation of cognitive capabilities.

(iii) Assessment of Cognitive Performance in Large-Scale Environments: Virtual reality technology facilitates the examination of cognitive abilities within expansive settings that may present difficulties in accurately reproducing them in real-world scenarios. Academic researchers have the ability to replicate vast settings, such as urban areas, intricate architectural designs, or extensive natural landscapes, through simulation techniques. This ability is especially advantageous when studying spatial navigation, memory, and decision-making in complex and expansive environments, offering valuable insights into individuals' interactions and navigation within intricate spaces.

(iv) Addressing Real-World Impossibilities: In certain instances, the execution of comparable experiments in practical settings may present challenges of feasibility or ethical concerns. VR provides a viable solution by replicating situations that pose logistical difficulties, safety concerns, or are impractical to replicate in reality. For example, the evaluation of cognitive reactions in emergency situations, hazardous environments, or infrequent scenarios becomes viable within the controlled virtual setting. This advantage enables researchers to investigate cognitive responses to scenarios that would otherwise be unachievable in actuality.

(v) The utilization of VR technology allows for the precise measurement and capture of participants' body position and movement. Sophisticated motion tracking systems offer precise measurements of participants' gestures, postures, and locomotion. The utilization of granular data provides a valuable contribution to the comprehension of the complex interaction between cognitive processes and motor actions, thereby illuminating the intricate and multifaceted connection between cognition and movement across diverse tasks.

(vi) The utilization of VR allows for the integration of cognitive assessments and concurrent physiological recording, presenting a distinctive opportunity. Scholars have the ability to incorporate various measurements, including heart rate, skin conductance, and brain activity (such as EEG or fMRI), in conjunction with cognitive tasks. This integration facilitates a comprehensive examination of the interaction between cognitive processing and physiological responses, thereby enhancing our understanding of cognitive functioning. VR has in fact the potential to facilitate the utilization of physiological monitoring in challenging circumstances. Skin conductance responses can be influenced by various environmental factors such as ambient temperature, humidity, and physical exercise, thereby posing challenges for field-based measurements (Christopoulos et al., 2019; Doberenz et al., 2011). The utilization of ambulatory EEG is challenged by the presence of heightened artifacts associated with movement (B. S. Chang, 2005). The utilization of magnetoencephalography (MEG) necessitates participants to maintain a seated position, while functional magnetic resonance imaging (fMRI) mandates participants to assume a supine position within an enclosed chamber (Mancuso et al., 2020).

VR has the potential to address, alleviate, or at the very least regulate these challenges by confining participants within a controlled setting and minimizing or quantifying their physical exertion. Once again, it is imperative to contemplate the comparability of physiological data obtained from VR experiments with data gathered in real-world settings. In their study, Meehan and colleagues investigated the impact of virtual height on participants by creating an illusion of a pit that was several feet below them(Meehan et al., 2002). The researchers discovered that VR elicited physiological alterations, specifically changes in heart rate, skin conductance, and skin temperature. These changes exhibited a strong correlation with stress responses observed in real-life scenarios. Remarkably, the aforementioned effects appear to persist even in social situations facilitated by VR. Owens and Beidel (2015) demonstrated comparable physiological responses in adults diagnosed with Social Anxiety Disorder when exposed to both real and virtual environments (Owens & Beidel, 2015). In a similar vein, Fich et al. (2014) employed VR technology to demonstrate that social stress responses, specifically cortisol secretion and heart rate, were influenced by the presence of multiple exits within a room(Fich et al., 2014). Previous research endeavors have sought to discern commonalities and distinctions between tangible reality and simulated virtual reality settings. In their study, Simeonov et al. (2005) conducted a comparative analysis of physiological and psychological reactions to elevated heights, examining both VR and real-world environments (Simeonov et al., 2005). Similar patterns of responses were observed in specific measures, such as anxiety and skin conductance, while no significant correlations were found in relation to heart rate. In their study, Kelly et al. (2007) conducted a direct comparison between VR and real environments by employing a social stress test (O. Kelly et al., 2007). Comparable psychobiological responses were observed in VR environments, specifically in situations where participants were unable to visually perceive others in the room (imagined audience). However, it is important to note that both the VR and imagined audience conditions resulted in lower stress responses compared to situations where participants were required to perform tasks in the presence of a physical group of individuals (real audience). This finding was observed despite the participants' indication of moderate levels of immersion, potentially influencing the stress response. Upon synthesizing these aforementioned studies, it becomes evident that VR has the potential to serve as a viable substitute for conventional laboratory tests. However, it is crucial to acknowledge that disparities between virtual environments and physical environments may diminish the robustness of typically observed effects.

(vii) Evaluation of Sensory Modalities in a Controlled Setting: VR technology allows for the systematic evaluation of sensory modalities in isolation, providing researchers with the ability to separate and manipulate individual senses such as vision, audition, or touch. This particular benefit proves to be highly advantageous in the examination of sensory integration, the processing of multiple sensory inputs, and the impact of distinct sensory stimuli on cognitive functioning. The deliberate manipulation of sensory modalities within virtual reality scenarios provides valuable insights into the role of sensory information in cognitive processes.

(viii) Improved Data Collection and Analysis: VR technology enables the acquisition of comprehensive and accurate data pertaining to participants' interactions, behaviors, and cognitive responses. VR systems employ a range of sensors and tracking technologies to collect comprehensive data, encompassing reaction times, gaze patterns, and interaction sequences. The degree of data granularity at this level facilitates comprehensive examinations of cognitive processes and their temporal dynamics. Researchers have the ability to acquire valuable insights into the intricate subtleties of cognitive behavior that may not be readily apparent in conventional assessment environments. This contributes to the development of a more refined comprehension of cognitive functioning.

(ix) Customizable Scenarios and Personalization: VR technology provides the opportunity to customize scenarios and tasks according to the specific needs and characteristics of individual participants. This customization enhances the ecological validity of assessments, ensuring that the assessment environment closely resembles real-world situations. Researchers can develop customized settings and tasks that align with the real-life encounters, inclinations, and preferences of participants. The utilization of personalization not only enhances the level of engagement among participants but also facilitates the exploration of how cognitive abilities are demonstrated in situations that are contextually relevant. Customizable scenarios have the ability to cater to a wide range of populations, encompassing individuals with different cognitive capacities and cultural heritages. This promotes inclusivity within assessment methodologies.

One further benefit of utilizing VR for cognitive evaluation is its distinct capacity to tackle the intricacies presented by the constructed environment, a notion emphasized by the developing discipline of neuro-architecture (Higuera-Trujillo et al., 2021). The integration discussed in this study serves to establish a connection between architectural design and human cognitive responses. By doing so, it aims to provide a thorough comprehension of the impact of environmental factors on cognitive performance (Coburn et al., 2017).

Conventional psychological assessment methods frequently encounter challenges in addressing the influence of environmental factors on individuals' cognitive reactions. Concerns have been frequently raised by individuals who undergo psychometric tests regarding the impact of the testing environment on their performance. This concern has the potential to result in systematic variations across different populations. The emerging discipline of neuro-architecture explores the complex relationship between architectural environments and human behavior, emphasizing the importance of controlled settings in cognitive evaluations. VR technology, due to its precise replication and manipulation of environments, is in perfect harmony with the principles of neuro-architecture. In contrast to traditional approaches that aim to reduce environmental variability through controlled laboratory conditions, VR surpasses these constraints. Instead, it establishes a framework in which standardized yet ecologically valid situations can be implemented. The calibration of lighting conditions, spatial dimensions, and sensory stimuli allows for the recreation of real-world situations with precise control over important parameters.

Within the realm of neuro-architecture, VR offers a method to recreate real-life environments that may be inaccessible in a physical sense, thereby enhancing the ecological validity of research. For example, previous studies in the field of clinical research have employed virtual environments to replicate educational settings, commercial spaces, and workplace environments (Matheis, Schultheis, Tiersky, DeLuca, et al., 2007; Rand, Rukan, et al., 2009b; Rizzo et al., 2004). The incorporation of environment in cognitive assessment and the examination of human interaction with architectural contexts are both underscored by this integration, highlighting the importance of environment as a crucial factor in these areas.

The advantageous aspect of VR lies in its capacity to mitigate environmental variability. However, it is important to acknowledge that variations in task presentations can have an impact on outcomes.

An illustrative example can be found in the differentiation between a virtual classroom and a conventional Continuous Performance Task (CPT) utilized for the diagnosis of ADHD, wherein diverse visual presentations yielded disparate outcomes (Adams et al., 2009). In a study conducted by Adams et al. (2009), a comparison was made between a virtual classroom and a standard CPT to evaluate their efficacy in diagnosing ADHD. The researchers discovered that the virtual classroom exhibited a higher degree of efficacy in distinguishing between participants with ADHD and those in the control group, as compared to the standard CPT. However, it is possible that this could be attributed to the way the CPT was presented. In both experimental conditions, the stimuli were presented on a VR display dome positioned in front of the participants. This observation indicates that although the virtual classroom provided an illusion of immersion, the participants were only able to perceive the standard CPT within a featureless backdrop, highlighting a significant disparity in the visual setting. This interpretation is substantiated by previous research, which has found no significant variation in predictive outcomes between a virtual classroom displayed through an HMD and a standardized computerized performance test presented on a computer monitor (Bioulac et al., 2012). However, the complex interaction between the visual environment and cognitive responses is a subtle aspect that is investigated in the field of neuro-architecture. Despite users not explicitly reporting differences in the environment, it is plausible that even minor visual alterations can still have an impact on performance. It is commonly observed that individuals often exhibit limitations in accurately reporting alterations within the visual environment. Although explicit reports frequently do not accurately identify changes, implicit change detection still takes place. Furthermore, this implicit detection has the potential to influence responses in tasks that are related (Korpela et al., 2002). The study conducted by aimed to assess the suitability of Virtual Environments (VEs) as accurate representations of Physical Environments (Heydarian et al., 2015). This was achieved by analyzing the performance of participants in three tasks related to office settings. The researchers manipulated the physical environment and the immersive Virtual Environment by modulating the lighting conditions, transitioning from dim to bright. This manipulation was conducted within the context of a within-subjects design, employing a 2x2 factorial arrangement. Although distinctions were noted between the physical environment and the immersive virtual environment, the crucial aspect of comparing the performance change from dark to light in these two settings, known as the delta, revealed no discernible impact when transitioning from the Physical Environments to the immersive virtual environment. The researchers reached the conclusion that while there were observable effects on performance associated with the use of a virtual environment, these effects were primarily attributed to variations in participant interaction with the environment. For instance, the use of a wand to navigate the virtual space versus physically walking within the space. Moreover, when accounting for environmental manipulations, participants demonstrated comparable performance in both the virtual and physical environments.

In conclusion, the integration of neuro-architecture principles within the domain of VR-enhanced cognitive assessment demonstrates the capacity of this technology to provide a holistic method for establishing standardization and ecological validity. VR serves as a tool for understanding and manipulating environmental factors, thereby influencing our perception and assessment of cognitive processes in various settings, by establishing a connection between architecture and cognition.

4.2. 360-Degree Technologies

360-degree video also known as spherical video-based VR, is a form of video recording that utilizes omnidirectional or multi-camera systems to capture visual content from all directions simultaneously (Barić et al., 2020; Chang et al., 2018; Fraustino et al., 2018; H. C. Lin et al., 2019; Zulkiewicz et al., 2020). The process of creating a comprehensive spherical field of view involves utilizing software to seamlessly combine multiple videos. During the process of video playback, users have the ability to engage with the video content by means of a mouse click or by manipulating the orientation of a mobile device, thereby enabling them to view the video recording from various perspectives. The incorporation of ambisonics can enhance the auditory experience by providing a comprehensive surround sound effect that encompasses the entire spherical space. 360-degree videos can be accessed and watched without the need for specialized equipment, apart from commonly available devices such as computers, smartphones, or tablets. Alternatively, it is possible to observe them by utilizing a HMD, which enhances the user's experience by incorporating VR elements (Kavanagh et al., 2016a).

360-degree video is frequently referred to as VR and is often used interchangeably with VR due to its shared characteristic of providing an immersive viewing experience. One notable distinction between 360° video and VR lies in their respective generation processes. Specifically, 360° video is produced using real-world footage, whereas VR is generated through the utilization of computer software (Borghesi et al., 2022). According to Ward (2017), 360° video enables viewers to observe left-right and top-bottom perspectives within a confined spherical environment that is determined by the filmmakers' perspectives. Furthermore, individuals possess the capability to visually explore their surroundings in a comprehensive manner, encompassing a full range of directions, and exercise agency in determining their visual focus. The aforementioned objective is accomplished through the utilization of a 360-degree video camera, which enables the capture of a comprehensive view of a given scene (N. Taylor & Layland, 2019). According to academic sources, researchers assert that this technology is readily accessible and relatively affordable (Shadiev et al., 2021). According to Chen and Hwang (2020), the utilization of 360-degree video technology is characterized by its user-friendly nature, making it accessible to individuals without professional expertise, such as teachers and students (M. R. A. Chen & Hwang, 2020). This affordability enables them to generate personalized content. Furthermore, the implementation of this technology significantly diminishes the expenses and time associated with content development (Shadiev & Sintawati, 2020).

Currently, the utilization of 360° technology is offering a novel means of engaging with virtual environments through the incorporation of 360° panoramic images, diverse viewing options, and interactive capabilities. In addition, the utilization of 360° video has introduced a novel means of enhancing user experience by fostering a heightened sense of presence, thereby expanding upon the benefits offered by traditional video technology. Numerous applications have integrated 360-degree videos, which are captured using omnidirectional cameras, in order to provide users with enhanced realism and the ability to navigate through various perspectives. The prevalence of such videos is increasing on popular video-streaming platforms such as YouTube and Facebook (Tran et al., 2017). In recent times, significant progress has been achieved in enabling the consumption of 360-degree videos across various technological platforms. The observation of content can be facilitated by the utilization of HMDs that possess stereoscopic capabilities. These HMDs allow users to engage in a fully immersive experience. Additionally, mobile devices that employ smartphones as VR displays offer users a partially immersive experience. HMDs enable users to manipulate the orientation of the camera and have the ability to rotate their head freely in order to observe the surrounding environment. According to a study, individuals who engage with 360-degree videos on mobile devices have the ability to manipulate the camera perspective through physical movements of the device or by utilizing touch gestures on the screen to navigate within the virtual environment (Pavel et al., 2017). Moreover, within desktop-based media players, users possess the capability to manipulate the camera orientation by dragging the video horizontally and vertically using their cursor, as indicated by reference. The aforementioned viewing conditions encompass a spectrum of immersion levels. The manipulation of the viewport can be achieved using conventional peripheral devices, such as a mouse and keyboard for desktop computers, or sensors for mobile devices. This manipulation can be performed either by manually synchronizing the device's movements with the user's head movements to simulate real-life changes in perspective (Zhou et al., 2017).

Over the past few years, there has been a gradual incorporation of 360° video functionality into prominent social media platforms and video sharing websites. This trend commenced in 2015 with the introduction of this feature on YouTube and Facebook, followed by its subsequent integration on Vimeo in 2017. The aforementioned advancements have resulted in enhanced user-friendliness for the playback of 360° videos, as well as widespread availability of an expanding array of online 360° video content (Saba, n.d.; Vimeo Staff, 2017; YouTube Creator Blog, 2015). YouTube provides users with the opportunity to access and engage with 360° videos, thereby enabling them to immerse themselves in various experiences such as riding on a Roller Coaster, encountering a shark, or observing a pride of lions in their natural habitat. In a similar vein, Facebook offers comparable capabilities for the sharing and storage of photographs and videos. Therefore, individuals have the ability to generate and distribute content that is produced using cameras possessing the capability to generate 360° content. An alternative approach to accessing this genre of material involves the utilization of VR headsets or viewers. In this particular scenario, the immersive nature of experiences is heightened due to their ability to be observed in three dimensions, thereby providing the user with a heightened sense of depth perception. The VR headsets or viewers encompass a spectrum that spans from entry-level options such as Google Cardboard to more advanced headsets like the Oculus Quest, which was utilized in the present study. One additional factor contributing to the widespread adoption of this technology was the introduction of PeakLensVR, a mobile application designed to generate panoramic content specifically for social media platforms. PeakLensVR is a mobile application designed to facilitate the acquisition of mountain images and subsequently convert them into panoramic representations. The panoramic images have the capability to be subsequently observed alongside annotated data pertaining to the peaks. These visual representations can be observed through VR apparatus and can be disseminated on various social media platforms.

The primary application of panoramic photography has predominantly revolved around the generation of virtual tours for expansive environments (Ramsey, 2017). Additionally, this technique has also found utility in capturing immersive representations of enclosed spaces, including museums and churches. Two examples of closed spaces are the Imperial Cathedral in Königslutter, Germany (Walmsley & Kersten, 2020), and the Yingxian Wooden Pagoda in China (Lai et al., 2019). One instance of an open space can be observed in the urban area of Wolverhampton, located in the United Kingdom (Ramsey, 2017) (https://tourmkr.com/F1yxQEojqj/10786094p&145.32h &85.51t).

Panoramic images can be utilized for various purposes as well. For example, panoramic photographs have been employed as virtual components that are integrated into a tangible setting within an

Augmented Reality (AR) framework for the purpose of addressing acrophobia (Carmen Juan et al., 2006). The aforementioned studies examined the efficacy of panoramic photography within an AR system in eliciting a sense of verticality among users. A study was conducted by (Carmen Juan et al., 2006) involving a sample of 41 participants who did not exhibit fear of heights. The participants traversed the identical environment, employing both physical locomotion and augmented reality technology, as detailed in their research. The researchers arrived at the conclusion that the panoramic photography experience yielded a significant level of satisfaction, and they posited that this technological innovation could potentially contribute to the management of acrophobia. However, the participants were able to discern the differences between the simulated panoramic photography settings and the actual physical environments.

The utilization of panoramic images obtained through Google's Street View Image API has been observed in various contexts. Nguyen et al. (2018) employed panoramic images, specifically street view images, along with computer vision techniques to facilitate the automated characterization of built environments within the context of neighborhood effects research (Q. C. Nguyen et al., 2018). The authors employed panoramic images obtained from Google's Street View Image API for three selected cities in the United States, namely Charleston, Chicago, and Salt Lake City. These images were then processed using convolutional neural networks. The researchers employed log Poisson regression models to assess the correlations between the attributes of constructed environments and the individual rates of diabetes and obesity in Salt Lake City. Based on their analyses, it was deduced that the conditions prevailing in a neighborhood have the potential to exert an influence on the outcomes of chronic diseases.

The widespread availability of affordable devices and the increasing popularity of 360-degree videos have made VR accessible to a larger audience. Consequently, this has led to the emergence of practical uses for VR in diverse sectors, including education, entertainment, and news (Brautović et al., 2017; Kavanagh et al., 2016b; Rhee et al., 2017). Numerous news organizations, including prominent entities such as The New York Times, The Guardian, Euronews, CNN, and BBC, have incorporated VR technology into their news production. This integration enables their audiences to immerse themselves in the events or circumstances depicted in their narratives (de la Peña et al., 2010a; Porter, 2017). The introduction of Google Cardboard in 2014 offered a cost-effective solution for these entities, enabling the dissemination of virtual reality news to broader demographics. Furthermore, prominent video-streaming platforms such as Facebook and YouTube have introduced features that enable users to publish and view 360-degree VR videos. This significant development has played a pivotal role in shaping the advancement of VR technologies (Jones, 2017). The consumption of 360-degree VR videos through Google Cardboard headsets has emerged as a widely accessible form of immersive technology for a broad audience (Hardee & McMahan, 2017).

3.2.1. Advantages of 360-degree technologies

The present benefits of 360-degree videos pertain to the augmentation of audience experiences and engagement. 360-degree videos provide a wide range of benefits in comparison to non-VR videos, resulting in enhanced audience experiences and increased engagement. These advantages encompass a multitude of dimensions, spanning from an enhanced perception of presence to augmented levels of empathy, emotion, and engagement (Wang et al., 2018).

The concept of "sense of presence" refers to an individual's subjective experience of feeling present or immersed in a particular environment or situation. It holds significant importance in VR encounters, as it denotes the psychological condition in which users perceive themselves to be physically present in a particular location, despite being physically situated elsewhere (Huang & Liu, 2014). 360-degree videos are highly effective in augmenting the feeling of presence by utilizing various mechanisms. To begin with, the wide field-of-view characteristic of these videos enhances their authenticity and realism, allowing viewers to cultivate a deeper sense of spatial awareness (Prothero, 1995; Ijsselsteijn et al., 2001; Lin et al., 2002). Additionally, the inclusion of a first-person point of view in an event or situation enhances the perception of being immersed in that particular moment. Furthermore, the immersive quality of 360-degree videos, which enables users to manipulate their perspective and examine all facets of their environment, enhances the feeling of being present in the virtual environment in comparison to videos that are not in VR (Philpot et al., 2017; Sundar et al., 2017a; Van Den Broeck et al., 2017). It is noteworthy to acknowledge that certain studies have revealed limited immersion in 360-degree video consumption, as participants tend to maintain a connection with their real-world surroundings. However, research emphasizes the influence of display devices on the overall VR experience. For example, studies have consistently shown tha HMD are more effective than tablets and desktop displays in enhancing users' sense of presence.

Empathy is a psychological construct that involves the ability to understand and share the feelings and perspectives of others. The notable advantage of VR, particularly in the form of 360-degree VR videos, lies in its ability to enhance empathetic capacity. Previous studies have provided evidence that virtual environments possess the capacity to enhance individuals' empathy towards the characters they encounter within such environments (Gillath et al., 2008; Hasler et al., 2014). The development of empathy is facilitated through the transmission of an individual's experiences or emotions to the intended recipients (D. H. Shin, 2017). The immersive nature of VR, which encompasses 360-degree videos, facilitates a heightened sense of proximity to virtual characters, thereby increasing viewers' inclination to empathize with their emotions or circumstances (D. Shin, 2018). Remarkably, empirical research has demonstrated that individuals who engage with narratives through 360-degree VR videos exhibit higher levels of presence and empathy compared to those who experience the same narratives through text and images (Sundar et al., 2017b).

The topic of emotion is a significant aspect of human experience and has been the subject of extensive research and scholarly inquiry. Numerous studies have demonstrated a significant correlation between the concepts of presence and emotions, as well as empathy and emotions(de la Peña et al., 2010b; Diemer et al., 2015; Sánchez Laws, 2017; Visch et al., 2010). The primary characteristic of 360-degree elicit VR videos resides in their capacity to emotional responses among viewers. The videos possess an inherent capacity to generate intense emotional involvement among viewers, as a result of their utilization of first-person perspectives that evoke a profound emotional reaction (Sánchez Laws, 2017). The existing body of research has also demonstrated a correlation between the predominant moods experienced by viewers while consuming 360-degree videos and the elicitation of positive emotions, including but not limited to feelings of amusement, joy, and astonishment (Ramalho & Chambel, 2013).

The concept of involvement refers to the active participation or engagement of individuals in a particular activity, organization, or community. The term "involvement" denotes a state of heightened cognitive awareness in which the attention of the audience is fully engrossed by the presented content (Hardee & McMahan, 2017). The inclusion of an expanded field of view and the incorporation of stereoscopy in 360-degree virtual reality videos contribute to a heightened level of visual accuracy, thereby promoting increased engagement with the content (McMahan et al., 2012; Ulenius et al., 2017). The videos' ability to immerse and engage viewers effectively captures their attention, resulting in a heightened level of engagement and an overall more immersive experience.

In summary, the inherent characteristics of 360-degree videos provide notable benefits that range from enhancing the feeling of being present to fostering empathy, emotion, and engagement. This technology offers a versatile platform for creating captivating narratives that strongly resonate with audiences and introduce a novel phase of content engagement.

4.2.2. Limitations of 360-degree technologies

360-degree videos offer numerous advantages over traditional non-VR videos. However, there are several challenges that hinder the smooth integration of this innovative medium. Despite the potential for immersion that VR technologies provide, there are several concerns that raise doubts about their feasibility. These concerns encompass various aspects, including user comfort, cognitive processes, content focus, and technological limitations.

Motion sickness: One significant obstacle that poses a threat to the immersive nature of 360-degree videos is the presence of motion sickness, which is often unwelcome. The unsettling experience, which is marked by feelings of unease, confusion, and potential queasiness, frequently occurs when using modern HMD systems (Coxon et al., 2016; Munafo et al., 2017). The occurrence of this ailment is primarily instigated by the dynamic interaction between the motion depicted in the video and the viewer's real-world perceptions, particularly when the viewer's control over the protagonist's actions is restricted (Melo et al., 2017). The phenomenon of camera movement during the recording of a 360-degree video has been identified as a significant factor in the onset of motion sickness among viewers, leading to sensations of discomfort and physical discomfort (Afzal et al., 2017; Hardee & McMahan, 2017). The presence of this sense of unease causes viewers to potentially shorten their sessions of watching 360-degree videos, resulting in a reduced level of sustained engagement compared to conventional videos. The topic at hand concerns the challenge of reconciling the use of technology with the need for physical comfort. The endeavor to achieve a state of complete immersion in virtual reality experiences often entails physical consequences, as VR devices, especially those utilizing head-mounted displays, frequently elicit feelings of discomfort. The experience is marred by the requirement to maintain uncomfortable postures, such as holding the device at eye level, resulting in a pervasive sense of fatigue. The use of devices that require complex hand movements or extended arm reaches exacerbates the difficulty, leading to fatigue even during relatively short periods of time. The conflict between technological progress and user satisfaction highlights the need to find a balance between state-of-the-art immersion and the ergonomic welfare of users. In the following section, three possible disadvantages will be discussed in more detail:

Cognitive Obstacles: The Delicate Balance Between Engagement and Distraction: The introduction of 360-degree videos presents a paradoxical situation. On one hand, it enhances user engagement by providing a more immersive experience. On the other hand, it also gives rise to cognitive challenges that can hinder the seamless absorption of content. The captivating nature of presence experienced by users may paradoxically lead to a diversion of their attention away from the main content, resulting in their fascination with exploring the virtual environment rather than focusing on the essential information (Rupp et al., 2016). One specific type of 360-degree videos, distinguished by their dynamic viewports, exacerbate the cognitive load experienced by users, necessitating their undivided attention as a result of the continuous changes in perspectives (Van Den Broeck et al., 2017). This cognitive phenomenon, which has both positive and negative aspects, adds complexity to the process of creating 360-degree virtual reality content that successfully combines immersive engagement with the effective retention of crucial information.

Navigational Challenges: Exploring the Complexity of User Control in Interactive Interfaces: The advent of 360-degree videos presents viewers with the ability to control camera orientation, but it also gives rise to navigational complexities. The recent ability to examine the environment from various perspectives brings about the potential danger of wayward observations and the inadvertent omission of crucial information (Pavel et al., 2017). The constant presence of potential distractions in the surrounding environment presents a significant risk of deviating from the intended path, unintentionally abandoning the engaging storyline in favor of irrelevant stimuli (Kavanagh et al., 2016a). The presence of ambiguous navigation elements in the landscape raises questions about the viewers' ability to maintain interest and engagement in the 360-degree experience. This also gives rise to concerns about whether their focus aligns with the intended narrative direction. Various strategies have been suggested to assist in reorienting oneself within the intended field-of-view. These strategies highlight the importance of developing innovative solutions to address the complexities of this navigational challenge.

The phenomenon of satiation involves a delicate equilibrium between the introduction of new stimuli and the repetition of familiar ones. The occurrence of satiation, a natural human reaction to repetitive consumption, presents an interesting obstacle within the realm of 360-degree videos (Chugani et al., 2015). As individuals repeatedly interact with these videos, the initial attraction may diminish, resulting in a decrease in their curiosity and involvement (Chugani et al., 2015). The act of viewing, which is initially filled with opportunities for exploration and novelty, can quickly become monotonous, leading to a decrease in sustained engagement (Van Den Broeck et al., 2017). Achieving a careful balance between providing engaging and timeless content while avoiding the boredom of repetitive experiences presents a significant obstacle, which relies on meticulous curation and design of the content.

The pursuit of high fidelity in visual quality: One notable obstacle that poses a significant concern for 360-degree VR videos is their visual quality, primarily limited by the capabilities of current capturing devices (Kavanagh et al., 2016a). The limitations in resolution have broader implications that go beyond just pixel density, affecting the level of audience engagement and immersion, regardless of the visual realism being presented [47, 55]. The pursuit of improved video quality presents a complex challenge in balancing storage capacity and network bandwidth, highlighting the multifaceted nature of this issue.

In summary, although 360-degree VRvideos offer the potential for engaging and immersive encounters, they are not impervious to a variety of obstacles. The challenges encompass various aspects including physiological comfort, cognitive dynamics, navigational clarity, satiation management, and technological constraints. The resolution of 360-degree VR videos will have a significant impact on shaping the direction of visual storytelling and audience engagement, as these videos continue to redefine the landscape in this domain.

5. Virtual reality technologies for memory assessment

The evaluation of memory impairments and their effects on daily functioning is of utmost importance, given the prevalence of various diseases that can compromise memory abilities. Nevertheless, conventional neuropsychological tasks are specifically crafted to elicit the individual's highest level of performance under ideal circumstances, thereby inadequately capturing deficits in everyday memory functioning. Real-life situations that involve memory tend to exhibit greater complexity compared to traditional memory tasks, primarily due to the presence of multitasking and distracting conditions or the individual's engagement in physical movement. Moreover, conventional assessments exhibit minimal similarity to typical, routine memory scenarios. The relationship between performance on traditional memory tests, such as the California Verbal Learning Test (CVLT) or Wechsler Memory Scale-Revised (WMS-R), and measures of everyday functioning, such as self and informant memory diaries, patient and informant memory questionnaires, and clinical ratings, is generally moderate at best. Several studies (Chaytor & Schmitter-Edgecombe, 2003b; Goldstein & Scheerer, 1941; Kaitaro et al., 2009; Makatura et al., 2009; Sunderland et al., 1983) have reviewed this relationship and found only moderate associations. In some cases, the relationship is even absent (Higginson et al., 2000).

The utilization of VR presents a potential remedy for assessing memory within ecologically valid and standardized contexts. The cognitive assessment technology is intriguing due to its ability to replicate naturalistic environments (Rizzo et al., 2008), while maintaining experimental conditions that are safe, replicable, and completely controlled by the experimenter.

Several studies provide evidence for the construct validity of VR protocols, indicating their capacity to accurately measure the intended concept (O'Leary-Kelly & Vokurka, 1998). Numerous studies have documented significant associations between performance on VR tasks and conventional or neuropsychological assessments that assess the same cognitive functions (Armstrong et al., 2013; Lalonde et al., 2013; Matheis, Schultheis, Tiersky, DeLuca, et al., 2007; Nolin et al., 2016). Furthermore, previous research has demonstrated that various VR tests can effectively distinguish between two distinct groups based on their performance levels in tasks. For instance, studies have examined the differentiation between healthy older adults and those with dementia (Allain et al., 2014; Banville et al., 2010; Duffy et al., 2008; Rand, Katz, et al., 2009; M. Rizzo et al., 1997; Tarnanas et al., 2013; Werner et al., 2009; Zygouris et al., 2015). Moreover, a number of studies have demonstrated that VR assessments possess ecological validity, meaning that they have the capacity to forecast performance in real-world settings (Franzen & Wilhelm. K.L., 1996). The measurement of performance in VR tasks was conducted through a comparison with performance in corresponding real-life tasks, as demonstrated in studies by (Allain et al., 2014; Duffy et al., 2008; Renison et al., 2012; Vallejo et al., 2017; Waller et al., 2001). Additionally, some studies utilized self-rated questionnaires of daily functioning, as seen in the works of (Plancher et al., 2010; Potvin et al., 2011; Tarnanas et al., 2013). In the spatial domain, previous studies have identified significant correlations between spatial learning as assessed through a virtual maze and a corresponding real-world maze (Waller et al., 2001). Additionally, correlations have been observed between spatial navigation as measured in a virtual hospital lobby and its real-world counterpart (Duffy et al., 2008).

Several studies have made significant contributions to the development of novel VR tools specifically designed for the evaluation of memory functions. Nevertheless, it is worth noting that a considerable amount of research in this field has predominantly concentrated on validating measures using samples consisting of younger individuals. Moreover, the current lack of research studies that provide evidence for the construct validity and convergent validity of VR-based assessments is a significant issue. These studies should employ rigorous correlation analyses with well-established neuropsychological tests.

The following paragraphs will now explore an analysis of VR memory assessment tools that have demonstrated a clear emphasis on verifying their efficacy among the older adult population, particularly individuals who are 60 years of age or older. Additionally, an essential requirement for the incorporation of data into this analysis is the inclusion of measures of concurrent validation, which establish a comprehensive correlation with well-established neuropsychological tests. These data are presented in table 1. The utilization of this methodology guarantees a comprehensive assessment of the effectiveness and conceptual soundness of the VR memory assessment tools designed for older adults. This research contributes to a more intricate comprehension of the suitability and possibilities of these tools in the field of cognitive assessment.

Through a thorough examination of the available literature, it emerges that VR tools that have been tested and proven to be reliable on older adults and have provided correlations with established neuropsychological assessments cover a wide array of memory areas such as episodic memory (Arvind Pala et al., 2014; Bruni et al., 2022; Corriveau Lecavalier et al., 2020; Eraslan Boz et al., 2020; Kempe et al., 2015; Limoncu et al., 2021; Ouellet et al., 2018; Pieri et al., 2022; Plancher et al., 2010; Sauzéon et al., 2016; Turner et al., 2021; Zygouris et al., 2015), verbal memory (Gottlieb et al., 2022), prospective memory (Hogan et al., 2023; Lecouvey et al., 2019), and spatial memory (Da Costa et al., 2022; Duffy et al., 2008; Lee et al., 2014; Mohammadi et al., 2018; Morganti et al., 2013; Rekers & Finke, 2023; Serino et al., 2015; Tippett et al., 2009; Zhang et al., 2021)

The demographic groups primarily subjected to examination through the utilization of VR tools for the purpose of memory assessment primarily consist of healthy older adults (Arvind Pala et al., 2014; Bruni et al., 2022; Corriveau Lecavalier et al., 2020; Da Costa et al., 2022; Duffy et al., 2008; Eraslan Boz et al., 2020; Gottlieb et al., 2022; Kempe et al., 2015; Lecouvey et al., 2019; Lee et al., 2014; Limoncu et al., 2021; Mohammadi et al., 2018; Morganti et al., 2013; Pieri et al., 2022; Plancher et al., 2010; Rekers & Finke, 2023; Sauzéon et al., 2016; Serino et al., 2015; Tippett et al., 2009; Zhang et al., 2021; Zygouris et al., 2015), Older adults with Subjective Cognitive Decline (Ouellet et al., 2018), individuals diagnosed with Mild Cognitive Impairment (MCI) (Duffy et al., 2008; Serino et al., 2015; Tippett et al., 2009); MCI-sinngle domain (SD) (Eraslan Boz et al., 2020; Lee et al., 2014; Mohammadi et al., 2018; Serino et al., 2015; Zygouris et al., 2015), MCI-multiple domain (MD) (Mohammadi et al., 2018; Zygouris et al., 2015) Parkinson Disease (PD) (Turner et al., 2021), PD-MCI (Turner et al., 2021), individuals cognitively normal with Small Vessel Disease (Limoncu et al., 2021), SVD with cognitive impairment (Limoncu et al., 2021); Stroke patients (Hogan et al., 2023), AD (Sauzeon et al., 2016; Lecouvoey et al., 2019; Morganti et al., 2013; Cushman et al., 2008; Serino et al., 2015; Mohammadi et al., 2018; Lee et al., 2022).

Authors	Population	VR TASK	Neuropsychological measure	Other measures	Results of the VR task	Correlations with neuropsychological tests
Arvind et al., 2014	16 young students (age, M =22.44, SD=2.05); 15 healthy older adults (age, M=66.53; SD=3.43; 15 young moderate-to-severe TBI patients (age, M=36.27, SD=12.72).	HOMES TEST	Mini-Mental State Examination (MMSE); Mattis Dementia Rating Scale (MDRS); Trail Making Test (TMT); Stroop Task; Digit Symbol Substitution Test; Memory Self-evaluation Questionnaire – short form (QAM); California Verbal Learning Test (CVLT).	New Technology (NT) experience; Simulator Sickness Questionnaire (SSQ)	Recall performances increased from trial 1 to trial 2. A post-hoc comparison revealed significant group differences between young controls and older adults and between young controls and TBI patients, with higher recall performances in controls compared with older adults and with TBI patients, but not between older adults and patients. Overall, performances were better on the recognition task compared to the free recall task. Post-hoc comparisons showed that older adults and TBI patients both performed less well compared with young controls. Also, healthy older adults and TBI patients had equally poor performances. Furthermore, there was a significant interaction, showing that the difference between performances on the recall and recognition tasks increased from young control to older adults and to TBI patients.	All of the neuropsychological indices were correlated with the HOMES learning and the HOMES corrected recognition.
Sauzéon et al., 2016	23 young adults (age, mean=22.20, SD=1.68), 23 older adults (age, mean=73,60, SD=9.10); AD (age, mean=78.63, SD=7.89)	HOMES TEST	MMSE; QAM-short form; Mental rotation; Backward Corsi Block, Stroop test, CVLT.	NT, SSQ	Younger adults performed significantly better on the free-recall tasks than older adults, who in turn showed better recall performances than AD patients. The same ANOVA conducted with the retrieval tasks (free-recall trial 2 vs. recognition hits) used, as the within-subject variable showed, a main effect of group, and a main effect of retrieval tasks. The post-hoc follow-up test revealed that poorer mean performances were recorded for older adults compared to younger adults, and these performances were even poorer in AD patients compared with both younger and older adults; overall, the performances were better on recognition than on free recall.	With regard to the relation between EF and HOMES true memory scores, the r value for the young group was not significant while that for another group conditions reached the significance. In summary, the HOMES true memory scores are mediated by both EF and EM scores, and an increased mediating effect of the EF score is obtained for old adults and the AD patients. In contrast, the HOMES false memory indices are only mediated by EM scores in such a manner that after controlling the EM score, the group effect is canceled. The self-reported memory complaints (QAM score) strongly correlated with the two HOMES memory indices indicating that low true memory and high false memory performances are associated with higher memory complaints in everyday life. Besides this, when the correlation analyses between QAM and HOMES indices are performed by group, they still

						remained significant only for young participants.
Corriveau Lecavalier et al., 2018	20 younger participants (age, mean=21,65, SD=2,46); 57 older adults (age, mean=67,77, S=7.031)	Virtual Shop (La boutique virtuelle)	A validated free recall word list test			Performance on the VR task correlated with the immediate and delayed free recall scores of the traditional verbal memory task in both younger and older adults
Ouellet et al., 2018	35 older adults with Subjective Cognitive Decline (SCD) (age, mean=67.20, SD= 7.87).	Virtual Shop (La boutique virtuelle)	Multifactorial Memory Questionnaire (MMQ); Story Recall II; Stroop-Victoria test; MOCA			Lower recall in the Virtual Shop task was associated with reporting more frequent difficulties related to shopping in daily life; the initiation time score of the Virtual Shop was also correlated with the MMQ-shopping complaint score; There was no association between time to complete the VR task and the MMQ-shopping complaint score. Importantly, performance on the Virtual Shop was not correlated with the global MMQ-ability score or with the MMQ-ability score that pulled out the 2 shopping items. This indicates that the relationship between the RV task and performance in daily life is specific to activities similar to those tested in the Virtual Shop. The scores for correct recall in the Virtual Shop task were positively correlated with traditional neuropsychological measure of episodic memory. Initiation time on the Virtual Shop was positively correlated with completion time for the first, second, and third plate of the Stroop-Victoria. The MMQ-shopping complaint score was positively correlated with completion time on the third plate. The low and high interference scores were not correlated with any of the VR scores.
Pieri et al., 2022	24 older adults (age, mean=70.4, SD=8.5)	ObReco	MMSE; Frontal Assessment Battery (FAB); Picture Recognition sub-test included in the Rivermead Behavioural	Independent Television Com-mission-Sense of Presence Inventory		The results indicate that for the Free Recall tasks, participants performed better after the 360° presentation than after the standard one (Rivermead) in

			Memory Test (RBMT-III) Italian Version; Babcock Story Recall Test Italian Version	(ITC-SOPI), System Usability Scale (SUS)		terms of accuracy percentages. For what concerns the Recognition indexes, the participants performed better in recognizing the objects after the standard presentation than after the 360° one
Bruni et al., 2022	20 older adults (age, mean= 68.2, SD=5.45)	ObReco2	MMSE, FAB, the Babcock Story Recall Test (BSRT) Italian Version, the Rey Auditory Learning test (RAVLT), the Tower of London (ToL), Attentive matrices (AM), test exploring Constructive Apraxia, TMT; Raven's progressive matrices; Picture Recognition sub-test included in the RBMT-III Italian Version	STAM, ITC SOPI, SUS		The results indicate that for the free recall tasks, participants performed better after ObReco-2 than RBMT-III in terms of the number of targets correctly recalled although the difference is not statistically significant. Concerning the recognition indexes, participants recognized more objects after the standard presentation compared to the 360◦ one, and the observed difference is statistically significant. In the experimental group ObReco-2 scores correlate with AM and delayed RAVLT.
Kempe et al., 2015	20 young adults (age, mean=24.89, SD=3.16); 23 older adults (age, mean=70.28, SD=4.65)	Supermarket test	Digit span, Grid test, Digit Complex Span test, Grid Complex Span, Verbal Simple Span (VS), Verbal Complex Span (VC), Spatial Simple Span (SS), Spatial Complex Span (SC), Stroop Test		Young adults memorized more items than older ones in all memory tasks domains. Time needed to fulfill the supermarket tasks was significantly lower for younger than for older participants. For older adults, as expected, the laboratory memory tasks correlated with each other. In the younger age group, just the verbal tasks significantly correlated with each other, but there was no connection between the two spatial difficulties or between the verbal and the spatial tasks.	Short term memory in the VR task correlated with VC for older adults and with SC for younger adults. The Stroop test did not show any connection with other tasks in the older group, but with EDS-M and EDS-STM in the younger group.
Zygouris et al., 2014	21 healthy older adults (age, mean=66.57, SD=1.20), 11 single domain MCI (aMCI-SD) (age, mean=66.55, SD=1.71), 23 multi domain amnestic MCI (aMCI-MD) (age, mean=72.13, SD=1.50)	Virtual Supermarket (VSM)	MMSE, RAVLT, Greek version of the "FAS" verbal fluency test, Rey-Osterrieth Complex Figure Test (ROCFT), RBMT, Test of Everyday Attention (TEA) items 1, 4, and 6; TMT part B; Functional Rating Scale for Symptoms of Dementia (FRSSD), Functional Cognitive Assessment Scale (FUCAS), Clinical Dementia Rating (CDR); Greek dementia screening scale; Greek self-report	Beck Anxiety Inventory (BAI), Beck Depression Inventory (BDI), Geriatric Depression Scale (BDS), and the Perceived Stress Scale (PSS)		The supermarket test duration significantly negatively correlated with MMSE, FUCAS, CDR, TRAIL B, TEA, RBMT, ROCFT, BAI. VSM correct types correlated with MMSE, TRAIL B, RBMT. VSM correct quantities correlated with MMSE FUCAS TRAILB RAVLT-learning abilities. VSM Bought Unlisted correlated with TRAIL B, TEA, RBMT, RAVLT.

			questionnaire assessing early signs of cognitive decline.			
Boz et al., 2019	37 patients with aMCI (age, mean=70.41, SD=7.297); 52 healthy controls (age, mean=67.56, SD=6.044).	Virtual Supermarket (VSM)	Oktem Verbal Memory Processes Test, Wechsler Memory Scale-Revised (WMS-R); Visual Reproduction Subtest, Stroop Test, Digit Span, Figure Copying Test, Clock Drawing Test, the Turkish version of revised MMSE, Verbal Fluency Test (categorical and phonemic), Boston Naming Test, Wechsler Adult Intelligence Scale-III (WAIS-III) Similarities Subtest, Luria Alternan Sequences Test, Lawton Instrumental Activities of Daily Living (IADL)	BAI, GDS		The general cognitive status negativeley correlated with correct quantities, bought unlisted, correct money and duration. Verbal memory and visual memory negatively correlated with all the measures of the VSM. Executive functions correlated with all measures except for correct money. Attention negatively correlated with bought unlisted, correct money and duration. Visuo-spatial construction negatively correlated with correct quantities, count unlisted and correct money.
Limoncu et al., 2021	30 Healthy control (age, mean=67,27, SD=7,79); 37 patients with Small Vessel Disease cognitively normal (SVD-CN, age, mean=62,73, SD=10.16); 32 patients with SVD with cognitive impairment (SVD-CI, age, mean=67,16, SD=9,35).	The Virtual Supermarket Test (VST)	MMSE, Oktem Verbal Memory Processes Test and Wechsler Memory Scale-Revised (WMS-R), Visual Reproduction Subtest for visual and verbal memory; Stroop Test, Clock Drawing Test, phonemic fluency, Wechsler Adult Intelligence Scale–III (WAIS- III) Similarities Subtest, Luria Alternant Sequences Test; Digit Span; figure copying test for visuospatial function; Boston Naming Test and semantic fluency for language; IADL	BAI, GDS	A significant difference was found between SVD-CI and HC in terms of “Correct Types”, “Correct Money”), and “Duration”. In addition, there was a significant dif- ference between SVD-CN and SVD-CI in terms of “Bought Unlisted” and “Duration”. However, there was no significant difference between SVD-CN and HC in VST variables.	There were negative moderate and strong correlations between “Duration” variable and general cognitive status and visuospatial functions on SVD-CI patients. In addition, a positive moderate correlation was found between “Correct Quantities” and general cognitive status on SVD-CI patients. The “Duration” variable was positively correlated to memory, executive function, and visuospatial functions on SVD-CN patients. The “Correct Money” variable was positively associated with executive function and negatively associated with visuospatial functions on SVD-CN patients. No significant correlation was found between VST variables and composite Z score of cognitive domains on HC.

Turner et al., 2021	14 PD patients (age, mean=65.5, SD=7.38), 15 PD-MCI patients (age, mean=67.67, SD=8,04)	Virtual Reality Functional Capacity Assessment Tool (VRFCAT)	MDRS, Brief Visuospatial Memory Test (BVMT-R, Total Learning and Delayed Recall), Hopkins Verbal Learning Test (HVLT-R, Total Learning and Delayed Recall), Judgment of Line Orientation (JOLO), Neuropsychological Assessment Battery (NAB) : Numbers & Letters A (Time and Errors), Digits Forward and Digits Backward, and Naming subtest; Hayling Sentence Completion Test (Direct Time, Inhibition Time, Inhibition Errors), Controlled Oral Word Association Test (FAS and Animals); TMT	GDS, Geriatric Anxiety Inventory (GAI)	For the overall sample, the average completion time for the VRFCAT-SL was 791 seconds (SD = 242) or about 13 minutes, with a minimum completion time of 504 seconds, and maximum completion time of 1461 seconds.	T-score for VRFCAT-SL Time was positively associated with T-scores for NAB Numbers & Letters A Time, and BVMT-R Delayed Recall. The T-Score for VRFCAT-SL Errors was inversely correlated with Inhibition Errors (raw) on the Hayling, indicating greater errors on the VRFCAT-SL were associated with increased errors on the Haylling. T-score for VRFCAT-SL forced progressions was positively correlated with T-score for NAB Naming.
Plancher et al., 2010	78 healty older adults (age, mean=63.73, SD=10.74), 82 students (age, mean=21.47, SD=2.99)	Car accident scene	MMSE; Cognitive Difficulties Scale (CDS); TMT		The post hoc test exhibited no difference between young and older adults with intentional encoding, but the older adults scored higher in incidental encoding compared to the younger adults. In addition, there was a significant interaction on verbal where recalls. Indeed, post hoc Tukey's tests indicated that the young participants performed better on verbal where recalls than the older participants on intentional encoding but also on incidental encoding. Moreover, we observed an interaction on the visuospatial where recalls, showing that the younger adults recalled more visuospatial information in intentional encoding compared to the older adults, although no difference between younger and older participants was observed in incidental encoding. An interaction was also observed on when recalls, showing that the younger adults scored higher than the older adults in intentional encoding, but not in incidental encoding. Finally, we observed an interaction on recognitions of the virtual town, indicating that the younger participants made more correct recognitions than the older adults in intentional, but not in incidental encoding. In	The correct recalls and recognitions on the verbal episodic memory test were significantly correlated with the when recalls. However, other scores on the virtual town did not correlate with the scores of the verbal test, which in turn did not correlate with any scores on the neuropsychological tests. In addition, the TMT–A test score was significantly negatively correlated with what score, the visuostial where score and the recognition score. By contrast, it did not correlate with the score on the verbal episodic memory test. Any of the scores on the VR and verbal episodic memory tests correlate with the TMT–B–A. Fur- thermore, the MMSE significantly correlated with score on visuo- spatial where, but the MMSE did not correlate with the verbal episodic memory test. Finally, the score on the CDS significantly correlated with the quantity of b0, and b1 and correct recognitions of the town. In contrast, CDS score did not

					other words, the performance of older adults was similar in both forms of encoding, but the performance of younger adults obviously increased in intentional encoding compared to incidental encoding. However, no effect of age and encoding was observed on the detail's memories.	correlate with score on the verbal episodic memory test.
Gottlieb et al., 2022	29 young adults (age, mean=24,1, SD=2.9); 29 Middle Aged Adults (age, mean=57.7, SD=4,0); 20 Older adults (age, mean=71.8, SD=5.1)	VR-RAVLT	RAVLT, MOCA, digit symbol test, digit span test, Verbal fluency		Group effects were observed for the ACQUISITION and the RETENTION variables in the VR-RAVLT, respectively with poorer scores for the older-adults group.	Statistically significantly correlations were found between the GS-RAVLT and the VR-RAVLT for two of the three outcome measures: ACQUISITION and RETENTION correlated with MOCA score, digit symbol test and verbal fluency. The digit span correlated only with VR-RAVLT acquisition. The retroactive interference did not correlate with any neuropsychological measures.
Hogan et al., 2023	12 individuals with stroke (age, mean=63.00, SD=10.90), 12 controls (age, mean=55.33, SD=9.95)	Virtual Reality Prospective Memory Shopping Task (VRPMST)	CAMPROMPT, Lexical Decision Prospective Memory Task (LDPMT), TMT; HVLT-R, MoCA	User-friendliness scale (UFS)	Both groups scored similarly on the ongoing task, indicating that they did not find the task too difficult. Controls performed significantly better on time-based PM compared to individuals with stroke (medium effect size). Additionally, controls monitored the time significantly more than indi- viduals with stroke (large effect size). Controls scored higher than individuals with stroke on event-based PM; however, no significant difference was found. VRPMST monitoring significantly correlated with VRPMST time-based PM for both groups.	Time- and event-based VRPMST scores were significantly strongly correlated with both time- and event-based PM on the CAMPROMPT for the stroke sample. For controls, only event-based VRPMST significantly strongly correlated with both time- and event-based PM on the CAMPROMPT. Significant strong correlations were found between VRPMST time-based PM and LDPMT event- and time-based PM for the stroke sample but not for the control group. For individuals with stroke event-based PM on the VRPMST was significantly strongly correlated with the TMT, both HVLT- R scores, and MoCA, while time-based PM was significantly strongly correlated to the TMT, HVLT-R total recall score, and the MoCA. For controls VRPMST event- and time-based PM was significantly strongly correlated to TMT; however only the HVLT-R percent retained score was significantly correlated with time-based PM.

Lecouvey et al., 2019	15 cognitively normal older individuals (age, mean=76,47, SD=4,45); 17 patients with mild AD (age, mean=79.29, SD=4.45).	Virtual city	MDRS, MMSE, RL- RI16 (retrospective episodic memory), picture-naming task, categorical and lexical fluency tests, Stroop test, TMT; Zoo Map test	BDI, State Trait Anxiety Inventory (STAI)	Cognitively normal older individuals needed lower number of trials to encode - and recalled more - Link-EB, NoLink-EB, and TB intentions when compared to patients with AD.	In AD patients, NoLink-EB intentions correlated with shifting tested by TMT part B and semantic memory. No correlation was significant with Link-EB intentions. Prospective component correlated with TMT part B and planning.
Tippett et al., 2009	26 control participants (age, mean=69, SD=7.7); 8 MCI patients (age, mean=72, SD=7)	Sunnybrook City task	ROCFT, TMT, Digit Span subtest (Forward and Backward), Dementia Rating Scale, MMSE	SSQ	Both participant groups were similarly successful in navigating Sunnybrook City to learn Paths A and B by memory. both groups improved at a similar rate across trials, but overall MCI participants moved at reduced speed	The VE navigation index showed significant correlation with the Trail Making Test (A error, and B error). The VE movement and memory indices did not show statisti- cally significant correlations. The VE movement index also was significantly correlated with the Trail Making Test measures (A, A error, B error), whereas the VE memory index was correlated with measures of the Rey immediate recall and delayed recall
Zhang et al., 2021	31 young adults (age, mean=22.68, SD=3.07), 30 older adults (age, mean=67.30, SD=5.10).	Virtual maze	Multifactorial Memory Questionnaire, the digit span (forward and backward), the block design (visuo-spatial abilities).		The main effect of learning trials was significant in speed, rotation, and distance error. The main effect of learning trials did not reach significance in the percentage of successful trials. Non-egocentric strategy users completed the virtual star maze task with more rotations and higher distance error. No significant effects were found in speed and percentage of successful trials.	For older adults, the WAIS block-design score was positively correlated with navigation speed and the percentage of successful learning trails, none of the other correlations were significant.
Morganti et al., 2013	26 early-stage Alzheimer's patients (age, mean=80.96, SD=6.3); 26 healthy participants (age, mean=77.23; SD=5.25).	VR-Maze	MMSE, Corsi's Span; Supraspan Test, TOL, TMT; Manikin's Test (body representations); Benton Line Orientation Test		For the VR Maze spatial task, the CG showed more correct performances than the AD group in the PP-MT and in the VR-MT	The VR-MT results correlated with the Mini Mental State Examination, Corsi's span, Corsi's supra-span, Manikin Test and Trial Making Test). The VR-RMT results correlated with the Mini Mental State Examination and Corsi's supra-span.

Cushman et al., 2008	35 young normal controls (age, mean=23.18, SD=0.72), 26 older normal controls (age, mean=73.40, SD=0.80), 12 MCI (age, mean=73.10, SD=1.27), 14 early Alzheimer disease (age, mean=74.69, SD=1.24).	Virtual hospital lobby task	Categorical Name Retrieval, Money Road Map test, line Orientation, Figural Memory, Verbal Paired-Associates Test, MMSE.		In both the real-world and virtual environments, young subjects performed best, with successively lower scores in first the older normal group and MCI groups and then the Early AD group. There was a significant difference in performance between the two environments, with the virtual test yielding somewhat lower scores across all groups.	Stepwise multiple linear regression selected the virtual navigation and delayed verbal memory scores as the two best predictors of real-world navigation testing to results with an adjusted r2 of 0.82. The inclusion of MMS and judgment of line orientation scores enhanced the regression model to yield an adjusted r2 of 0.84. Thus, it seems that real-world testing might reflect the influence of factors well described by virtual testing along with factors well described by delayed verbal memory testing.

Serino et al., 2015	15 AD patients (age, mean=82.93, SD=5.61), 15 aMCI patients (age, mean=77.53, SD=5.52), and 15 cognitively healthy individuals (age, mean=73.87, SD=7.38).	Virtual room task	Short Story Recall, MMSE, Milan Overall Dementia Rating Scale, Corsi Block Test, Money Road Map, Manikin's Test, Judgment of Line Orientation		For Task 1, there were no absolute significant differences between groups in the ability to retrieve spatial allocentric information independent of point of view. For task 2, post hoc comparisons indicated that AD patients performed more poorly when compared with the CG. This means that AD patients showed very weak abilities in retrieving the position of the object without allocentric spatial information.	A series of linear multiple regression analyses, including all participants, with the accuracy of spatial location for both tasks in each trials as the dependent variable, and general cognitive functioning (MMSE) and traditional Money Road Map, Corsi Block Test – Span, Corsi Block Test- Supraspan, Manikin's Test, The Judgment of Line Orientation) as independent variables, were carried out. As concerns findings from the second tasks, results showed that these neuropsychological tests in combination with each other predict impairment in the ability to retrieve the position of the object without allocentric spatial information only in the Trial 2 . However, findings revealed that there are only two significant predictors of performance in the third trial of the Task 2, namely, the scores on the Money Road Map and the scores on the Manikin's Test. These two tests, indeed, evaluate respectively the ability in the spatial navigation, which requires the cognitive ability to correctly retrieve the position of the object in large environment, and the mental rotation ability, which is fundamental in the Trial 3, since it required a 180◦ spatial rotation to memorize the object.

Rekers & Finke, 2023	79 participants (age, mean=67.8 years, SD = 8.89).	VIENNA task	ROCF, block tapping, visual memory span forward and backward, Wechsler Memory Scale-Revised Version, MMSE, Testbatterie zur Aufmerksamkeitsprüfung (TAP), Vandenberg's Mental Rotation Test (MRT), Five-point Test, productivity, flexibility, and strategy [FPT), Perspective Taking Test (PTSOT)	Complainer Profile Identification (CPI), the German translation of the Santa Barbara Sense of Direction Scale (SBSOD); GDS	VIENNA scores in the sample were normally distributed in the upper half of the theoreti- cally possible test score range of 0 to 24. The distribution of the VIENNA scores and error types is portrayed in the Supplementary information in Figure B1. The distribution of perspective rotation errors was slightly right-skewed while updating errors showed significant right skewness, with only 10 participants making more than one updating error. The median VIENNA administration time, including pretest and instructions, was 16 min. Furthermore, no outlier scoring below or above 2.5 standard deviations from mean VIENNA performance was observed.	VIENNA performance correlated significantly with the following tests: (i) large correlations with Mini-Mental State Examination, visuospatial working memory, perspective tak- ing, and visuoconstructive productivity; (ii) medium to large correlation with mental rotation; (iii) medium correlations with visuoconstruction and visuospatial short-term memory; (iv) and small to medium correlation with the executive function strategy application. VIENNA did not correlate sig- nificantly with episodic memory, operationalized by the per- centage of recalled elements in the delayed free recall of the Rey-Osterrieth Complex Figure Test, cognitive flexibility or attention regarding processing speed, and selective attention. Correcting for participant age, all previously significant correlations, except for strategy application, remained significant, and effect sizes for correlations with working memory, productivity, and mental rotation decreased significantly. When correcting for average performance in neuropsychological tests, only the correlations with MMSE, perspective taking, and visuoconstructive productivity remained significant and showed medium-sized effects. Perspective rotation errors correlated significantly with the Perspective Taking Test, but not with the mental rotation task.

da Costa et al., 2022	20 cognitively healthy elderly (age, mean=70.21,SD= 5.28); 19 MCI (age, mean=72.53, SD=6.50)	SOIVET Maze and SOIVET Route	ACE-R, Corsi Block Test, the Benton's Judgment of Line Orientation Test (BJLO), TOL, MRMT.		The SOIVET Maze task was able to significantly differentiate groups while the MRMT showed no statistically significant difference. In the SOIVET Route task, the control group significantly outperformed the MCI group in the immediate phase as well as in the delayed phase.	The SOIVET Maze task revealed a significant correlation with the MRMT, Tower of London, BJLO test, and total ACE-R score. No significant correlation was found between the SOIVET Maze and Corsi Block Test forward or backward scores. Additionally, ACE-R-memory and ACE-R-visuo- spatial scores correlated with the SOIVET Maze. The SOIVET Route immediate also correlated with the MRMT and the ACE-R total score. In addition, the memory and visuospatial categories ($r = .319$, $p = 0.045$) from the ACE-R correlated with SOIVET Route immediate scores. SOIVET Route delayed scores did not correlate with any neuropsychological test, or with ACE-R total score and its categories.
Mohammadi et al., 2018	20 with miAD (age, mean=73.65, SD=2.48), 30 with pure aMCIsd (age, mean=70.00, SD=1.68), 30 with pure aMCImd (age, mean=70.07, SD=1.67), and 30 cognitively normal controls (NC) (age, mean=69.87, SD=1.43)	Virtual reality navigation task (VRNT)	MMSE; Boston Naming Test; RAVLT; R-OCFT		Comparisons of the scores among the miAD, aMCIsd, aMCImd, and NC subjects across the five trials showed significant differences on the virtual neighbourhood task. Further analysis showed that miAD patients performed significantly worse than the NC and aMCI subjects on the virtual neighbourhood task. Similarly, the results indicated that the aMCImd subjects were significantly more impaired than aMCIsd and NC subjects, but they were less impaired than the miAD subjects. Comparing the performance of all groups across the five virtual maze trials showed significant differences in the response scores and response times. Tukey's post-hoc test revealed that miAD subjects performed worse than the NC and aMCI groups on the virtual maze task. The response time analysis for all groups showed that miAD subjects required more time to complete the trials than the others. Also, there was a significant difference between aMCIsd and aMCImd subjects. A comparison of aMCI and NC subjects indicated that there were no significant differences with regard response scores or response time	The results showed a strong positive correlation between neuropsychological and virtual neighborhood scores in all groups. A strong negative correlation was found between neuropsychological scores (RAVLT total scores, immediate recall, and delayed recall; R-OCFT immediate and delayed recall) and the mean response time for the virtual neighborhood task.

Lee et al., 2022	20 controls (age, mean=70.8, SD=5.2), 20 aMCI (age, mean=70.7, SD=5.0), 20 AD (age, mean=72.4, SD=5.6)	The virtual radial arm maze (VRAM)	Korean MMSE, CDR, simplified Rey figure test (SRFT); Spatial Span Forward and Backward		Repeated measures ANOVAs revealed a significant main effect of number of trials on working and reference memory errors. All three groups committed fewer working and reference memory errors as the trials proceeded. Additionally, a significant effect of group was found on working and reference memory errors. According to the post hoc analysis, aMCI and NC participants committed a comparable number of working memory errors, but both groups committed fewer working memory errors than the AD subjects. aMCI subjects committed more reference memory errors than NC subjects and committed a similar number of reference memory errors to AD subjects. A significant main effect of trial was observed on distance traveled to find the rewards; hence, all three groups traveled shorter distances to find the rewards as the trials progressed. A significant main effect of group on distance traveled to find the rewards was also observed. Specifically, NC subjects found the rewards after traveling shorter distances than aMCI subjects and aMCI subjects found the rewards after traveling shorter distances than AD subjects. Finally, the data reflected a significant main effect of trial on time latency to find the rewards. All participants spent less time finding the rewards as the trials proceeded. Moreover, a significant group effect was found of latency, revealing that NC subjects found the rewards more quickly than aMCI subjects, whereas the time to find the rewards did not differ between aMCI and AD subjects.	The numbers of working and reference memory errors on the VRAM had significant linear correlations with each other and with scores on all neuropsychological tests except the Spatial Span Forward.

Table 1. Description of population, neuropsychological measures, and results of each study.

5.1. Virtual reality assessment tools for episodic memory

VR provides individuals with the chance to assess the reliability and effectiveness of cognitive functions within environments that closely resemble real-life situations. This technology provides users with an immersive experience within a dynamic virtual environment, enabling them to engage in cognitive and sensorimotor activities while interacting with virtual stimuli (Fuchs et al., 2006). A significant advantage of VR lies in its ability to create immersive environments that accurately replicate the sensory aspects of the physical world, such as visual scenes and audible conversations. Furthermore, VR can effectively incorporate the cognitive and physical challenges that individuals encounter in their daily routines. Consequently, it can be argued that well-constructed VR tasks have the potential to more accurately represent real-world abilities when compared to conventional neuropsychological assessments (Rizzo et al., 2008). In addition, VR holds significant promise in assessing the transferability of neuropsychological interventions to individuals' everyday functioning, a significant hurdle in the field of rehabilitation research (Adamevich et al., 2005; Lehmann et al., 2005; Ouellet et al., 2018; Riva et al., 2020).

VR is a relatively new technological advancement, and its utilization in the field of cognitive measurement is also a recent development. There are several justifications for assessing the feasibility of VR in older adults. There is a scarcity of studies that utilize VR protocols with older adults, resulting in a significant knowledge gap regarding the suitability and reliability of VR tasks for this population. Consequently, numerous essential inquiries pertaining to the effectiveness and accuracy of VR tasks among older adults have yet to be explored. The investigation of designing and evaluating tasks that accurately mirror memory processes in real-world scenarios holds particular significance within the framework of the aging population. The decline of episodic memory is observed in individuals as they age, often exhibiting impairment due to brain diseases, and is recognized as an early indicator of Alzheimer's disease. Therefore, it is imperative for clinical neuropsychologists to have access to a diverse range of sensitive and valid tools in order to evaluate and enhance episodic memory. Moreover, in addition to the existence of numerous meticulously designed tasks aimed at assessing the intricate mechanisms underlying episodic memory, VR presents a valuable set of tools capable of replicating the multifaceted nature of memory in real-world contexts.

The domain of memory assessment has experienced significant growth in recent years due to the increased accessibility of VR technologies. Nevertheless, it is important to highlight that a considerable proportion of these studies predominantly focused on comparatively younger demographics, despite the expected applicability of these methodologies for older individuals. Furthermore, it is worth noting that there is a noticeable deficiency in the existing body of literature, as several of these studies have neglected to include convergent validity measures, thereby restricting the thorough validation of these memory assessment tools that are based on VR. This specific section of the discussion aims to fill the existing gap in knowledge by shifting attention towards studies that have specifically focused on validating these tools among older populations. This overview aims to provide insights into the efforts made to determine the effectiveness and practicality of VR technology in evaluating memory functions among older adults.

Two studies (Pala et al., 2014; Sauzeon et al., 2016) assessed episodic memory using the HOMES test: The participants were presented with a large display screen that depicted two versions (referred to as versions A and B) of a virtual apartment. Each version contained a total of 40 objects, with 20 objects unique to each version and 20 objects shared between both versions. There were four distinct categories, namely a bedroom, a bathroom, a kitchen, and an unspecified fourth category. Each of these categories consisted of ten objects, with five objects being specific to each category and five objects being common to both versions. The participants were initially exposed to a specific iteration of the apartment, referred to as version A. This iteration was shown to the participants on two separate occasions, and after each presentation, the participants were asked to engage in a free recall task. Following the completion of the preceding recall task, participants engaged in a mental visualization exercise wherein they envisioned the alternative version of the apartment (version B). Subsequently, they were instructed to perform a single immediate free recall task. Following a duration of 10 minutes, a conclusive yes/no recognition task was subsequently administered to all participants. In (Arvind Pala et al., 2014) all of the neuropsychological indices (general cognition, executive functions and episodic memory) were correlated with the HOMES learning and the HOMES corrected recognition. In (Sauzéon et al., 2016) the HOMES true memory scores of both the older adults' group and AD group correlated with executive functions and episodic memory. Moreover, a significant positive correlation was found between self-reported memory complaints, as measured by the QAM score, and the two HOMES memory indices. This suggests that individuals who exhibit lower true memory performance and higher false memory performance are more likely to report experiencing greater memory complaints in their daily lives.

Another tool used to assess episodic memory is the Virtual Shop (La boutique virtuelle) (Corriveau et al., 2018; Ouellet et al., 2018). In this task, participants initiated the task by positioning themselves in proximity to a cashier situated behind a countertop. They were subsequently provided with a compilation of 12 virtual images depicting commonly encountered items (e.g., belt, milk), which they were instructed to commit to memory and subsequently retrieve within the store environment. During the process of encoding, extraneous dialogues were delivered through the use of head-gear with the intention of replicating a disruptive auditory setting. After the conclusion of the previous item, the program implemented a 20-second conversation between the cashier and the participant. This conversation served as a filled interference delay, wherein the cashier asked the participant about the time displayed on their right, for example. Following the conclusion of the designated delay period, the cashier issued instructions to the participant, tasking them with retrieving the items within the store that they had previously observed. Subsequently, the participant was granted unrestricted mobility within the room in order to locate and choose the items that were previously presented on the learning list. The shop contained a total of 24 items, consisting of 12 target items and 12 distractors. Corriveau et al., found a significant correlation between the performance on the VR task and the scores obtained from both the immediate and delayed free recall assessments of the traditional verbal memory task. In Ouellet et al., 2018 there was a significant correlation between lower recall performance in the Virtual Shop task and a higher frequency of self-reported difficulties pertaining to shopping in everyday life. No significant correlation was found between the duration required to complete the virtual reality task and the score obtained on the Multifactorial Memory Questionnaire (MMQ)-shopping complaint scale which assesses subjective memory complaints. Significantly, there was no observed correlation between performance on the Virtual Shop task and either the overall MMQ-ability score or the MMQ-ability score specifically pertaining to the two shopping items. This finding suggests that the correlation between performance in the VR task and daily life activities is limited to tasks that closely resemble those assessed in the Virtual Shop.

There was a positive correlation observed between the scores for correct recall in the Virtual Shop task and the traditional neuropsychological measure of episodic memory. Nevertheless, there was no

observed correlation between performance on the episodic memory measure and the MMQ-shopping complaint score, the global MMQ-ability score, or the MMQ-ability score when the two shopping items were excluded.
There was a positive correlation observed between the initiation time on the Virtual Shop and the completion time for the first, second, and third plate of the Stroop-Victoria task. The Virtual Shop task exhibited a comparable outcome, as correct recall was observed to be inversely associated with the completion time for the initial, second, and third plate of the Stroop-Victoria. There was a positive correlation observed between the MMQ-shopping complaint score and the completion time on the third plate. There was no observed correlation between the low and high interference scores and any of the VR scores.
Obreco is another tool developed to assess episodic memory using 360° videos and images. In the first version (Pieri et al., 2022) participants wear a head-mounted display and adopt the viewpoint of the 360-degree camera. The clinician engages in movement within the room and brings the target objects in close proximity to the camera for a duration of 5 seconds. During this time, the participants are required to verbally identify the object being presented. Subsequently, the tasks solely necessitate the retention of the ten objects that were previously presented during the Encoding Phase, with a time interval of ten minutes. Subsequently, participants are instructed to locate and nominate all ten objects that were previously presented during the encoding phase, amidst a set of 17 additional non-target objects. In the second one (Bruni et al., 2022), participants are exposed to a domestic environment, a living room, from the experimenter's first-person perspective. They follow the prospective of the video 360 which selectively stops at the 15 designated objects for a duration of 3 seconds each, while simultaneously affixing a label inscribed with the appellation "Marco" to each item. In the living room, there are an additional 15 objects present, serving as distractors. During this phase, participants are provided with instructions to verbally label all the targets. Following a period of 15 minutes, participants are given instructions to recall and identify as many objects as possible from the previous encoding phase. Subsequently, the participants are provided with instructions to thoroughly examine the previously observed living room environment, identify and label the specific target objects from the previously encountered items, as well as an additional set of 15 unfamiliar distractor objects. The findings of the first version (Pieri et al., 2022) suggest that participants exhibited superior performance in terms of accuracy percentages during the Free Recall tasks following the 360° presentation (ObReco) compared to the standard Rivermead presentation (RBMT-III). With regard to the Recognition indexes, it was observed that the participants exhibited superior performance in object recognition following the standard presentation as compared to the 360° presentation. The findings of the second version (Bruni et al., 2022) suggest that, in the context of free recall tasks, participants exhibited superior performance in terms of accurately recalling the number of targets after engaging with ObReco-2 compared to RBMT-III. However, it is important to note that this difference did not reach statistical significance. With regards to the recognition indices, it was observed that participants exhibited a higher level of object recognition following the standard presentation as opposed to the 360-degree presentation. This difference in recognition rates was found to be statistically significant. In the experimental group, there is a significant correlation between ObReco-2 scores and attentional matrices, which measure attention, as well as delayed RAVLT, which assesses verbal memory.
One common task/environment frequently used to assess episodic memory is the supermarket task which typically requires memorizing a shopping list and then buying those products in the

supermarket with additional different demands like picking the products in the order they walk by them (Kempe et al., 2015) or correctly select the precise amount needed to pay for the items bought (Zygorius et al., 2014; Boz et al., 2029: Limoncu et al., 2021).
Results showed a significant relationship between the virtual supermarket scores and general cognition (Zygorius et al. 2014; Boz et al., 2019; Limoncu eet al., 2021), executive functions (Zygorius et al. 2014; Boz et al., 2019; Limoncu et al., 2021); memory (Kempe et al., 2015; Zygorius et al. 2014; Boz et al., 2019; Limoncu eet al., 2021); and visuospatial functions (Boz et al., 2019; Limoncu et al., 2021).
Similarly, in the Virtual Reality Functional Capacity Assessment Tool (VRFCAT) (Turner et al., 2021), a tool developed to measure functional capacity of subjective cognitive decline, participants engage in an exploratory activity within a kitchen environment to ascertain the available culinary resources for the recipe at hand. Subsequently, individuals employ a bus timetable to locate a suitable bus route that will transport them to a grocery store. The individuals locate and acquire the requisite items from the retail establishment, subsequently employing the aforementioned timetable to identify the bus that will facilitate their return to their place of residence. They found that VRFCAT Time was positively associated with Neuropsychological assessment battery-Numbers & Letters A Time, and memory (BVMT-R Delayed Recall).
With the same purpose but a different setting, Plancher et al., 2010 developed an episodic assessment tool set in a virtual urban environment based on Paris' photos: At the site of a vehicular collision, two automobiles collided, resulting in the activation of a horn and the emission of black smoke. The interconnectedness of buildings facilitated seamless transitions between distinct areas. Various elements comprised the town, including individuals, waste receptacles, obstacles, vegetation, advertising displays, and stationary vehicles. Each specific area is comprised of a distinct combination of these various elements. In the vicinity of the town hall, a pedestrian can be observed traversing the area, accompanied by a billboard, barricades, and a cluster of trees. Following their experience of driving in the town, all participants were subjected to identical episodic memory tests. Participants were instructed to engage in free recall of verbal components by providing written responses. Specifically, they were asked to recall the "what" (i.e., the content), "where" (i.e., the location), "when" (i.e., the time), and associated details of as many elements as they could remember. Following the completion of the recall task, a recognition test was administered. The participants were required to select the item they had observed in the town from a set of three distinct images. The examination consisted of a total of ten inquiries pertaining to the various elements and their respective positions within the municipality.
There was a significant correlation observed between the accurate recalls and recognitions on the verbal episodic memory test and the temporal aspect of the recall. Nevertheless, the scores obtained in the virtual town were found to have no significant correlation with the scores obtained in the verbal test, which in turn exhibited no significant correlation with any of the scores obtained in the neuropsychological tests.
Furthermore, there was a significant negative correlation between the TMT-A test score and the score on what task, the visuospatial where task, and the recognition task. In contrast, there was no observed correlation between it and the score obtained on the verbal episodic memory test. There exists a correlation between the scores obtained on the tests assessing verbal episodic memory and visual recognition and the performance on the TMT-B-A. The results indicate a significant correlation

between the score obtained on the Cognitive Difficulties Scale (CDS) and the ability to correctly bind and recognize information related to the town.

(Gottlieb et al., 2022) developed and validated a virtual reality-based Rey Auditory Verbal Learning Test (VR-RAVLT): VR-RAVLT immerses the participant within a simulated office environment, wherein a virtual personal assistant (represented as an avatar) is positioned behind a desk. The avatar provides the participant with a compilation of 15 locations that they are required to visit within a single day and subsequently challenges them to recall as many of these locations as they can. The avatar notifies the participant of her impending early departure and states her intention to reiterate the list in order to enhance the participant's recall of all the locations, employing a procedure akin to that used in the standard RAVLT. List B comprises a total of fifteen locations that the participant is required to visit on the following day. The research assistant documents participant responses using a format akin to that employed in the GS-RAVLT. Significant statistical correlations were observed between the standard RAVLT and the VR-RAVLT for two out of the three outcome measures. Specifically, the measures of ACQUISITION and RETENTION were found to be correlated with the scores obtained from the Montreal Cognitive Assessment (MOCA), digit symbol test, and verbal fluency assessment. The correlation between digit span and VR-RAVLT acquisition was observed. There was no observed correlation between retroactive interference and any neuropsychological measures. See Table 2 for the description of the virtual reality memory tasks.

5.2. Virtual reality assessment tools for prospective memory

Regarding Prospective Memory, two virtual tools have been developed: the Virtual Reality Prospective Memory Shopping Task (VRPMST) (Hogan et al., 2023), and a ride in a virtual car (Lecouvey et al., 2019).

Prospective memory refers to the cognitive ability to remember and successfully execute intended actions or tasks at a future point in time. According to Einstein and McDaniel (Einstein & McDaniel, 1990), the ability to remember and execute a planned action at a predetermined future time is facilitated by the process known as prospective memory, which can be performed alongside an ongoing task. The process of retrieving an intention involves two components: the prospective component, which involves recalling at the appropriate time that a task needs to be completed, and the component of remembering the specific details of what needs to be done (Einstein & McDaniel, 1990). The differentiation between time-based (TB) and event-based (EB) intentions is commonly made based on the characteristics of the stimulus that initiates the retrieval process. Within this particular framework, the activation of TB intention retrieval is prompted by either a predetermined time, such as 1:30 pm, or the conclusion of a specific interval, such as 30 minutes. Given the absence of any external cues, it is recommended that the recollection of TB intentions be contingent upon self-generated mechanisms for time monitoring. The recall of TB intentions is commonly perceived to be more difficult compared to EB intentions due to the reliance on self-initiated controlled processes for monitoring the passage of time (D'Ydewalle et al., 2001). Undoubtedly, the act of monitoring time while simultaneously engaging in concurrent activities necessitates substantial cognitive resources, encompassing executive functions, attentional resources, and time estimation capabilities. In the context of event-based intentions, the activation of an intention is prompted by the presence of an external event, also known as a prospective cue, within the individual's environment. An example of this would be the intention to purchase a book of stamps when one encounters a post office while passing by. It has been proposed that the retrieval of episodic memory intentions primarily depends on automatic cognitive processes.

VR procedures are well-suited to address the demand for ecologically valid instruments in the functional assessment of memory impairments. While conducting behavioral experiments in real-world settings can yield valuable data, it is often impractical to test patients outside of clinical settings. In such cases, computer-based VR tasks can serve as an intermediary between traditional neuropsychological tests and behavioral observation. One notable advantage of VR assessments is their capacity to replicate the challenges encountered in real-life situations, where individuals often need to remember and initiate responses to multiple tasks simultaneously, a phenomenon commonly referred to as multitasking. Moreover, in the context of daily life, it is common for there to be a lack of an external entity (comparable to the tester) that prompts the desired reaction. As a result, it is imperative for patients to possess the ability to independently identify significant events or cues in their surroundings and respond appropriately. This represents a crucial component of prospective memory tasks. In order to replicate this phenomenon, computers can be employed to create an interactive setting that offers prompts and cues for action, which are administered autonomously, without the involvement of a human tester.

An additional significant factor pertaining to memory in real-life situations is that individuals seldom establish intentions or comply with instructions that they do not reasonably anticipate recalling. In the context of daily life, there exists a process of self-monitoring during the encoding of intentions, which entails a precise recognition of one's own memory capacity (Wise et al., 2009). The primary objective of administering prospective memory (PM) tests to patients, from the perspective of a neuropsychologist, is to ascertain whether they possess a typical ability to recall a basic set of future intentions, and if not, to identify the extent of their cognitive limitations. Additionally, it is frequently advantageous to assess whether there exists any incongruity between patients' anticipated ability to recall information and their actual cognitive performance (Knight et al., 2009). Virtual environment (VE)-based tests are often valuable in this context, as they allow individuals with disabilities to safely and non-threateningly assess the boundaries of their abilities. A notable disparity between anticipated and realized performance may indicate a deficiency in understanding, which can influence the establishment of objectives for rehabilitation and the patient's inclination to engage in retraining.

There are only two tests that provide convergent validity of the VR tools and neuropsychological measures.

The Virtual Reality Prospective Memory Shopping Task (VRPMST) (Hogan et al., 2023) involves the completion of a task consisting of 12 errands within a virtual shopping center. Participants navigate through the virtual environment and enter stores in a predetermined sequence. The tasks have been designed to replicate the routine activities typically carried out within a shopping center setting. In the context of time-based project management, individuals are informed by their healthcare provider to monitor their heart rate. Consequently, they are required to assess their heart rate at regular intervals of 3 minutes by pressing the designated key (H) on the iPad. Participants have the ability to verify the elapsed time on their virtual watch for a brief duration of three seconds by engaging the TIME button on the iPad. The Virtual Reality Project Management System Tool (VRPMST) encompasses two distinct categories of event-driven project management tasks. Initially, participants are informed that they will be monitoring their food expenses. Consequently, upon the acquisition of food items, specifically four items, it is necessary for individuals to obtain a receipt. Furthermore, the participants are provided with information regarding the loss of their glasses during their previous

shopping excursion. Consequently, it is necessary for them to inquire with the security personnel at the center on each occasion (a total of four times) regarding the potential retrieval of their glasses.
Researchers found a significant and strong correlation between the scores of time- and event-based Virtual Reality Prospective Memory Screening Task (VRPMST) and the scores of time- and event-based Prospective Memory (PM) on the Comprehensive Assessment of Prospective Memory (CAMPROMPT), which is a widely used measure of PM, for the sample of stroke patients. The study revealed noteworthy and robust associations between time-based prospective memory tasks in VRPMST and event- and time-based prospective memory tasks in laboratory-based dual-task paradigms (LDPMT). Furthermore, there was a notable and robust correlation between event-based prospective memory (PM) on the VRPMST and the Trail Making Test (TMT), as well as the scores obtained from both the Hopkins Verbal Learning Test-Revised (HVLT-R) and the Montreal Cognitive Assessment (MoCA). Similarly, time-based PM exhibited a significant and strong correlation with the TMT, HVLT-R total recall score, and the MoCA.
In the study of (Lecouvey et al., 2019), following a period of familiarization, the participants were notified that they would be immersed in a virtual city with the objective of retrieving a companion from the train station, located at the conclusion of said city. Additionally, they were tasked with fulfilling various intentions throughout their journey. The participants were presented with a set of seven intentions displayed on a laptop computer. In 50% of the cases, a significant association was observed between the anticipated cue and the subsequent retrospective component (referred to as Link-EB). Examples of Link-EB scenarios include purchasing a stamp booklet at the post-office. Conversely, in the remaining 50% of cases, a weak association was found between the anticipated cue and the retrospective component (referred to as NoLink-EB). An example of a NoLink-EB scenario is buying a pair of glasses at the fountain. The persistent intention involved the regular administration of medication for tuberculosis, with a frequency of once every two minutes. Subsequently, to verify the accuracy of the encoding process, a cued recall assessment was conducted subsequent to the presentation of the intentions. A 10-minute interval was observed between the encoding and retrieval of intentions, during which participants completed questionnaires. The individuals were reminded of their obligation to collect a companion from the train station and accomplish various objectives during their journey. In order to accomplish this, participants were required to bring the vehicle to a halt at the designated moment or location (referred to as the prospective component) and subsequently inform the experimenter of the specific action they were instructed to execute (known as the retrospective component). See Table 2 for the description of the virtual reality memory tasks.

5.3. Virtual reality assessment tools for spatial memory

Traditionally, researchers have conducted studies on visuospatial cognition in humans using paper-and-pencil tasks, such as the Mental Rotations test (Vandenberg & Kuse, 1978) and the Object Location Memory test (Eals & Silverman, 1994). Additionally, real-world tasks have been employed to investigate how individuals utilize environmental cues to acquire knowledge about spatial layouts (Hegarty et al., 2006; D. M. Kelly & Gibson, 2007; Marchette et al., 2017; Vandenberg & Kuse, 1978). The utilization of two-dimensional paper- and-pencil spatial location tasks has significantly contributed to the advancement of our comprehension of spatial cognition. Nevertheless, the spatial cues utilized in these tasks differ significantly in terms of quantity and quality compared to those present in real-world navigation. As a result, it is highly probable that the cognitive load and processing involved in these tasks will also vary (Hegarty et al., 2006). The water maze, which was introduced by Richard Morris in the 1980s (R. Morris, 1984), has emerged as a widely employed method for assessing spatial learning in rodents, encompassing both typical and genetically altered mice. The water maze has gained significant popularity as a result of its comprehensive validation as an assessment tool for learning and memory that relies on the hippocampus. The impairment of water maze learning can be observed when the hippocampus is lesioned or inactivated, as demonstrated in several studies (Logue et al., 1997; R. Morris, 1984; Moser et al., 1993; Riedel et al., 1999; Teixeira et al., 2006). Furthermore, studies have shown that genetic or pharmacological interventions that interfere with activity-dependent plasticity in the hippocampus have been found to impede water maze learning (Silva et al., 1992; Tsien et al., 1996). Moreover, it has been observed that mouse models used to study human diseases characterized by hippocampal dysfunction demonstrate deficiencies in their ability to learn in water maze tasks (Chapman et al., 1999; Chen et al., 2000). It is important to note that each of these significant findings has been consistently reproduced in various laboratories and across different species.

The water maze task involves a training period that usually spans multiple days. This training is conducted in a circular tank of considerable size, which is filled with water that is not transparent. During each training trial, a mouse is provided with the chance to navigate towards a submerged platform beneath the surface of the water. Since the platform is not visible, the mouse must rely on a variety of distal, visual cues present in the surroundings of the pool in order to locate it. As the training program advances, there is a tendency for the latency to locate the platform to decrease. The observed decrease in escape latencies is indicative of the implementation of a focal search strategy, characterized by a concentrated search around the previous location of the platform with minimal variation. Nonetheless, it is important to note that decreased escape latencies could also indicate the utilization of non-spatial tactics, such as mice acquiring the ability to swim in concentric circles at a consistent distance from the wall (Clapcote & Roder, 2004; Gallagher et al., 2015; Lipp & Wolfer, 1998). Hence, in order to differentiate between spatial and non-spatial strategies, mice are commonly subjected to a probe test. During this test, the platform is removed from the pool, and the mouse is permitted to search for it within a designated time frame, typically lasting 60 seconds. Mice that have adopted a spatial strategy exhibit a tendency to concentrate their search efforts in close proximity to the previous location of the platform.

The Morris water task has been utilized in real-world settings with human participants, as demonstrated by Bohbot et al. (2002), as well as in virtual environments. Studies conducted over the past 15 years (e.g., (Astur et al., 1998; D. A. Hamilton & Sutherland, 1999; Jacobs et al., 1998; Moffat et al., 1998; Sandstrom et al., 1998) have focused on the use of virtual reality simulations in humans, primarily emphasizing the visual aspect. In the context of the water maze task, participants are tasked with locating a concealed platform, referred to as the hidden target, amidst a collection of surrounding landmarks.

Moreover, conventional investigations on real-world navigation necessitate individuals to acquire knowledge of a specific path within an enclosed space, a structure, or an open environment such as a college campus or a commercial complex (Bell & Saucier, 2004; Foreman et al., 2005). While real-world navigation tasks provide a more ecologically valid means of assessing spatial ability compared to traditional paper-and-pencil tasks, it is important to acknowledge the limitations associated with such paradigms. The tasks under consideration suffer from a lack of precise control due to their extensive spatial scope, which hinders the investigation of various aspects of spatial ability such as eye-tracking, behavioral responses, and attention assessment. The process of designing experimental scenarios is frequently associated with significant costs, such as the construction of specialized scenarios, as well as potential risks and hazards (Vasser et al., 2017). Modifying or removing significant global cues presents a formidable challenge, if not an insurmountable one. In practical circumstances, it is unfeasible to exercise complete control or manage every variable. For instance, the presence of distracting factors such as ambient wind noise, tree (Vasser et al., 2017)motion, and bird flight cannot be effectively regulated. Simultaneously, adverse weather conditions pose a significant drawback in outdoor experimental designs, particularly when these designs span multiple consecutive days. Furthermore, in order to ensure consistent exposure of participants to the experimental conditions, it is necessary to replicate the environment for each participant across various times of day and climates. However, this task becomes unfeasible in a natural setting where the landscape undergoes continuous changes, including variations in sunlight, climate, and the presence of flora and fauna. Nevertheless, the aforementioned inconveniences can be effectively circumvented through the utilization of VR technology (Brookes et al., 2020; Ouellet et al., 2018; Starrett et al., 2020).

Navigation refers to the process of locating and sustaining a course of travel within a known or unknown setting (N. Burgess et al., 2002). One of the primary cognitive functions that experiences the most significant decline as individuals age is discussed in the literature (Lester et al., 2017). Previous research has indicated that the process of navigation can be negatively affected by the aging process (Moffat, 2009). In contrast to young adults, older adults exhibit a higher propensity for committing errors and experiencing longer durations when engaging in navigation tasks (Zhong & Moffat, 2016). Numerous studies have yielded findings indicating the existence of two primary navigation strategies, namely the egocentric strategy and the allocentric strategy (Bohbot et al., 2012; Bullens et al., 2010; Iglói et al., 2009a). The allocentric strategy is predicated upon a representation that is centered on the world, while the egocentric strategy is founded upon a representation that is centered on the self, specifically the body, involving a sequence of left and right turns (Iglói et al., 2009b; Migo et al., 2015). The allocentric strategy is primarily rooted in a cognitive representation that resembles a map, allowing navigators to effectively navigate detours or reach a desired destination from various initial points (Sanders et al., 2008; Spiers & Maguire, 2008). On the other hand, the egocentric strategy relies on the establishment of associations between stimuli and responses, specifically involving idiothetic information such as body turns and vestibular sense. This strategy enables individuals to navigate through a predetermined path (Iglói et al., 2009b; Migo et al., 2015). This particular approach allows individuals to effectively traverse from a predetermined starting point to a predetermined endpoint using the identical pathway (Sanders et al., 2008). In addition to the aforementioned two strategies, the guidance strategy was also found to play a role in human navigation. This approach necessitates that the navigators retain in memory a prominent landmark in proximity to the intended destination. In order to determine the intended location, navigators employ a strategy of continuously progressing towards a prominent point of reference, rather than relying on a mental representation resembling a map or a sequence of bodily rotations (Bullens et al., 2010; Collett, 1992). The implementation of a guidance strategy results in minimal cognitive load. On the other hand, the allo-centric strategy necessitates the navigator's recollection of spatial connections among landmarks and the construction of a cognitive map, resulting in a greater cognitive burden. The utilization of a spatial memory task that incorporates both egocentric and allocentric strategies has the potential to serve as a valuable tool for identifying cognitive decline in the aging population. Previous research has demonstrated a selective relationship between visuo-spatial memory and real-world navigation through the use of various 2-dimensional visuoconstructive tasks (Peter et al., 2018). While there is a correlation between visuo-spatial working memory and navigation performance in both young and older adults, it has been observed that visuo-spatial working memory performance tends to decline with age (Perrochon et al., 2018). Hence, it can be inferred that visuo-spatial ability potentially enhances the utilization of strategies and the overall navigation performance among older individuals. While there is a general consensus that effective navigation requires the utilization of both egocentric and non-egocentric strategies (N. Burgess, 2006), it is important to note that these strategies have distinct neurobiological foundations. The non-egocentric strategy primarily relies on the hippocampus and the retrosplenial cortex, whereas the egocentric strategy is primarily dependent on the caudate nucleus, medial parietal lobe, and posterior parietal area. The hippocampus and retrosplenial cortex undergo a rapid deterioration in both structure and function as individuals age (Moffat, 2009; Morganti et al., 2013; M.-C. Pai & Yang, 2013). This decline ultimately results in a greater impairment in non-egocentric navigational abilities. The challenges associated with constructing and storing spatial information have led researchers to investigate non-egocentric navigation deficit as a potential biomarker for early Alzheimer's disease diagnosis (Bellassen et al., 2012; Serino et al., 2014). The investigation of age-related declines in egocentric and non-egocentric navigation, which are less influenced by verbal, cultural, and educational biases, may offer valuable insights into the cognitive markers of Alzheimer's disease (AD) and measures of cognitive intervention outcomes. Recent research has indicated that the effectiveness of navigation is primarily dependent on the ability to adaptively select the most suitable strategy based on the specific requirements of the task, rather than relying on a single predetermined strategy (Bohbot et al., 2007; Colombo et al., 2017). Hence, while certain evidence indicates that the egocentric strategy remains intact in older individuals, their navigation abilities are still compromised if they do not select the suitable strategy.

Due to the inherent complexities, high costs, and challenges in controlling real-world studies, researchers are increasingly turning to virtual environments as a viable method for investigating navigation (Garcia-Betances et al., 2015; Wolbers & Hegarty, 2010). Prior research has indicated that individuals with navigational abilities have the capacity to develop two distinct spatial representations through the passive observation of basic optic flow (M. A. Harris & Wolbers, 2012). In contrast, the non-immersive virtual environment has the capacity to offer a greater abundance of environmental details and effectively simulate the real world. A prior investigation documented a robust association between virtual environments and actual navigation abilities (Duffy et al., 2008), suggesting the suitability of virtual environments for conducting navigation research. Furthermore, non-immersive virtual environments have the potential to be utilized in the diagnosis of spatial navigation disorders (Cogne et al., 2017). In contrast, the paper-pencil tests exhibited only a partial correlation with the real space tests (Hegarty et al., 2006). In contemporary times, the utilization of the non-immersive virtual environment method, which incorporates intricately crafted scenes, has gained significant popularity in navigation-related activities. Notable examples include the Morris Water maze (Driscoll et al., 2005), the Eight-Arm maze (Bohbot et al., 2007; Iaria et al., 2003; Konishi et al., 2016), and the star maze (Iglói et al., 2009b, 2015). Nevertheless, it is important to acknowledge that a virtual environment navigation paradigm may excel in differentiating navigation strategies but may lack effectiveness in assessing navigation performance, such as navigational speed and distance traveled, or vice versa (M. A. Harris & Wolbers, 2012; Konishi et al., 2016). The virtual star maze presents a potential compromise for assessing both navigation performance and navigation strategy, as discussed in reference (Fouquet et al., 2010). The virtual star maze task involves participants freely navigating within a virtual environment shaped like a pentagram. The objective of trhe task remains constant, which is to locate a predetermined destination.

Among all the studies investigating spatial memory in VR, only 9 of these compare the performance of older adults with classical neuropsychological tests:

In Tippet et al., 2009, two distinct routes, labeled as Path A and Path B, were selected, each having predetermined starting and ending points. The VE task comprised three learning trials for Path A, followed by a single learning trial for Path B. In each trial, the participant initially observed the relevant path through the city in a passive manner. The participants were provided with instructions to direct their attention towards the spatial positioning of different landmarks within the city, as well as their relative positions in relation to one another. Following the comprehensive observation of the path, participants were subsequently instructed to return to the initial position and tasked with reproducing the path to the best of their capacities. Path B was utilized as an interference condition and implemented through the utilization of a distinct path design within the identical urban setting, with the intention of mitigating the influence of perceptual priming effects. Subsequent to these experimental trials, participants engaged in recall trials with short-delay (5 min) and long-delay (20 min) intervals. During these trials, participants relied solely on their memory to navigate Path A, without any passive viewing component. The VE navigation index showed significant correlation with executive functions (measured by the Trail Making Test). The VE movement and memory indices did not show statistically significant correlations. The VE movement index also was significantly correlated with the Trail Making Test measures (A, A error, B error), whereas the VE memory index was correlated with measures of the Rey immediate recall and delayed recall.

In Zhan et al., the objective of the virtual environment task was to identify and sustain a fixed position that would remain consistent throughout the subsequent nine learning trials. It is imperative that participants consistently arrive at the same destination throughout the entirety of the study. The location in question is not readily apparent, and participants must rely on instructions and tasks to locate it while navigating the entirety of the virtual environment in subsequent trials. If participants were unable to reach the designated destination within a time frame of 90 seconds, the trial was promptly terminated, and the subsequent trial commenced. During the acquisition phase, participants had the option to navigate to the target location by relying on their memory of the sequential body turns at each Y-shaped intersection, also known as the egocentric strategy, or by employing alternative strategies. In order to assess the navigational proficiency of each participant, several metrics were computed for the 9 learning trials. These metrics included speed, distance error, rotation, percentage of successful individuals, and percentage of successful trials. During the probe trial, the maze structure remained consistent with that of the learning phase, albeit lacking any prominent landmarks. Specifically, all distal cues were intentionally removed. Results showed a positive correlation between the block-design score of the Wechsler Adult Intelligence Scale (WAIS) and both navigation speed and the percentage of successful learning trails. However, no significant correlations were found between the block-design score and any other variables.

Morganti et al., 2013 developed two spatial assessment tasks in which no distinctive landmarks were provided as navigational aids, and all buildings exhibited the same texture. In the VR-Maze spatial task (VR-MT), Participants were positioned in front of the computer screen and were given one of

the paper-and-pencil versions of five distinct complex mazes (referred to as PP-MT). To evaluate allocentric spatial knowledge in the PP-MT, participants are instructed to depict the trajectory from the initial point to the exit while attempting to identify the optimal route connecting these two points. Following the completion of each Point-to-Point Mapping Task (PP-MT), participants were instructed to utilize the PP-MT method to determine the location of the exit point within the corresponding Virtual Reality Mapping Task (VR-MT). This was done to evaluate the transfer of spatial knowledge from an allocentric to an egocentric frame of reference. In order to initiate the investigation of VR-MT, the participants were provided with clear indications regarding the correspondence between the initial positions on the physical paper and the corresponding virtual representation of each maze. The successful completion of a maze was determined by the ability of the participant to reach the exit point within the designated time limit of 10 minutes.
In the VR-Road Map task (VR-RMT), The participants were positioned in front of the computer screen, with the physical copy of the Money's Road Map Test (PP-RMT) positioned at the bottom of the screen. The PP-RMT comprises a stylized urban map wherein individuals are required to indicate, through a series of 32 dotted steps, the direction (left or right) taken at each turn in order to successfully navigate a predetermined route. The solutions necessitate the utilization of an egocentric mental rotation strategy, as the dotted pathway exhibits a non-linear trajectory that extends both away from and towards the individual in question. It is important to note that the individual is prohibited from manipulating the map or engaging in any physical movements of the head or body in order to arrive at the correct response. Subsequently, the participants were instructed to utilize the PP-RMT in order to navigate the VR-RMT by adhering to the prescribed path denoted by the dotted line on the PP-RMT. The primary aim of this task is to assess whether the process of converting spatial knowledge from an allocentric to an egocentric frame of reference, which is necessary for navigating a simulated virtual reality environment, differs from the process required for mentally simulating the same environment using a sketched map. In the initial form of simulation, known as VR-RMT, participants possess an egocentric viewpoint of the environment and are actively capable of navigating within it. In the second category of simulation, known as PP-RMT, participants adopt an allocentric viewpoint of the environment, necessitating a cognitive effort to convert mental imagery into potential actions. It is posited that the ability to engage in wayfinding, rather than simply envisioning the process, necessitates a distinct ego-to-allocentric translation. This particular translation is deemed essential for further exploration as the primary determinant in the early detection of Alzheimer's disease. The results of the VR-MT demonstrated a significant correlation with various cognitive assessments, including the Mini Mental State Examination, Corsi's span, Corsi's supra-span, Manikin Test, and Trial Making Test. The results of the VR-RMT exhibited a significant correlation with both the Mini Mental State Examination (MMSE) and Corsi's supra-span task.
In Cushman et al., 2008, the researchers devised a total of eight tasks. During the route learning task, participants were presented with the route on the computer screen. During the second presentation, the video playback was halted at the ten decision points. During the Free recall phase, following the completion of the test trip along the designated route, participants were allotted a duration of 1 minute to verbally identify and recollect as many objects or landmarks as they could remember. During the Self-orientation phase, participants were presented with a series of 10 images depicting various objects or locations along the test route. These images were carefully selected and divided into two sets of five, with each set being presented sequentially. The locations were strategically positioned at

45° intervals in relation to the subject's position, with the subject facing an outside wall. During the process of Route drawing, participants employed a computer mouse to designate the precise location of the subsequent decision point while observing a scaled representation of the lobby on the video display. During the recall phase of the Landmark experiment, participants were instructed to identify exclusively those objects or fixtures that facilitated navigation during their self-guided second traversal of the lobby. In the task of photograph recognition, a total of ten photographs were individually displayed on the screen. Specifically, five photographs were selected from the test route, while the remaining five were chosen from various locations within the Medical Center. The subjects discerned the origin of each photograph, determining whether it belonged to the test route or not. During the Photograph location task, participants were presented with an additional set of 10 photographs taken from the test route. They were provided with a scale outline of the lobby, which included 10 marked locations represented by letters. Participants were required to indicate the corresponding location on the outline for each scene, and their performance was measured based on the number of correct responses. In the previous task, the video location task, a series of ten brief video clips, captured from the perspective of the subject while navigating the test route, were shown three times consecutively. Following the conclusion of each visual presentation, participants proceeded to mark an X on an empty map to indicate the starting point of the clip. Additionally, they drew an arrow originating from the X to illustrate the direction and magnitude of the portrayed movement. Correctness of responses was determined based on the accurate placement of X in the appropriate location and the correct indication of direction by the arrow. Statistical analysis examined the hypothesis that virtual navigational testing could serve as a reliable predictor of real-world navigational performance. Additionally, the researchers incorporated the outcomes of eight standard neuropsychological tests to assess the collective predictive ability of these measures. The process of stepwise multiple linear regression was employed to identify the most effective predictors of real-world navigation testing. The virtual navigation and delayed verbal memory scores were found to be the two most significant predictors, resulting in an adjusted r2 value of 0.82. The incorporation of MMS (Multiple Mini-Steps) and the assessment of line orientation scores significantly improved the regression model, resulting in an adjusted r2 value of 0.84. Hence, it appears that real-world testing may encompass the impact of factors that are effectively elucidated by virtual testing, as well as factors that are effectively elucidated by delayed verbal memory testing. In Serino et al., 2015, a simulated room was established as a controlled setting for experimentation. The setup consisted of two distinct entities, specifically a botanical specimen and a mineral specimen, accompanied by a visual representation in the form of an arrow inscribed on the ground. This arrow, oriented towards the North, served as a symbolic indication denoting the commencement of the navigational process. The participants were provided with instructions to commit to memory the varying positions of the plant, which were presented in three separate trials. Two distinct tasks were formulated for the retrieval phase. During the initial task, participants were instructed to identify the location of the object on an authentic map. Specifically, they were required to recall spatial allocentric information that was independent of their own point of view. During the second task, participants were instructed to access an unoccupied iteration of the identical virtual environment. The participants were required to indicate the location of the plant relative to the position of another object, specifically, a retrieval task without any spatial allocentric information. A set of linear multiple regression analyses was conducted to examine the relationship between the accuracy of spatial location in both tasks across multiple trials. The dependent variable was the accuracy of spatial location, while the independent variables included general cognitive functioning (as measured by the MMSE) and various cognitive tests (such as the traditional Money Road Map, Corsi Block Test - Span, Corsi Block Test - Supraspan, Manikin's Test, and The Judgment of Line Orientation). Regarding the findings of the second task, it was observed that the utilization of multiple neuropsychological tests collectively predicted a decline in the capacity to recall the location of the object without relying on allocentric spatial information, specifically during Trial 2. The results of the study indicate that there are two main factors that significantly predict performance in the third trial of Task 2. These factors are the scores obtained on the Money Road Map and the scores obtained on the Manikin's Test. These two assessments assess distinct cognitive abilities: spatial navigation and mental rotation. Spatial navigation involves accurately determining the location of an object within a large environment, while mental rotation is crucial in Trial 3 as it necessitates a 180-degree spatial rotation for object memorization.

Rekers & Finke 2023 tested the feasibility of VIENNA, which comprises of a single instruction trial, followed by two practice trials, and finally, 12 main trials. The trials conducted exhibit a visual representation from the viewpoint of a protagonist engaging in the exploration of virtual hallway environments. Furthermore, a representation of the environment is presented in the form of an allocentric map during every trial. Participants are instructed to engage in mental tracing of the character's position and subsequently indicate the door that the character selected at the conclusion of the trial. Significantly, the design of this task does not depend on episodic memory and does not necessitate active exploration or navigation by the participant. As a result, the information available to solve the task is made uniform across all participants. The performance in VIENNA demonstrated a significant correlation with the results of the following tests: The results indicate significant associations between the variables under investigation. Specifically, there are strong positive correlations observed between the Mini-Mental State Examination score and visuospatial working memory, perspective taking, and visuoconstructive productivity. Additionally, a moderate to strong positive correlation is found between mental rotation and the variable of interest. Furthermore, moderate positive correlations are observed between visuoconstruction and visuospatial short-term memory. Lastly, a small to moderate positive correlation is observed between the executive function strategy application and the variable being examined. The city of Vienna did not exhibit a statistically significant correlation with episodic memory, as measured by the percentage of recalled elements in the delayed free recall of the Rey-Osterrieth Complex Figure Test. Additionally, there was no significant correlation observed between Vienna and cognitive flexibility, attention in terms of processing speed, or selective attention.

After controlling for the age of the participants, all correlations that were previously found to be significant remained significant, except for the correlation with strategy application. Additionally, the effect sizes for the correlations with working memory, productivity, and mental rotation showed a significant decrease. After adjusting for average performance in neuropsychological tests, it was found that only the correlations with MMSE, perspective taking, and visuoconstructive productivity remained statistically significant and exhibited moderate effect sizes. There was a significant correlation observed between perspective rotation errors and performance on the Perspective Taking Test, while no significant correlation was found between perspective rotation errors and performance on the mental rotation task.

Da Costa et al., 2022 developed two tasks: the SOIVET Maze Task and the SOIVET Route Task. In the first one, participants were instructed to navigate through a virtual maze by following the route indicated on the original MRMT map as a point of reference. To minimize cognitive load, a green indicator was placed on the map to denote the most recent accurate change in direction. The absence of any topographical landmarks was observed. In order to navigate from a first-person perspective, participants were instructed to adhere to the prescribed route illustrated on the map. Additionally, they were tasked with continuously updating their spatial awareness by incorporating information derived from their bodily position at each juncture within the maze. In the second one, SOIVET Route Task, participants proceeded to access the virtual reconstruction of the lobby area within the Central Institute of the University of São Paulo Clinics Hospital. A virtual representation, known as an avatar, executed a predetermined sequence of five distinct locations within the hospital lobby and its immediate vicinity. The participants were instructed to adopt a first-person perspective and track the movements of the avatar. Following that, the participants were instructed to independently traverse the identical route and sequentially visit the five designated locations in the prescribed order, known as the SOIVET Route immediate. Following a 20-minute intermission, the participants proceeded to replicate the route once more, with a delay in the SOIVET Route. The findings of the SOIVET Maze task demonstrated a noteworthy association with the MRMT, Tower of London, BJLO test, and overall ACE-R score. There was no statistically significant correlation observed between the scores obtained from the SOIVET Maze and the Corsi Block Test, both in the forward and backward conditions. Furthermore, there was a significant correlation observed between the ACE-R memory and ACE-R visuo-spatial scores and the performance on the SOIVET Maze task. The immediate SOIVET Route was found to have a significant correlation with both the MRMT and the ACE-R total score. Furthermore, there was a significant correlation observed between the memory and visuospatial categories derived from the ACE-R assessment and the immediate scores obtained from the SOIVET Route task. The delayed scores of the SOIVET Route did not exhibit a significant correlation with any of the administered neuropsychological tests, nor with the total score of the ACE-R assessment and its respective categories.

Mohammadi et al., 2018 developed the Virtual reality navigation task (VRNT) with two environments, namely the virtual neighborhood and virtual maze, which consisted of a three-dimensional first-person perspective as well as a two-dimensional overhead perspective of the surroundings. Initially, the participants were presented with a two-dimensional aerial perspective for a duration of 60 seconds, followed by the subsequent presentation of a three-dimensional first-person viewpoint. The participants were subsequently directed to locate the designated objective (e.g., parking in the simulated neighborhood; the ball in the virtual maze), which had been indicated on the two-dimensional aerial perspective. Each participant was given three practice trials to become acquainted with the task, followed by five assessment trials. The findings indicated a robust and significant positive association between neuropsychological performance and virtual neighborhood ratings across all participant groups. A robust inverse relationship was observed between neuropsychological scores, specifically the total scores, immediate recall, and delayed recall of the RAVLT, as well as the immediate and delayed recall of the R-OCFT, and the average response time for the virtual neighborhood task.

Lee et al., 2022 developed the virtual radial arm maze (VRAM) in which participants were informed that they were situated within a simulated environment featuring a central region from which six appendages emanated. The virtual room was equipped with a variety of objects of different colors and visual cues that served to indicate the relative directions. It is worth noting that the room remained unaltered throughout each trial. Despite being given instructions to locate the three treasures in a timely manner, no specific time constraint was enforced. Upon the successful acquisition of all three treasures, the trial concluded, prompting the participants to reconvene at the central location of the maze in preparation for the subsequent trial. A total of five trials were carried out, with each trial being separated by an intertrial interval of 10 seconds. All participants were presented with the identical arrangement of rewarded arms. The assessment quantified working memory errors through the frequency of a subject's reentry into the same arm, while reference memory errors were quantified by the frequency of a subject's reentry into arms that did not contain any rewards. The distance covered and the duration of time taken to locate all rewards in each trial were also documented. There were notable linear correlations observed between the quantities of working and reference memory errors on the VRAM, as well as with scores on all neuropsychological tests, with the exception of the Spatial Span Forward. See Table 2 for the description of the virtual reality memory tasks.

Table 2. Description of the virtual reality memory tasks

Reference	**Memory**	**Virtual memory task**	**Hardware**	**Virtual environment**
Arvind et al., 2014	**Episodic memory**	HOMES TEST: Each participant visualized two versions (versions A and B) of a virtual apartment consisting of 40 objects: 20 objects that were specific to each version and 20 objects common to both versions. There were four categories [a bedroom, bathroom, kitchen, therefore, each category contained 10 of these objects, five specific and five common to both versions. Participants first watched a target version of the apartment (called version A) which was presented twice, and each participant had a free recall task immediately after each presentation. Immediately after the last recall task, participants visualized the other version of the apartment (version B) followed by only one immediate free recall task. After 10 minutes, a final yes/no recognition task was then administered to all participants.	The virtual environment was viewed using an F1+ overhead video projector on a 2x1.88 m large screen fixed onto the wall. Participants sat 2 m away from the display screen in a dark, silent room to visualize the VE projected in front of them.	Virtual apartment (a bedroom, bathroom, kitchen and sitting room)
Sauzéon et al., 2016	**Episodic memory**	HOMES TEST: **learning phase:** participants first watched a target version of the apartment (version A). The target version was presented twice (trial 1 and 2) and each participant was asked to complete a free-recall task immediately after each presentation. Immediately after the second trial, participants visualized the other version of the apartment (version B) followed by only one immediate free-recall task. **Recognition phase:** After 10 minutes delay, a verbal yes/no recognition task was administered to participants as a final retrieval phase.	The virtual environment was viewed using a F1+ overhead video projector on a 2x1.88 m large screen fixed onto the wall. Participants sat 2 m away from the display screen in a dark, silent room to visualize the VE projected in front of them.	Virtual apartment (a bedroom, bathroom, kitchen and sitting room)
Corriveau Lecavalier et al., 2018	**Episodic memory**	Virtual Shop (La boutique virtuelle): Participants began the task in front of a cashier working behind a countertop and were presented with a list of 12 familiar virtual images of common items (e.g., belt, milk) that they were asked to memorize and then fetch in the store. During encoding, irrelevant conversations were presented via the headgear in order to mimic a noisy environment. Following the presentation of the last item, the program initiated a 20-s conversation between the cashier and the participant (e.g., Could you tell me the time, which is displayed on your right?) as a filled interference delay. At the end of the delay period, the cashier instructed the participant to fetch the items in the store he/she had previously seen. The participant could then walk freely in the room to find and select the items that were shown on the learning list. There were 24 items displayed in the shop: 12 target items and 12 distractors.	The virtual environment was in 3D and the immersion was produced by an Nvisor ST50 audio-visual headgear and by a Worldviz PPT-X studio tracking system that allowed the participant to rotate his/ her head in a 360-degree view around the room, as well as look up and down, and interact and walk freely in the virtual environment. Participants used a hand remote control to select and retrieve items.	Virtual Shop (La boutique virtuelle)

Ouellet et al., 2018	**Episodic memory**	The Virtual Shop: The participant was first positioned in front of the countertop, with the shop shelves behind him/her. The experimenter explained to the participant that s/he would be presented with a list of items to memorize and that s/he would later have to "buy" these same items. The experimenter explained that the cashier of the shop will ask two questions the participant will have to answer and will then be instructed to start shopping. The pictures of 12 items were then presented on the flipping pages of a notepad situated on the countertop When presentation was over, the cashier asked the participant a set of brief questions (e.g., "What is the weather like today?") during 20 s as a way to empty the content of the participant's working memory. The cashier then instructed the participant to walk into the store and fetch the objects that had been shown on the pad. The objects were located on shelves, inside refrigerators, hung on walls, or were placed on the floor. Twelve distractors that belonged to the same semantic category as the target items were placed in simi- lar locations. Ambient verbal noise – a conversation between two customers – was presented dichotically through the HMD during the whole task.	HMD	Virtual Shop (La boutique virtuelle)
Pieri et al., 2022	**Episodic memory**	**Encoding:** the clinician moves around in the room and presents the target objects closely to the camera for 5 s; in the meanwhile, the participants must name the object showed. **Free recall:** The tasks simply require the participant to remem- ber the 10 objects presented 10 min earlier in the Encoding Phase. **Recognition:** participants are asked to find and nominate all the ten objects previously showed in the encoding phase, located among other 17 non-target objects.	Oculus Go	Virtual medical office
Bruni et al., 2022	**Episodic memory**	OBRECO2: **Encoding.** Participants experience a household setting, such as a living room, in which they can with a first-person perspective which is the one of the experimenters. This one moves about the room highlighting the 15 target items for 3 s each and attaching a tag bearing the name "Marco" to each one. In the living room, there are also 15 other objects used as distractors. In this phase, participants are instructed to name all the targets. **Free recall.** After 15 minutes, hey are instructed to name as many objects from the encoding phase as they can. **Recognition.** Participants are instructed to explore the prior living room, discover and name the target objects among all of the previous things and an unknown set of 15 distractor objects.	Oculus Quest-2	Virtual living room
Kempe et al., 2015	**Episodic memory**	Supermarket test: participants had to perform two shopping tasks in counterbalanced order. In each, they saw a shopping list with 12 prod- ucts. Each item was presented for 3.5 s on a computer screen, followed by a black screen for 0.750 s. Following the presentation, participants were asked to walk through the supermarket and to collect all products they remembered into a shopping basket. They were instructed to pick the products in the order they walk by them, which was not necessarily the order they appeared on the list.	Computer	Virtual upermarket
Zygouris et al., 2014	**Episodic memory**	Virtual Supermarket (VSM) : The patient is asked to navigate inside the virtual supermarket and buy the items displayed on a shopping list, appearing on the upper right corner of the screen. Upon purchasing all items of the list, s/he is required to locate the cash desk and proceed to pay. The payment screen is then displayed. The user must select the precise amount needed to pay for the items bought, using a selection of Euro bills and coins.	Tablet	Virtual upermarket

Boz et al., 2019	**Episodic memory**	Virtual Supermarket: (VSM): A shopping list appears in the upper right corner of the screen during the VSM exercise. The person is expected to locate the items on this list, place them in the shopping cart, take them to the cashier desk and pay the correct amount for the purchases. The participant is asked to move the shopping cart and navigate inside the virtual supermarket by touching green footprints on the screen. It is an exercise designed for examining multiple cognitive domains such as visual and verbal memory, executive functions, attention, and spatial navigation.	Tablet	Virtual Supermarket (VSM)
Limoncu et al., 2021	**Episodic memory**	The Virtual Supermarket Test (VST): the participant is given a shopping list and is expected to place the items on this list in the shopping cart quickly and accurately and complete the shopping. Then, the user is expected to pay the correct amount for these products at the cashier desk. VST measures five variables: “Correct Items”, “Correct Quantities”, “Bought Unlisted”, “Correct Money”, and “Duration”.	Tablet	The Virtual Supermarket Test (VST)
Turner et al., 2021	**Episodic memory**	Virtual Reality Functional Capacity Assessment Tool (VRFCAT): First, participants explore a kitchen to see what items they have for the recipe. Then, they use a bus schedule to find a bus that will take them to a grocery store. They find and purchase the necessary items at the store and use the schedule once again to find the bus that will take them home. Across the 4 scenarios, there is total of 139 12 different tasks or “objectives".	Tablet	Virtual kitchen, bus, grocery store
Plancher et al., 2010	**Episodic memory**	In the car accident scene, two cars crashed into one another, a horn was honked, and black smoke appeared. Buildings connected each specific area to the next. People, garbage containers, barriers, trees, billboards, and motion- less cars constituted some other elements of the town. Each specific area is composed of certain of these other elements. For example, in front of the town hall, there is a woman walking, a billboard, barriers, and trees. Free-recall test. After driving in the town, all participants underwent the same episodic memory tests. We asked for the free recall of verbal components in writing: what, and where, when and details associated with the maximum of elements as possible. This test was limited to 5 minutes but in fact it was enough as no participant was stopped while still working. Recognition test. A recognition test was presented after the recall task. Participants had to choose which item they had seen in the town from among three different images. This test was com- posed of 10 questions concerning the elements and their locations in the town. Five questions were dedicated to the accident—for example, “Who did you see in front of the accident site?”—and five questions to other elements of the town, for example, “What color were the containers?”	The environment was run on a PC laptop computer and explored with a virtual car using a real steering wheel, a gas pedal, and a brake pedal. It was projected with a video projector onto a screen 85 cm high and 110 cm wide. The participants were seated in a comfortable chair. The VE was projected 150 cm in front of them.	An urban environment based on photos of Paris
Gottlieb et al., 2022	**verbal memory**	The VR-RAVLT places the participant in a virtual office with a virtual personal assistant (avatar) seated behind a desk. The avatar tells the participant a list of 15 places s/he needs to visit on the same day, and that s/he must recall as many as possible. The avatar informs the participant that as she will be leaving early for the day, she will repeat the list to ensure the participant remembers all the places (i.e., similar to the procedure employed in the GS-RAVLT). List B consists of 15 places that the participant would need to visit on the next day. Participant responses are recorded by a research assistant in a form similar to what is used in the GS-RAVLT.	HTC-Vive	Virtual office

Hogan et al., 2023	**Prospective memory**	Virtual Reality Prospective Memory Shopping Task (VRPMST): The ongoing task (12 errands) is completed by moving around the virtual shopping center and entering stores in a set order. The tasks are designed to mimic everyday activities completed at a shopping center. For time-based PM, participants are told that their doctor has instructed them to keep track of their heart rate; therefore, they need to check their heart rate (press H on the iPad) every 3 min. Participants can check their virtual watch (elapsed time appears for three seconds) by pressing the TIME button on the iPad. The VRPMST features two types of event-based PM tasks. Firstly, participants are told that they are keeping track of food expenditure. Therefore, after purchasing food items (4 items), they are required to collect a receipt. Secondly, participants are informed that they lost their glasses on their previous shopping trip. There- fore, they need to ask the center's security guard every time they see one (4 times) whether they have found their glasses.	Dell M6700 note-book computer.	Shopping center
Lecouvey et al., 2019	**Prospective memory**	After a familiarization phase, participants were informed that they would be immersed in this virtual city, this time to pick up a friend at the train station (i.e., at the end of this city), and they would have several intentions to fulfill along the way. **Encoding:** Participants were shown seven intentions on a laptop computer. For half of them, there was a strong link between the prospective cue and the retrospective component (Link-EB; e.g., buy a stamp booklet at the post-office), while for the other half, there was a weak link between them (NoLink-EB;e.g., buy a pair of glasses at the fountain). The remaining intention was a TB one repeated over time (i.e., take medication every 2 min). Then, to ensure that they were correctly encoded, a cued recall test was administered after the intentions had been presented. **Storage**: There was a 10-min interval between the encoding and retrieval of intentions, filled by the completion of questionnaires. **Retrieval**: They were reminded that they would have to pick up a friend at the train station and fulfill several intentions along the way. To do so, they had to stop the car at the appropriate time or place (i.e., prospective component) and tell the experimenter which action they had to perform (i.e., retrospective component).	The virtual environment was run on a PC laptop computer and projected onto a 180 × 240 cm widescreen. Participants could use two pedals (gas and brake) to drive the car through the city, but they could not control the wheel.	Virtual town with various buildings, traffic lights, stores, trees, hoardings, parked cars, pedestrians crossing and corners
Tippett et al., 2009	**spatial memory**	Two paths (A and B) were chosen with fixed start and end points. The VE task consisted of a set of three learning trials for Path A followed by one learning trial for Path B. For each trial, the participant first viewed the pertinent path through the city passively. Participants were instructed to pay attention to where various landmarks were located within the city and with respect to one another. After the path was completely viewed, participants were returned to the start position and were required to replicate the path to the best of their abilities. Path B served as an interference condition and was conducted using a separate path design in the same city environment to counteract perceptual priming effects. Following these trials were short-delay (5 min) and long-delay (20 min) recall trials, during which participants navigated Path A by memory alone, with no passive viewing component.	The virtual environment was presented to the participant using an LCD projector (Boxlight Corp). Interaction was achieved using a modified eight-way gameport joy- stick (PC Gamepad, Gravis, Inc.). The device allowed recording of both button-press responses as well as navigational control.	Sunnybrook City

Zhang et al., 2021	**spatial memory**	**Learning phase:** Before the start of the entire experiment, participants were informed that the goal of the virtual environment task was to find and maintain a location, which would always be located at the same place during the following tests. They should always reach this same destination during the entire study. This destination is invisible, participants should find it according to the instructions and tasks during exploring the entire virtual environment in the following trials. Participants were provided with 9 learning trials. Each learning trial had a 90-s time limitation; if participants failed to reach the destination within 90s, the trial terminated immediately and the next trial began. In the learning phase, participants could reach the destination by remembering the sequence of body turns of each Y-shaped intersection (egocentric strategy) or other strategies. To evaluate the navigation performance of each participant, the following parameters were calculated for the 9 learning trials: speed, distance error, rotation, percentage of successful people and percentage of successful trials. **Probe phase:** The probe trial shared the same maze structure as the learning phase but with no salient landmarks (i.e., all distal cues were removed).	Participants were comfortably seated in front of the computer screen and moved the joystick (Sony Dual- Shock 4) freely in a first-person view	Virtual maze
Morganti et al., 2013	**spatial memory**	**VR-Maze spatial task (VR-MT):** participants faced the front of the computer screen, and they were provided with one of the paper-and-pencil versions of five different complex mazes (PP-MT). In order to assess allocentric spatial knowledge in the PP-MT, they are requested to draw the path from start to exit trying to find the most efficient way between the two points. After each PP-MT was performed, in order to assess the allo- to egocentric translation of spatial knowledge, participants were asked to use the PP-MT in order to locate the exit point in the corresponding VR-MT. In the VR-MT exploration, a maze was considered as correctly performed if the participant was able to reach the exit point within the maximum time provided (10 minutes). **Virtual Road Map task (VR-RMT):** the participants faced the front of the computer screen with the paper version of the Money's Road Map Test (PP-RMT) placed at the base of the screen. The PP-RMT consists of a stylized city map in which participants have to indicate on a 32-step dotted pathway the direction taken at each turn (left or right) in order to follow a designated route. Afterward, the participants were asked to use the PP-RMT to specifically navigate the VR-RMT by following the route indicated by the dotted line on the PP-RMT. The main objective of this task is to evaluate if the allo- to egocentric translation of spatial knowledge required for the navigation in the simulated virtual reality environment might differ from the one required from a mental imagery simulation of the same environment based on a sketched map.	All virtual reality tasks were administered on an Intel Core 2 Duo personal computer and presented on a 15" desktop monitor. The participants were seated in a chair approximately 50 cm from the computer monitor and moved in VR using a narrow keyboard.	2 virtual mazes

Cushman et al., 2008	**spatial memory**	**Route learning:** After completing the route demonstration, subjects were asked whether they had gone left, right, or straight at each of 10 choice points. **Free recall:** After the test trip around the route, subjects had 1 minute to name as many objects or landmarks as they could recall. **Self-orientation:** Subjects were shown pictures of 10 different objects or locations from the test route, chosen to be distributed as two sequentially presented sets of five sites distributed at 45° intervals to the front and sides of the subject's position, the subject's back being toward an outside wall. **Route drawing:** Subjects used a mouse to indicate the location of the next choice point while viewing a scale map of the lobby on the video screen. **Landmark recall:** Subjects were asked to name only those objects or fixtures that were helpful in finding their way on the self-directed, second trip around the lobby. **Photograph recognition:** Ten photographs were presented singly on the screen, five from the test route and five from other locations in the Medical Center. Subjects identified whether each photo was from the test route or not. **Photograph location:** Another set of 10 photographs from the test route was presented while subjects used a scale outline of the lobby with 10 locations marked by letters to indicate the location corresponding to the scene, scored as the number correct. **Video location:** Ten short video clips, taken from the subject's view of the test route, were presented with three repetitions. After each display was completed, subjects drew an X on a blank map where the clip began and an arrow coming from the X showing the direction and extent of the depicted movement.	Laptot PC	Virtual hospital lobby
Serino et al., 2015	**spatial memory**	A virtual room was created as test environment. It included two objects (namely, a plant and a stone) and an arrow drawn on the floor, which pointed to the North and represented the start of the navigation. Participants were instructed to memorize the position of the plant, that varied across three different trials. For the **retrieval phase**, two different tasks were developed. In the first task, participants were asked to indicate the position of the object on a real map, namely, a retrieval with spatial allocentric information independent of point of view. In the second task, participants were asked to enter an empty version of the same virtual room. The participants had to indicate the position of the plant, starting from the position of the other object, namely, a retrieval without any spatial allocentric information.	Participants were seated in front of a horizontally placed 15″ monitor. The monitor screen was placed at a distance of 50 cm from the body plane. The virtual environments were rendered using a portable computer. The participants also had a gamepad which allowed them to explore and to interact with the environment.	Virtual room
Rekers & Finke, 2023	Rekers & Finke, 2023	VIENNA consists of one instruction trial, two practice trials, and 12 main trials. All trials show a first-person perspective of a character exploring virtual hallway environments. In addition, an allocentric map of the respective environment is displayed throughout each trial. Participants are required to mentally trace the character's position and indicate the door that the character chose at the end of the trial. Importantly, this task design does not rely on episodic memory and does not require active exploration or navigation by the participant, thus homogenizing the available information to solve the task across participants.		Virtual hall way environments

da Costa et al., 2022	**spatial memory**	**SOIVET Maze Task:** participants were required to navigate in a virtual maze using the route depicted on the original MRMT map as a reference. A green point marked the last correct turn on the map, in order to reduce working memory efforts. No topographical landmarks were provided. To navigate in the first-person perspective, participants were required to follow the route depicted on the map, but also update information from their body position at each turn on the maze. **SOIVET Route Task**: participants entered the virtual reconstruction of the lobby of the Central Institute of the University of São Paulo Clinics Hospital. An avatar performed a route consisting of five specific locations inside the hospital lobby and its surroundings. Participants were required to follow the avatar in a first-person perspective. Subsequently, participants were required to repeat the same route alone, and to visit the five locations in the same order (SOIVET Route immediate). After a 20-minute interval, the participants repeated the route one more time (SOIVET Route delayed).	Oculus Rift CV1 kit. Participants were able to navigate through the virtual environment using the touch controllers and their body position – turning the chair either right or left.	Virtual city
Mohammadi et al., 2018	**spatial memory**	Virtual reality navigation task (VRNT): Each of the virtual reality environments (virtual neighborhood and virtual maze) comprised a 3-D first-person view and a two-dimensional overhead view of the environment. First, the two- dimensional overhead view was shown to the subjects for 60 s, and then the 3-D first-person view was presented. Subjects were then instructed to find the specified goal (i.e. parking in the virtual neighborhood; the ball in the virtual maze), which had been marked on the 2-D overhead view. All subjects had three trials to familiarize themselves with the task and five trials for their assessment.		Virtual neighborhood and virtual maze
Lee et al., 2022	**spatial memory**	The virtual radial arm maze (VRAM): Participants were told that they were in a virtual room with six arms extending from a middle area. The virtual room had various colored objects and visual cues to indicate the relative directions, and the room remained unchanged throughout each trial. Although participants were instructed to find the three treasures as quickly as possible, no time limit was imposed. After discovering all three treasures, the trial ended, and participants returned to the center of the maze to begin the next trial. Five trials were conducted, and the intertrial interval was 10 seconds. The same configuration of rewarded arms was used for all participants. This test measured working memory errors by the number of times a subject reentered the same arm; reference memory errors were measured by the number of times a subject reentered the arms with no rewards.22 Distance traveled, and time required to find all rewards during each trial were also recorded.	Desktop computer with a color monitor and a joystick.	Virtual Maze

6. Experimental studies

6.1. Study 1: Mapping the Landscape of Research on 360-Degree Videos and Images: A Network and Cluster Analysis

5.1.1. Introduction

360-degree videos, alternatively referred to as panoramic, spherical, or omnidirectional videos/images, represent a novel form of multimedia that offers users an immersive and all-encompassing experience. The 360° video/image encompasses the entirety of a spherical surface, providing a comprehensive viewing experience spanning a range of 360 × 180°. In contrast to conventional two-dimensional (2D) video or imagery, 360° video or imagery provides a comprehensive and immersive visual experience by enveloping the viewer in a seamless manner, occupying the entirety of their field of vision. Consequently, spectators are not limited to observing solely a specific portion of the scene that has been selected by the producers. In recent years, there has been a notable advancement in the field of VR technology. 360° video and image, as a crucial form of VR content, has become increasingly prevalent in our everyday lives and has garnered significant interest. The user has the ability to manipulate their head movements in order to control the viewport and access specific content using contemporary commercial head-mounted displays (HMDs), similar to their actions in the physical environment. In this manner, the provision of immersive and interactive experiences is facilitated. In recent times, there has been a notable surge in the popularity of 360° videos and images due to their ability to offer a unique and immersive visual encounter. Through the utilization of these media formats, individuals are afforded the opportunity to engage with the content and delve into a comprehensive environment in manners that were hitherto unattainable with traditional two-dimensional videos and images. According to (Mangiante et al., 2017), the year 2016 witnessed a significant increase in the prevalence of 360° videos. Specifically, YouTube saw the emergence of over 8000 new videos that garnered a daily viewership of at least 250,000. Additionally, the Oculus platform witnessed the creation of more than 1000 novel videos. Moreover, prominent global events such as NBA games and the US Open golf tournament were broadcasted in real-time using the innovative technology of 360° video. One contributing factor to the proliferation of social media platforms such as Facebook and YouTube is the integration of 360° technologies. In the year 2015, these platforms began to provide support for 360° videos, thereby facilitating the dissemination of content produced by creators to a wider range of viewers. Consequently, this facilitated the augmentation of both viewer and creator cognizance regarding the technology. The adoption of 360-degree technologies has been facilitated by the increasing prevalence of cameras capable of capturing 360° video. Moreover, these technologies have been applied in various domains beyond the realm of entertainment, including journalism, tourism, education, and real estate. The adoption of this technology has had a significant impact on organizations seeking to create more immersive and captivating content for their target audiences. The integration of VR with 360° technologies has played a significant role in facilitating the adoption of these technologies. The utilization of 360° videos for the creation of immersive VR experiences is experiencing a notable rise in popularity. Nevertheless, the concept of 360° videos and photos is not novel. The term "panorama" was initially employed in London in 1792 to denote the inaugural instance of a prevalent form of public amusement. This entailed a substantial raised cylindrical chamber that was entirely adorned with a panoramic painting, offering a comprehensive 360° view. Nevertheless, the inception of panoramic photography can be traced back to the mid-19th century. The Movie Map serves as an illustration of this phenomenon (Lippman, 1980), wherein the thoroughfares of Aspen city were captured on film at regular intervals of 10 feet. In order to simulate the impact of walking on urban streets, a pair of videodisc players were employed to retrieve the relevant visual perspectives during playback. Subsequently, Digital Video Interactive (DVI) technology emerged, facilitating the utilization of digital videos for the purpose of exploration. The exploration of Palenque's Mayan ruins can be facilitated by employing digital video playback technology from an optical disk, as demonstrated by Ripley (1990) in the context of DVI (Ripley, 1990). Shortly thereafter, a comprehensive "Virtual Museum" was generated at designated areas within the museum, enabling users to engage in panoramic exploration. (G. Miller et al., 1992) employed a bi-directional transition movie that encompassed a frame for each step taken in both directions along the path connecting the two points in order to simulate the act of walking from one point to the other. In the year 1994, Apple introduced a software called "QuickTime VR" (S. E. Chen, 1995). This software enabled users to navigate a simulated environment by utilizing the mouse to click and drag in different directions. Additionally, it facilitated the creation and viewing of interactive 360° panoramas. The movie player has undergone a substitution with a real-time image processor, thereby distinguishing it from prior endeavors. A sequential guide can be generated by linking multiple images together. Nevertheless, the advancement of panoramic photography into 360° videos and images did not occur until the advent of the digital era. However, it was not until the mid-2010s that the widespread accessibility of 360° videos and images became possible, primarily due to the emergence of consumer-grade cameras and the availability of online platforms such as YouTube and Facebook for sharing and viewing such content. The advent of accessible and cost-effective 360° cameras has enabled individuals to create their own 360° videos and images. The utilization of 360-degree videos and photos expanded to various industries subsequent to their inception, including the field of education, where they have been employed to provide students with immersive simulations and virtual field trip experiences. For instance, VR technologies have been employed within the tourism sector to visually showcase various travel destinations. Similarly, in the realm of marketing, VR has been utilized to create interactive product demonstrations and advertisements. The rise in popularity of 360° videos and photos has prompted the emergence of research exploring their potential applications and impacts. A number of studies have been conducted by researchers to investigate the impact of 360-degree videos on various aspects such as learning outcomes (Blair et al., 2021; D. Hamilton et al., 2021; Rosendahl & Wagner, 2023; Snelson & Hsu, 2020), mental health intervention (Ionescu et al., 2021), emotional reactions (Li et al., 2017; Schöne et al., 2021), and attentional processes (A. Nguyen et al., 2018). This study aims to perform a comprehensive network and cluster analysis of the scholarly literature pertaining to 360° videos and images. Through a comprehensive examination of the prevailing body of scholarly works, our objective is to discern recurring patterns and themes, thereby offering valuable insights into the present state and prospective trajectories of research within this particular domain.

360-degree technology

The concept of 360-degree technology refers to the utilization of immersive technologies that enable users to experience a virtual environment from all angles,

360° videos allow viewers to observe their surroundings from any angle while engaging with an immersive video that encompasses a complete 360-degree field of view. VR videos are commonly observed on computer or mobile platforms utilizing VR headsets, enabling users to manipulate the video's perspective by altering their viewing direction. The Oculus Quest 2, HTC Vive, and PlayStation VR are widely recognized as three prominent VR headsets in the market. In addition, individuals have the option to access 360° videos on computers or mobile devices through the utilization of a web browser or a dedicated application. In this particular case, spectators have the ability to navigate the video by panning and explore the entire 360° field of vision through the use of a mouse or touch screen.

A camera equipped with multiple lenses is employed to record the entirety of the surrounding environment, enabling the capture of a 360° video. The production of a seamless 360° video involves the process of stitching together multiple images, which are captured simultaneously by the camera, utilizing specialized software. The technological advancements required for the production and consumption of 360° videos have progressed over the course of time. In the past, the utilization of early 360° cameras necessitated the use of specialized equipment and a proficient understanding of technical processes. Moreover, these cameras were characterized by their high cost and the inherent difficulties associated with their operation. Consumer-grade 360° cameras have become increasingly accessible and affordable due to the expansion of the 360° video market.

Currently, there exists a diverse range of 360° cameras, encompassing various styles, ranging from compact and portable devices to more advanced and sophisticated setups. Insta360, GoPro, and Ricoh are among the prominent brands in the market. These cameras often incorporate software that facilitates the process of combining multiple images captured by the camera to create a cohesive 360° video without any visible seams. The global market for 360° cameras exhibited a consistent growth trajectory, with an estimated value of US$ 0.92 billion in 2021. Projections indicate that this market is expected to surpass US$ 4.64 billion by the year 2030, reflecting a compound annual growth rate (CAGR) of 21.3% from 2022 to 2030 (360 Degree Camera Market Size).

Degrees of separation between 360° and virtual reality technologies

The utilization of immersive technologies, such as 360° videos and VR, has witnessed a significant surge in popularity across diverse sectors. One of the most noteworthy attributes of both technologies is their capacity to provide viewers with an immersive experience. VR provides users with a completely simulated environment that allows for interaction, whereas 360° videos create a sense of physical presence in the depicted environment for viewers. The considerable degree of interactivity offered by both technologies facilitates users in independently exploring their surroundings.

Notwithstanding their shared characteristics, the two technologies also exhibit notable disparities. 360-degree videos primarily emphasize the documentation of authentic real-world settings, whereas VR places greater emphasis on the creation of entirely artificial environments for the purpose of simulation.

Nevertheless, both technologies provide immersive and interactive experiences that have the capability to captivate and maintain the attention of viewers. Indeed, (Barreda-Ángeles et al., 2020) provided evidence that these findings exhibited comparable potential in attaining "spatial presence," which refers to the degree to which the immersive environment is perceived as authentic. Individuals have the ability to engage in a user-controlled training simulation or environment by utilizing immersive 360° videos and head-mounted displays (HMDs), thereby creating the illusion of being physically present in that particular setting. The ability to perceive immersive 360° video content without being confined to a singular perspective has been made feasible through the utilization of specialized cameras. These cameras enable the simultaneous capture and recording of the complete surrounding environment from a stationary vantage point. When utilizing a Head-Mounted Display (HMD), the observer has the capability to manipulate their head movements or employ touch or mouse input to modify the viewing angle, provided that the content is being presented on a screen. 360-degree videos and VR share many similarities, such as the utilization of a head-mounted display (HMD) and the creation of audio-visual content that allows for navigation in a 360-degree horizontal and 180-degree vertical field of view.

Moreover, virtual reality enables a heightened degree of interactivity, affording users the opportunity to engage with various objects and characters within the simulated environment. In contrast to VR, 360° videos are widely recognized for their limited interactivity. Nevertheless, despite their lack of intended interactivity, it may be conceivable to generate the illusion of interaction by establishing connections among them. For example, the utilization of specialized software enables the facilitation of interaction and navigation within various environments. By strategically incorporating a hyperlink or interactive element on a virtual door, it is possible to manipulate the digital environment and create the illusion of dynamic spaces, such as changing rooms. This feature has been found to have a wide range of potential applications in various studies (Borghesi et al., 2022; Mancuso et al., 2023; Pedroli et al., 2020, 2022).

VR and 360° videos share certain technical requirements while also exhibiting contrasting aspects. In order to ensure optimal functionality, both technologies necessitate robust hardware and software components. For example, the utilization of 360° videos is compatible with the majority of contemporary smartphones and computers, whereas VR headsets necessitate a robust computer or gaming console in order to operate effectively. Both technologies require a considerable amount of storage space, with VR applications necessitating the largest amount due to their intricate design. Significant disparities exist in terms of cost. Although VR necessitates the use of costly equipment, such as a headset and a high-performance computer or gaming console, the production of 360° videos can be achieved using relatively affordable tools, such as a 360° camera. Consequently, the production and consumption costs of VR content are significantly higher compared to 360° videos. In conclusion, the aspect of accessibility emerges as a pivotal consideration when comparing and contrasting 360° videos and VR. 360-degree videos are capable of being accessed on a diverse range of devices and are readily accessible on prominent online platforms such as YouTube, Facebook, and Vimeo. In contrast, VR requires specific hardware and software, potentially limiting its accessibility. Moreover, certain individuals may experience discomfort or nausea when utilizing VR headsets, thereby impacting the overall accessibility of this technology.

Despite the evident benefits, the adoption of immersive 360° videos remain limited in scope. The lack of substantial research data demonstrating the comparative advantages of this technology in relation to VR may be one of the reasons for its omission. The abundance of studies that utilize VR technologies provides substantiation for this claim (Cipresso et al., 2018).

AIM

Within the domain of scientific investigation, the current study conducts an examination of 360° videos through the application of network and cluster analysis techniques. These methodologies are rooted in the principles of science mapping and bibliometrics. Science maps are visual representations that show the connections between different disciplines, fields, specialties, documents, and authors. These maps have various uses in academic discussions (Bales et al., 2020; Small, 1999) and encompass various functions such as offering a comprehensive depiction of the cognitive structure within a specific field (Bales et al., 2009), identifying key contributors (Buter & Noyons, 2004), pinpointing centers of innovation, aiding in science policy development (Buter et al., 2006) and evaluating the evolutionary paths of scientific disciplines (Bales et al., 2011; Noyons et al., 2006; Polanco et al., 2001; Zitt & Bassecoulard, 1994)
Bibliometric maps, which are an essential component of this investigative framework, are created using citation data, common terminologies, or other bibliometric factors (Buter et al., 2006). The bibliometric representations discussed in this context have been appropriately referred to as "landscapes of science" (Noyons et al., 2006, 17-20), drawing an analogy with geographical maps. One notable aspect of these tools is their ability to provide a comprehensive representation of the scientific information landscape, allowing users to further explore specific sections by zooming in, similar to the exploration of geographic terrains.
The triad of bibliometric analyses relevant to the practice of science mapping comprises citation analysis, co-authorship analysis, and co-citation analysis. The analysis of co-citation, which refers to the frequency with which two documents are cited together, provides valuable insights into the intellectual associations within the scholarly domain. In the field of scholarly research, the analysis of co-authorship serves to examine the connections between authors and their affiliations, thereby revealing the complex social structures that exist within collaborative networks (Bales et al., 2020; Buter et al., 2006; Noyons et al., 2006). This comprehensive methodology holds the potential to provide a deeper understanding of the complex network of relationships within the domain of 360° video research, presenting nuanced viewpoints on the collaborative dynamics and intellectual terrain of this emerging discipline.

6.1.2. Materials and methods

Data Collection

The scientific database Scopus provided the initial data for the analyses (Falagas et al., 2008). including also Web of Science core collection, with the following query:

"360° video" or "360° videos" or "360 video" or "360 videos" or "360° images" or "360 images" or "360° image" or "360 image" or "equirectangular images" or "equirectangular image" or "equirectangular videos" or "equirectangular video" or "360-degree video" or "360-degree videos” or "360 degree video" or "360-degree images" or "360-degree image" or "360 degree images" or "360 degree image" or "sphering videos" or “sphering video" or "spherical videos" or "spherical video" or "360 videoing" or "360° technology" or "360-degree technology" or "360 technology" or "360 degree technology" or "360° technologies" or "360-degree technologies" or "spheric video" or "spheric videos" or "immersive video" or "immersive videos" or "immersive hypervideo" or "immersive hypervideos" or "360 hypervideo" or "360 hypervideos" or "360 degree hypervideo" or "360 degree hypervideos" or "spheric hypervideo" or "spheric hypervideos" or "spherical hypervideo" or "spherical hypervideos" or "360 media" or "360 medium" or "360 degree media" or "360 degree medium" or "360-degree media" or "360-degree medium"

WoS core collection is composed of: Citation Indexes, Science Citation Index Expanded (SCI-EXPANDED) –1970-present, Social Sciences Citation Index (SSCI) –1970-present, Arts and Humanities Citation Index (A&HCI) –1975-present, Conference Proceedings Citation Index- Science (CPCI-S) –1990-present, Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH) –1990-present, Book Citation Index– Science (BKCI-S) –2009-present, Book Citation Index– Social Sciences & Humanities (BKCI-SSH) –2009-present, Emerging Sources Citation Index (ESCI) –2015-present, Chemical Indexes, Current Chemical Reactions (CCR-EXPANDED) – 2009-present (Includes Institute National de la Propriete Industrielle structure data back to 1840), Index Chemicus (IC) –2009-present.

The Scopus’ resultant dataset contained a total of 3319 records. Numerous fields, including author, title, abstract, and all references, were included in the bibliographic record needed for the citation analysis. Cite space 6.1.R3 Advanced, running on Java Runtime v.8 update 91 (build 1.8.0 91- b15), was the research tool used to visualize the networks (Chen, 2006). Utilizing Stata MP-Parallel Edition, Release 14.0, StataCorp LP, statistical analyses were performed. Supplementary material contains additional details. The betweenness centrality of a node in a network measures the extent to which the node is part of paths that connect an arbitrary pair of nodes in the network (Brandes, 2001; C. Chen, 2006; Freeman, 1977). Betweenness centrality, modularity, and silhouette are examples of structural metrics. Citation burstiness and novelty are included in temporal and hybrid metrics. Each algorithm is described in detail (Chen et al., 2010).

6.1.3. Results

The results of the investigation have been subjected to a cluster and network analysis, thorough an analysis across multiple dimensions, such as subject category, country, journals and publishers, document type, authors, and co-citations. It is important to emphasize that the analyses regarding publishers and document types were specifically carried out on a subset of documents that were available through the Web of Science database, comprising a total of 1969 documents. The need for selective focus arises due to the lack of information pertaining to the subject in the Scopus database. The analysis of subject countries, journals, authors, and citations encompasses the entire dataset of 3319 records.

Subject category

Regarding the subject category, all the articles' "Category" fields from the WoS are used to calculate nodes and edges as co-occurring subject categories.
According to the subject category statistics, the top five categories with the most records are Engineering Electrical Electronic in Cluster #2, with citation counts of 669, Computer Science Information Systems in Cluster #0, with citation counts of 403, Computer Science Software Engineering in Cluster #0, with citation counts of 369, Computer Science Theory Methods in Cluster #0, with citation counts of 355, and Telecommunications in Cluster #0, with citation counts of 315. Clusters are shown in Table 1 with labels from the LSI, LLR and MI algorithms.

The examination of subject categories within the clusters provides insight into the interdisciplinary character of the research landscape in 360° technology. The five categories with the highest number of records, as determined by Web of Science subject category statistics, offer valuable insights into the prevailing domains that influence the field.
The network consists of 9 clusters. The largest cluster (#0) has 30 members and a silhouette value of 0.812. It is labeled as degree video by LLR, 360-degree video by LSI, and pedagogical activities (6.65) by MI. The major citing article of the cluster is "*Panomobi: panoramic mobile entertainment system"* (Takacs, 2007). Significantly, the members with the highest number of citations in this cluster correspond to the primary areas of focus in Computer Science, such as Information Systems, Software Engineering, and Theory & Methods. There is a clear correlation between research on degree video and fundamental computer science fields, highlighting the technical principles and approaches that support progress in 360° technology.
The second largest cluster (#1), labeled as radial arrayed echoendoscope by both LLR and LSI, and as pedagogical activities (0.04) by MI, has 28 members and a silhouette value of 0.88. It consists of a varied group of highly cited members from the fields of Psychology (Multidisciplinary and Experimentla) and Biomedical Engineering. The presence of this interdisciplinary network within the cluster demonstrates the wider significance of 360-degree technology, reaching beyond conventional computer science domains to areas such as psychology and biomedical engineering, where the applications and consequences of this technology are investigated. The most cited article here is "Does looking at a 360° video elicit stress-related psychophysiological activation? a case in emergency professions"(Cosoli et al., 2023)

Cluster #2, labeled as *degree video* by LLR, *360-degree video* by LSI, and *pedagogical activities* by MI, has 22 members and a silhouette value of 0.881. The most cited article in this cluster is "Challenging multi-sensor data models and use of 360 images. the twelve months fountain of valentino park in turin" (Teppati Losè et al., 2020). The most cited categories here exhibits a fusion of engineering, optics, and educational disciplines. This implies a comprehensive examination of 360? technology, which includes not just technical elements but also educational uses and the incorporation of optical technologies. The clusters and their nodes are shown in Figure 1.

Table 1. Summary of the largest 9 clusters.

ClusterID	Size	Silhouette	Label (LSI)	Label (LLR)	Label (MI)	Average Year
0	30	0.812	360-degree video	degree video (1091.96, 1.0E-4)	pedagogical activities (6.65)	2011
1	28	0.88	radial arrayed echoendoscope	radial arrayed echoendoscope (337.58, 1.0E-4)	pedagogical activities (0.04)	2013
2	22	0.881	360-degree video	degree video (816.03, 1.0E-4)	pedagogical activities (2.89)	2010
3	18	0.881	360-degree video coding	panoramic camera (478.24, 1.0E-4)	subjective quality assessment (0.53)	2013
4	9	0.981	feasibility pilot study	internet-based treatment (343.38, 1.0E-4)	360-degree video (0.04)	2019
5	4	1	using expert computer technology	worldwide identification (38.05, 1.0E-4)	360-degree video (0.05)	2006
6	3	1	clustering and synchrony in laying hens: the effect of environmental resources on social dynamics	laying hen (20.41, 1.0E-4)	360-degree video (0.05)	2011
7	2	1	qchromosomevisualizer: a new tool for 3d visualization of long simulations of polymer-like chromosome models	qchromosomevisualizer (20.92, 1.0E-4)	360-degree video (0.05)	2018

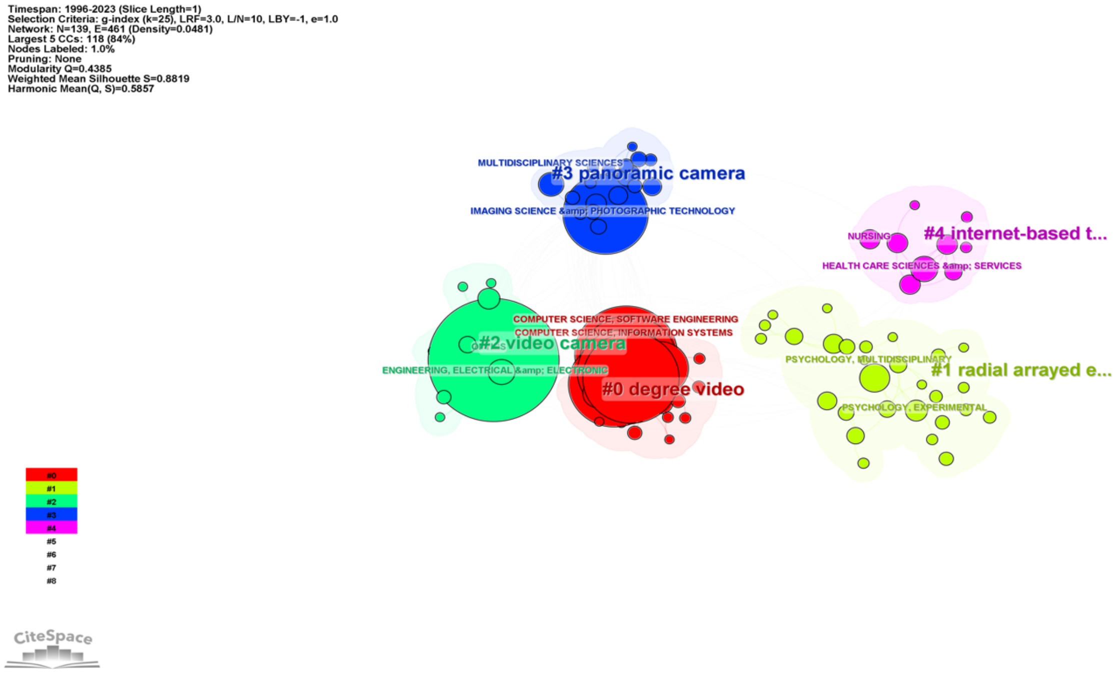

FIGURE 1 | Clusters from the WoS

Given the technical nature of 360-degree imaging technology, it is not surprising that most clusters pertain to technological fields, such as engineering, computer science, and telecommunications. However, it is intriguing to note that several clusters, including "Psychology," "Medicine," and "Education & Educational Research," are related to human factors. This implies that the application of 360-degree videos and images goes beyond technical uses and is being investigated in industries like education and healthcare. Overall, a variety of fields are being studied and applied for 360-degree videos and images, with both technical and human-centered aspects being explored, according to cluster analysis.

Country

In relation to the countries, nodes and edges are computed as networks of co-authors' countries. A country's multiple occurrences in the same paper are counted just once.

Of the 3319 articles, the United States, China, Japan, and United Kingdom published 680, 487, 224, and 223 articles, respectively. However, contributions also came from all over the globe, especially from Europe, with Germany, Italy, and France, taking positions of prominence, as shown in Figure 2 along with South Korea and Taiwan.

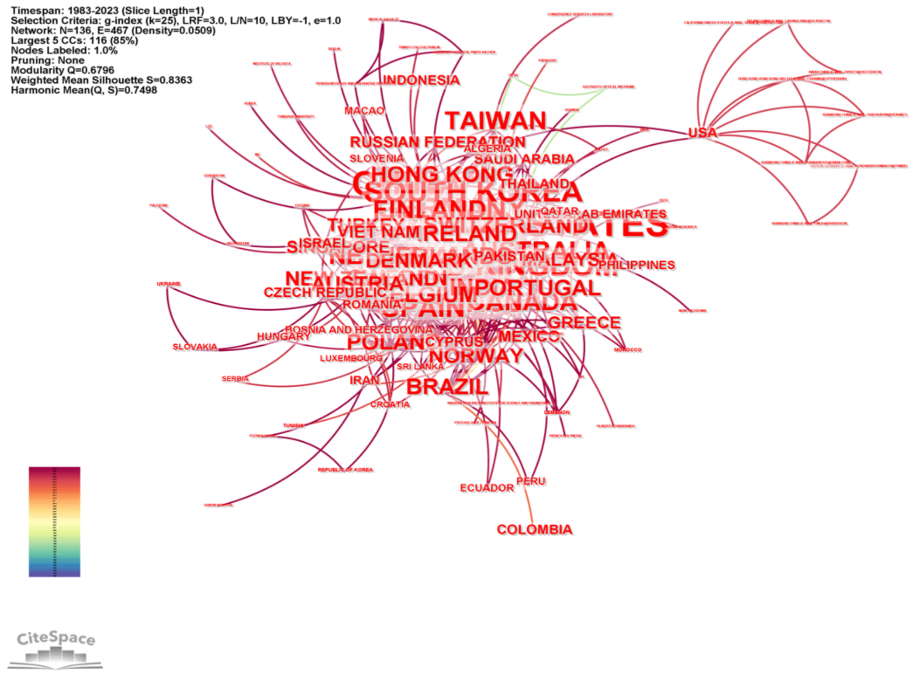

FIGURE 2 | Country network

Figure 3 displays the 12 institutions that have experienced the most significant increases in citations, highlighting notable trends of active research within the academic network. An especially compelling observation in this graphic representation is the presence of Adobe Systems alongside these establishments. This discovery highlights the importance of partnerships between academic institutions and technology companies in promoting research efforts. The collaboration between research initiatives and industry players is crucial, particularly in fields that involve the development and application of cutting-edge technologies and patents. The participation of corporations such as Adobe Systems implies a mutually advantageous collaboration where technological advancements and intellectual property are intertwined with scholarly contributions. The symbiotic relationship between academia and industry highlights the changing nature of research, where collaborative endeavors with industry entities contribute to the creation of knowledge that not only undergoes rigorous academic evaluation but is also documented and indexed for broader distribution.

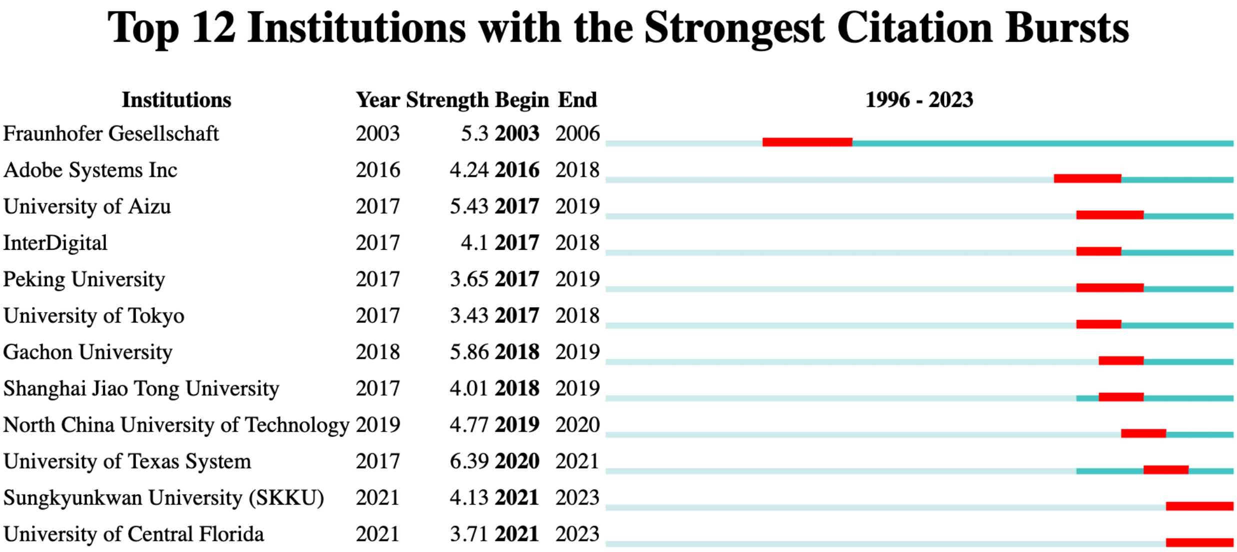

Fig. 3. The top 12 Institutions with the strongest citation bursts

Journals and Publishers

Regarding the journals, nodes, and edges are calculated as journal co-citation networks between each journal in the relevant field.

The top journal item by citation counts is Lecture Notes in Computer Science (2010) in Cluster #1, with citation counts of 402. The second one is IEEE Transactions on Circuits and Systems for Video Technology (2002) in Cluster #0, with citation counts of 385. The third is Conference on Computer Vision and Pattern Recognition (2004) in Cluster #1, with citation counts of 380. The 4th is IEEE Transactions on Image Processing (2002) in Cluster #1, with citation counts of 305. The 5th is IEEE Transactions on Pattern Analysis and Machine Intelligence (2003) in Cluster #1, with citation counts of 289. The 6th is IEEE Transactions on Multimedia (2011) in Cluster #0, with citation counts of 284. The 7th is IEEE Transactions on Image Processing (2005) in Cluster #0, with citation counts of 272. The 8th is Proceedings of the 8th ACM on Multimedia Systems Conference (2017) in Cluster #0, with citation counts of 254. The 9th is ACM Transactions on Graphics (2004) in Cluster #1, with citation counts of 209. The 10th is IEEE Transactions on Visualization and Computer Graphics (2016) in Cluster #1, with citation counts of 209.

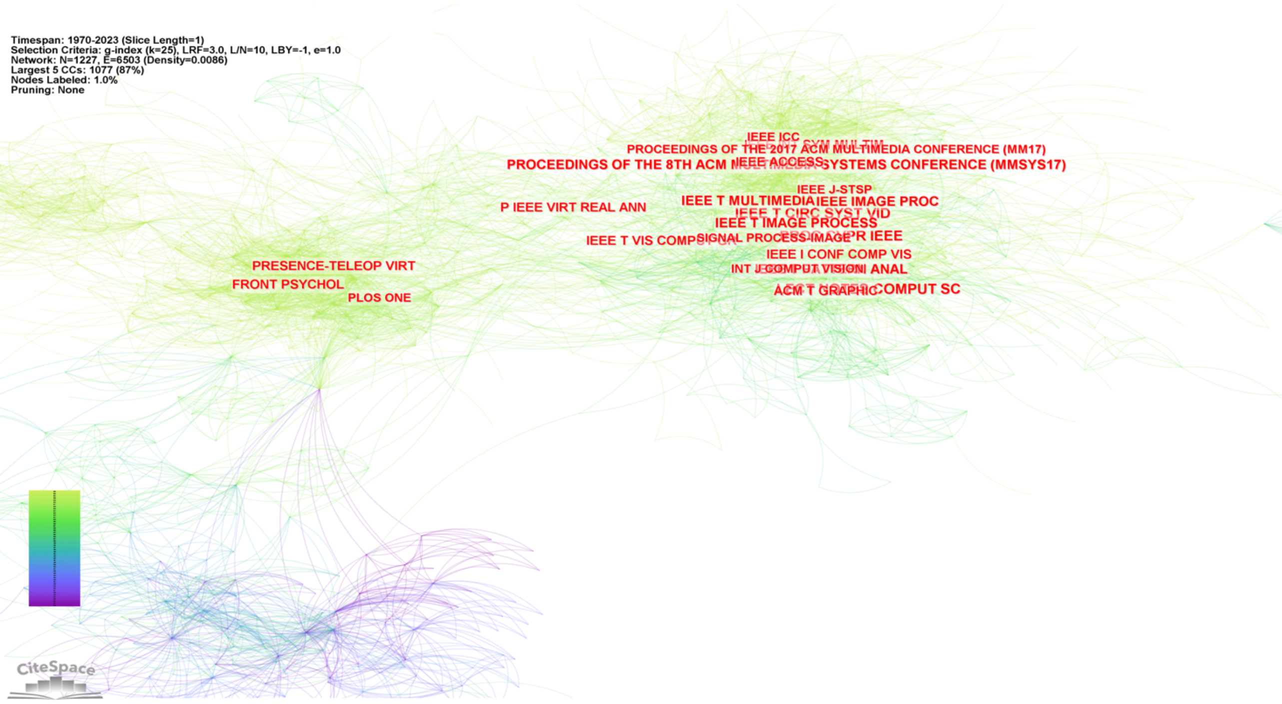

Fig. 4. Networks of journals

The analysis of the network has identified the existence of 16 separate clusters, as depicted in Figure 5. The supplementary materials contain detailed labels that have been generated using the LSI, LLR, and MI algorithms. These labels offer a higher level of granularity to the cluster categorizations. Significantly, this analysis has yielded intriguing insights pertaining to human factors, wherein specific clusters demonstrate distinct characteristics.

One noteworthy cluster, referred to as Cluster 1, stands out due to its highly cited article authored by Farmer, H (2021) entitled "Did you observe what I observed? A comparison of attentional synchrony during 360° video viewing on head-mounted displays and tablets"(Farmer et al., 2021), which was published in the Journal of Experimental Psychology-Applied. Cluster 3, designated as "Virtual Reality", primarily focuses on the theme of "From fomo to jomo: investigating the emotions of fear and joy associated with the fear of missing out and the sense of presence in a 360° video viewing experience"(Aitamurto et al., 2021). Notably, the cluster is characterized by the high citation counts of certain journals, namely Presence-Teleoperators and Virtual Environments (citation=184), Frontiers in Psychology (citation=178), and PLOS ONE (citation=153).

This comprehensive investigation reveals the changing dynamics between Virtual Reality and 360° videos. Over the course of its development, there has been a noticeable convergence between the domains of virtual reality and 360° videos, with the latter showing potential to encompass the entire range of functionalities inherent to VR. The various clusters, each characterized by its distinct emphasis, collectively contribute to the progressive narrative surrounding the gradual expansion of 360° videos beyond their conventional limitations.

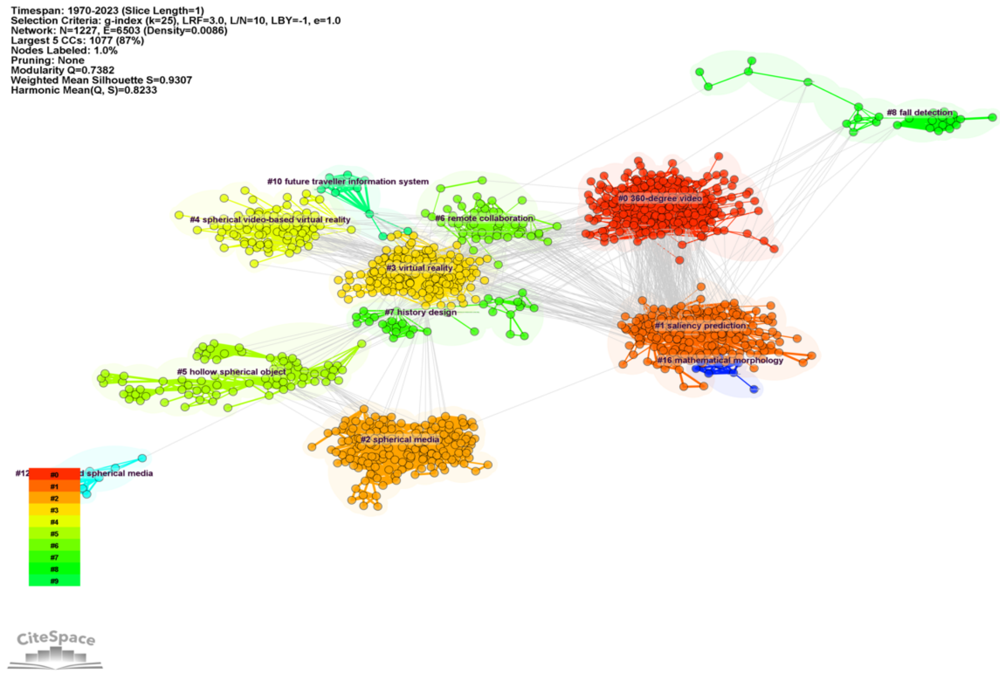

FIGURE 5 | Co-citation network of journals: the dimensions of the nodes represent centrality according to LLR algorithm.

Figure 6 instead shows the major publishers in the field of 360-degree video. The data showed that IEEE, which accounts for 45% of all publications, has the highest record count with 886 publications. With contributions of 11.80% and 9.44% each, Springer Nature and the Association for Computing Machinery came in second and third, respectively. Elsevier (5.74%), MDPI (4.01%), Taylor & Francis (3.35%), and Wiley (2.74%), were some of the other important publishers.

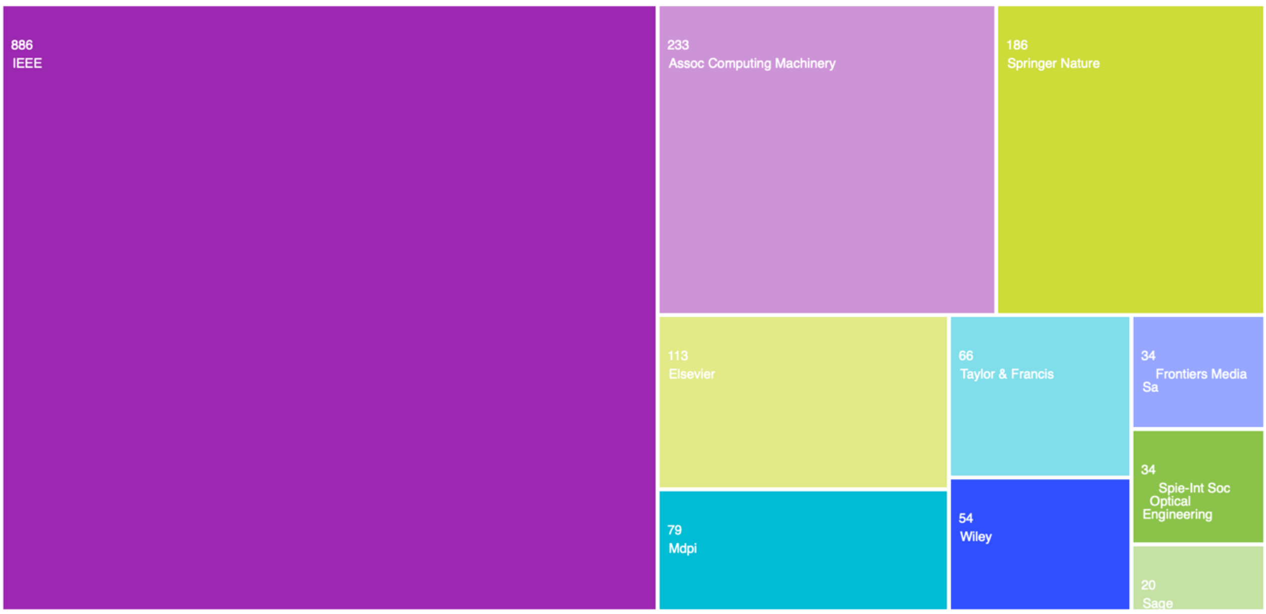

FIGURE 6 | Distribution of major publishers.

Document type

Notably, the analysis of the existing scientific literature has indicated that most of the publications (1049) are conference proceedings, followed by 894 articles. This outcome suggests that the research community is actively exploring this topic and that the field is still in its infancy. It is plausible that the increased publication of proceedings over articles is due to the fact that conference proceedings serve as the main vehicle for disseminating cutting-edge scientific concepts and innovations. Because of this, the proliferation of proceedings in this field may be an indication of the research community's eagerness to share and disseminate its findings in the form of preliminary results or work in progress. Additionally, the rise in proceedings may be a sign that the field is developing, and that additional study is required to fully realize the potential of 360-degree videos in research (See figure 7).

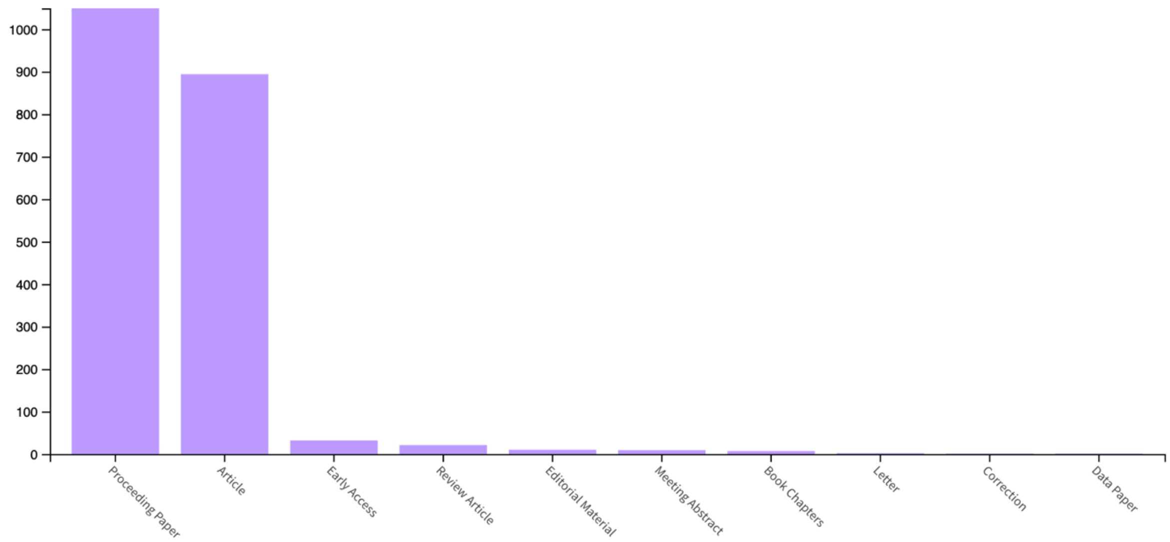

FIGURE 7 | Documents' type diffusion.

The Faces of 360° Research

Authors are the heart and mind of research, and it is up to them to define the direction of these fields as well as to make important discoveries that spark the development of novel theories. It is important to note that the purpose of highlighting the researchers who have contributed significantly to the field of 360° technology is not to create a ranking or hierarchy but rather to recognize the active researchers in this area. While the research on 360° technology is still in its early stages, many researchers have made important contributions that have advanced our understanding and application of this technology. By acknowledging the contributions of these researchers, we can gain a better appreciation of the current state of 360° technology research and the potential for future advancements.

The top ranked author by citation counts is CORBILLON X (2017) in Cluster #0, with citation counts of 282 and with bursts of 10.72. The second one is QIAN F (2017) in Cluster #0, with citation counts of 268. The third is SLATER M (2013) in Cluster #1, with citation counts of 238. The 4th is YU M (2017) in Cluster #2, with citation counts of 196 and the higher bursts of 22.86. The 5th is ZHANG Y (2017) in Cluster #0, with citation counts of 193. The 6th is SUN Y (2017) in Cluster #2, with citation counts of 190. The 7th is HOSSEINI M (2017) in Cluster #0, with citation counts of 187. The 8th is XU M (2018) in Cluster #2, with citation counts of 166. The 9th is WANG Z (2010) in Cluster #2, with citation counts of 165. The 10th is XIE L (2018) in Cluster #0, with citation counts of 155 (Figure 8).

The supplementary material provides a detailed explanation of how authors are organized into clusters. This elucidation enhances transparency and offers valuable insights into the organizational structure of the network analysis. This organization functions as a valuable reference for comprehending the affiliations and associations of authors within the identified clusters. By referring to this additional material, readers can enhance their understanding of the collaborative networks and thematic affiliations that form the basis of the contributions made by different authors in the field of 360° video research.

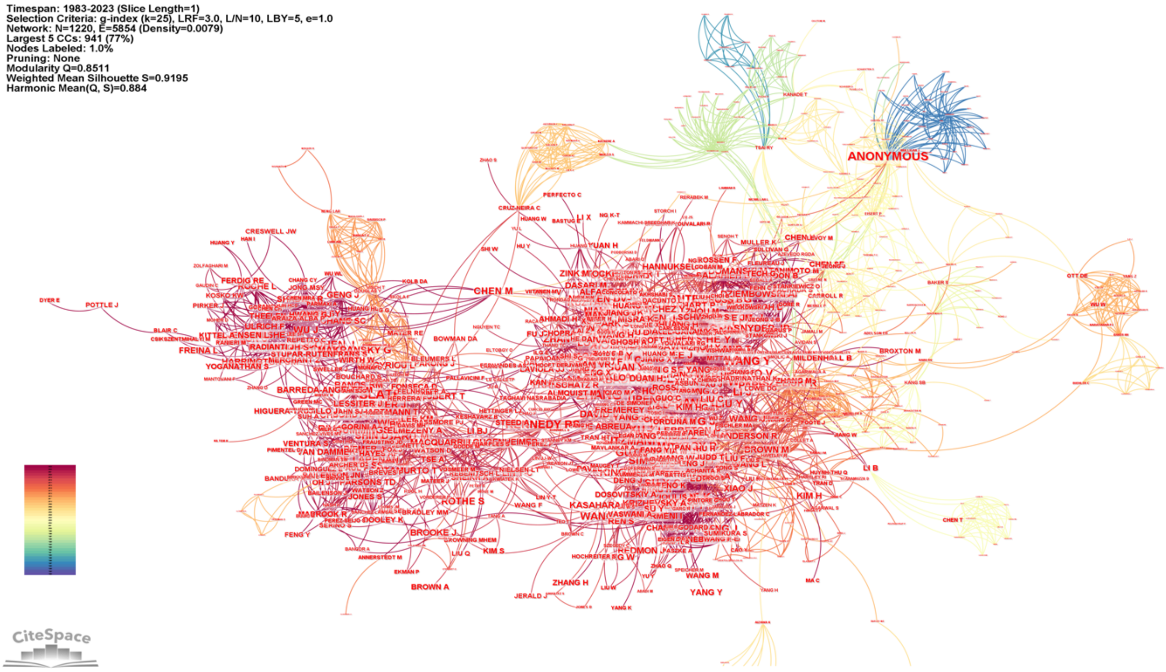

FIGURE 8 | The dimensions of the nodes represent the centrality index, and the dimensions of the characters represent the author's rank in a network of authors' numbers of publications.

In the domain of network analysis, author citation analysis and co-citation analysis are two discrete methodologies. Author citation analysis evaluates the influence and impact of specific authors through the examination of the frequency with which their works are referenced by others. This approach provides valuable perspectives on the eminence of particular scholars in a particular discipline, illuminating their contributions and impact on the academic dialogue. Conversely, co-citation analysis redirects attention away from specific authors and towards the interconnections among pairs of documents, encompassing journals, articles, or authors, predicated on their mutual citation patterns. Instead of identifying specific contributors, co-citation analysis uncovers thematic or conceptual linkages among frequently cited documents. This approach offers a more comprehensive viewpoint on the intellectual framework of a particular discipline, revealing collections of closely related works and revealing the fundamental thematic connections that run throughout the academic literature. Author citation analysis places emphasis on the impact of specific individuals, whereas co-citation analysis provides a more comprehensive comprehension of the interrelationships and thematic clusters that define the wider domain of academic knowledge(C. Chen et al., 2010b).

Citation Network and Cluster Analyses for all the published articles

Another analysis that can be used is the analysis of co-citations between documents, which enables us to concentrate on the highly cited documents that are typically also the most influential in the domain (Small, 1973; González-Teruel et al., 2015; Orosz et al., 2016).
The top-ranked article by citation counts is "Next-generation video encoding techniques for 360 video and VR" of Kuzyakov E. and Pio D. (Kuzyakov & Pio, 2016) in Cluster #0, with citation counts of 39. The second one is "Optimizing 360 video delivery over cellular networks" of Qian F (2016) in Cluster #0, with a citation counts of 36 (Qian et al., 2016). The third is "Developing reflective trainee teacher practice with 360-degree video" of Walshe N (2019) in Cluster #1, with citation counts of 30 (Walshe & Driver, 2019). The 4th is "Tiled-based adaptive streaming using MPEG-DASH" of Le Feuvre J (2016) in Cluster #0, with citation counts of 28 (Le Feuvre & Concolato, 2016). The 5th is "Weighted-to-Spherically-Uniform Quality Evaluation for Omnidirectional Video" of Sun Y (2017) in Cluster #2, with a citation counts of 26. The 6th is "Investigating learning outcomes and subjective experiences in 360-degree videos" of Rupp MA (2019) in Cluster #1, with a citation counts of 26 (Rupp et al., 2019). The 7th is "View-aware tile-based adaptations in 360 virtual reality video streaming" of Hosseini M (2017) in Cluster #0, with a citation counts of 24 (Hosseini, 2017). The 8th is "A Framework to Evaluate Omnidirectional Video Coding Schemes" of Yu M (2015) in Cluster #0, with citation counts of 22 (Yu et al., 2015). The 9th is "Streaming Virtual Reality Content" of El-Ganainy T (2016) in Cluster #0, with citation counts of 21 (El-Ganainy & Hefeeda, n.d.). The 10th is " Saliency in VR: How Do People Explore Virtual Environments?"of Sitzmann V (2018) in Cluster #3, with citation counts of 21 (Sitzmann et al., 2018).
Deep comprehension of the topic requires the ability to identify the potential knowledge conglomerate in the area, and this is why the network of document co-citations is so significant. Consequently, a cluster analysis was performed for this purpose (Chen et al., 2010; González-Teruel et al., 2015; Klavans and Boyack, 2015). Figure 9 shows the clusters, which are identified with the three algorithms in Table 2.

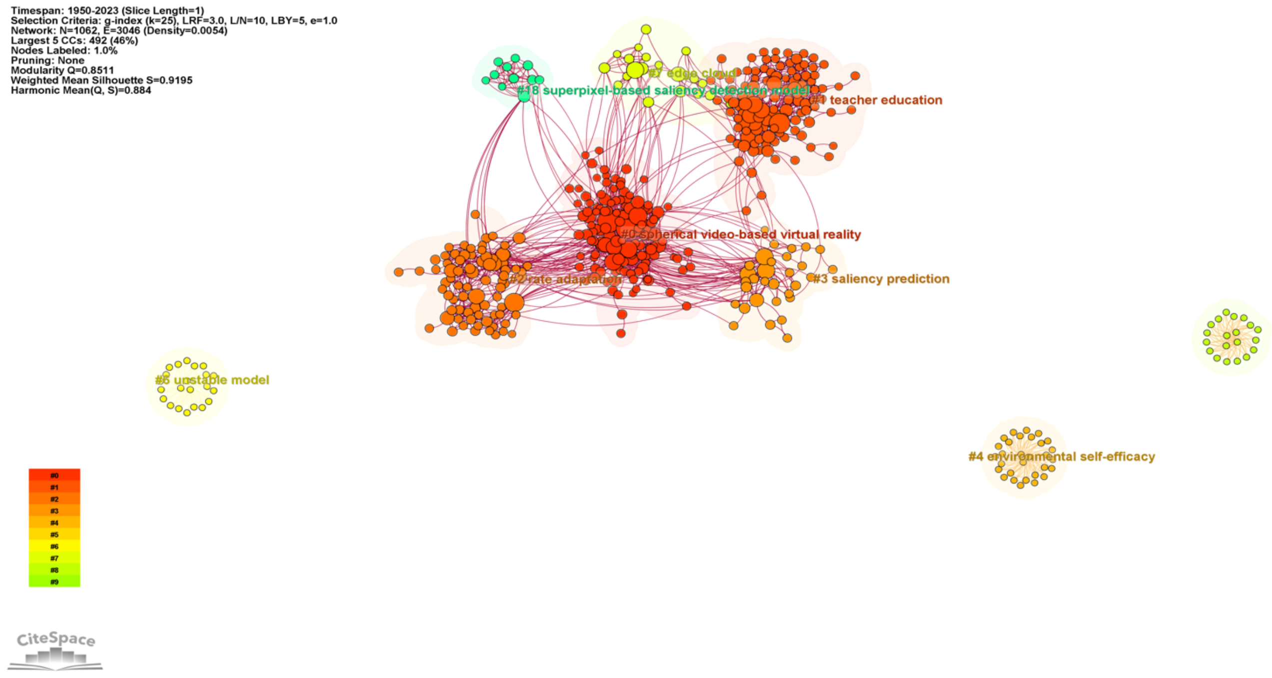

FIGURE 9 | Document co-citation network by cluster.

TABLE 2 | Cluster ID and silhouettes as identified with two algorithms, Latent semantic indexing and LLR (Chen et al., 2010).

ClusterID	Size	Silhouette	Label (LSI)	Label (LLR)	Label (MI)	Average Year
0	137	0.83	360-degree video	spherical video-based virtual reality (289.31, 1.0E-4)	tile-based 360-degree video (3.91)	2016
1	114	0.938	360-degree video	spherical video-based virtual reality (519.29, 1.0E-4)	mediating role (2.44)	2018
2	78	0.918	360-degree video	rate adaptation (261.64, 1.0E-4)	vr experience (0.99)	2018
3	31	0.931	saliency prediction	saliency prediction (226.76, 1.0E-4)	graph-based detection (0.18)	2017
4	30	1	towards video-based immersive environments	environmental self-efficacy (NaN, 1.0)	360-degree video (0.08)	1994
5	22	1	progress in video immersion using panospheric□ imaging	progress (21.37, 1.0E-4)	360-degree video (0.08)	1996

6	22	1	the saturnian ribbon feature-a baroclinically unstable model	unstable model (18.59, 1.0E-4)	360-degree video (0.08)	1982
7	21	0.97	mobile vr	edge cloud (145.15, 1.0E-4)	viewport-driven rate-distortion (0.14)	2017
8	20	1	three-dimensional imaging in aortic disease by lighthouse transesophageal echocardiography using intravascular ultrasound catheters: comparison to three-dimensional transesophageal echocardiography and three- dimensional intra-aortic ultrasound imaging	lighthouse transesophageal echocardiography (16.87, 1.0E-4)	360-degree video (0.08)	1994
18	11	0.993	superpixel-based saliency detection model	superpixel-based saliency detection model (49.19, 1.0E-4)	360-degree video (0.08)	2017
28	6	1	self-supervised learning	non-local dense prediction transformer (45.29, 1.0E-4)	360-degree video (0.08)	2018

Figure 10 portrays the changing research landscape in the context of 360° technology over the period from 1996 to 2023. The emergence and development of the main categories in the five clusters offer valuable insights into the growth and diversification of scholarly contributions over time. During the early years, up until the early 2000s, the main nodes and higher centrality were mainly linked to fundamental categories like Computer Science, Cybernetics, and Software Engineering. This observation is consistent with the inherent progression of technological advancements, wherein initial research primarily concentrates on the development of hardware and fundamental technical elements. In this phase, the initial stages of research on 360° technology mainly focused on its hardware components, which laid the necessary foundation for future multidisciplinary applications. Nevertheless, the image also depicts a subtle shift that occurred in the early 2000s, characterized by the appearance of new interconnected points associated with the field of medicine. The inclusion of categories such as Medical Imaging, Surgery, Physiology, Cardiac, Neuroimaging, Neuroscience, Psychology, Sport Science, Obstetrics, and Neurology represents a significant expansion of research in the medical and healthcare fields. The evolution of 360° technology has shifted from a primary focus on hardware to a wide range of applications in the fields of medicine and psychology. The consequences of this chronological advancement are significant. The increasing adoption of medical and psychological classifications demonstrates a growing acknowledgment of the diverse uses of 360° technology beyond its original technical boundaries. The incorporation of 360° technology in medical imaging, surgery, and neuroscience showcases its ability to make substantial contributions to healthcare practices, diagnostics, and behavioral studies. This diversification demonstrates the technology's changing role in tackling interdisciplinary challenges and advancing knowledge in different scientific fields. Moreover, the rising prominence of categories associated with psychology and sport science indicates a growing recognition of the influence of immersive technologies on human perception, cognition, and performance. The convergence of 360° technology with these fields presents potential for groundbreaking applications, spanning from therapeutic interventions to advanced training methodologies.

This figure represents thus the progressive path of 360° technology research, showcasing its development from initial technical investigation to widespread use in various scientific fields. The collaborative efforts shaping the future of 360° technology are underscored by the multidisciplinary nature of the emerging nodes. This highlights the potential of 360° technology to redefine the boundaries of research and application across the scientific spectrum.

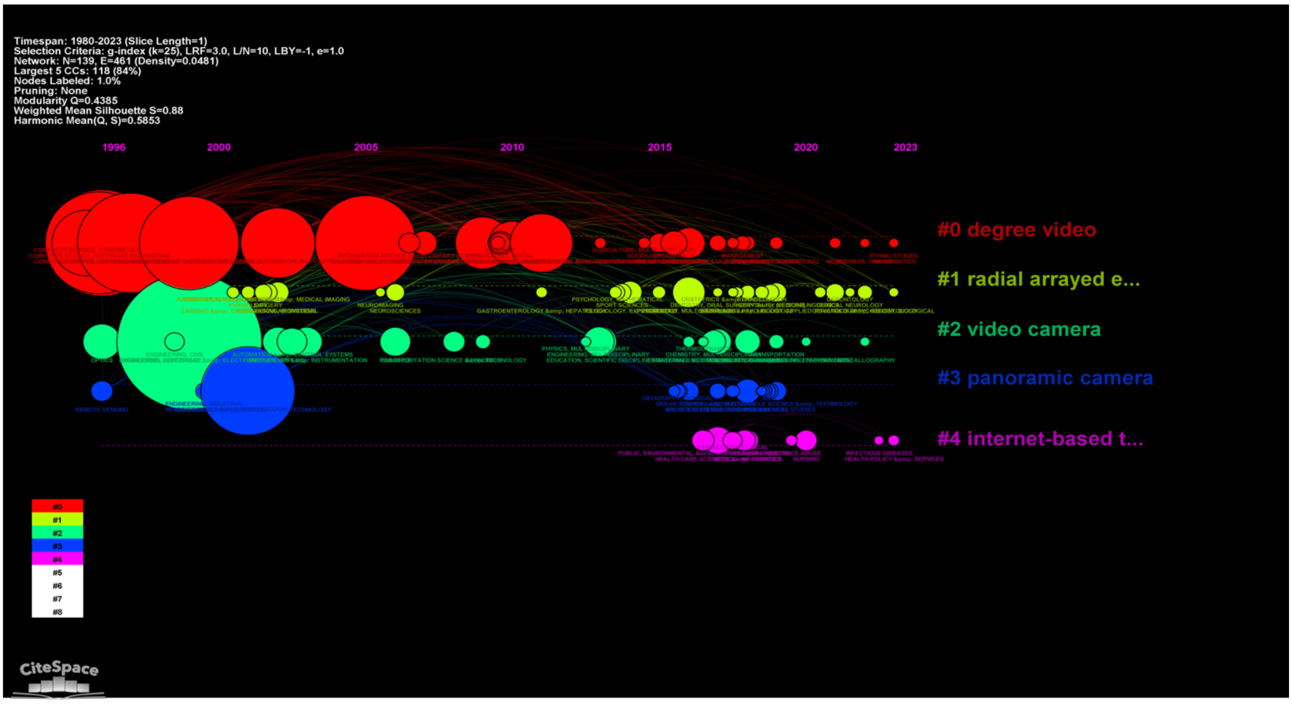

FIGURE 10 | Network of categories over years

6.1.4. Discussion

The aim of this study was to conduct a cluster and network analysis on scholarly publications in the field of 360° technology. This analysis holds significance due to multiple factors. Firstly, this approach facilitates the identification of the key areas of research within this field, as well as the subtopics that have received varying degrees of scholarly attention. This information may prove valuable to researchers seeking to develop novel studies or projects that build upon established knowledge and address existing gaps within the academic literature. Furthermore, the utilization of cluster and network analysis can enhance our understanding of the interconnections among different topics related to 360° technology and the dynamics of these relationships over time. The act of visualizing these relationships provides an opportunity to acquire a deeper understanding of the underlying dynamics and structural framework of this research, as well as to pinpoint potential domains for interdisciplinary collaboration or innovation. Ultimately, through the identification and

examination of interrelationships and shared patterns across diverse research domains, the utilization of cluster and network analysis techniques can effectively facilitate the integration and collaboration among scholars operating within different subfields of the discipline.
The conducted analysis included scientific articles from various categories obtained from Web of Science. The analysis took into account several parameters, including countries, institutions, journals, authors, citation counts, and publication years. Based on the collected data, it is apparent that the fields of engineering, computer science, and information systems have received significant research attention. The obtained results are not unexpected. The attribution of these advancements can be ascribed to the interdisciplinary characteristics of 360° video and image technology. This field extensively relies on engineering principles for the development of hardware and systems capable of capturing and processing immersive visuals. The development and fabrication of the hardware required for the acquisition and visualization of this type of media are founded upon principles of engineering. Computer science plays a crucial role in the development of algorithms, software frameworks, and data processing methods to efficiently manage high-resolution images and videos. In addition, a comprehensive comprehension of the amalgamation of diverse software and hardware elements to attain uninterrupted functionality in 360° media platforms necessitates knowledge of system information. Hence, the convergence of these disciplines exemplifies their collaborative efforts in propelling the domain of 360-degree videos and imaging forward.
Nevertheless, there is an emerging inclination towards the examination of human factors as well. Based on the conventional trajectory of technological innovation and subsequent market acceptance, our analysis findings align with anticipated outcomes. Typically, innovators prioritize securing patents for their ideas prior to commercializing them. After the submission and approval of a patent application, the functional technology can be utilized for commercial purposes and subsequently serve as the subject of academic publications.
Therefore, it is unsurprising that the integration of human factors into the realm of 360° video and image research has emerged relatively recently. The increased utilization of immersive media can be ascribed to the rapid progress in technology and enhanced availability, resulting in its widespread adoption across various domains. The importance of understanding human perception and interaction with technology has been recognized by researchers and developers. This understanding is crucial for improving the user experience, especially as an increasing number of individuals engage with 360-degree content.
Similarly, from its inception, VR has consistently followed a consistent pattern (Cipresso et al., 2018). Indeed, there has been a notable shift in the research on VRin the new millennium. This shift, commonly referred to as the clinical-VR era, has placed considerable emphasis on areas such as rehabilitation, neurosurgery, novel therapeutic approaches, and the development of laparoscopic skills. The quantity of applications and articles published in recent years aligns with the concurrent advancements in technology, specifically in terms of hardware and software. Notably, this includes the widespread adoption of head-mounted displays (HMDs) and the expansion of VR communities. VR, originally focused on engineering aspects such as hardware and software advancement, has progressively evolved into a multidisciplinary domain that considers the requirements of its users. The integration of VR technology into clinical domains has occurred as the technology has progressed and expanded beyond its initial applications. Indeed, the utilization of VR technology has transcended the confines of the gaming and entertainment industries as it has progressed and attained greater

complexity. This evolution has underscored the imperative of adopting a user-centric approach when designing VR experiences that cater to diverse user demographics.

The introduction of VR in the medical field provides additional evidence for the aforementioned growth trend. In contemporary times, healthcare practitioners employ technological advancements to facilitate patient rehabilitation and enhance surgical training. The transition from engineering to clinical application underscores the significance of incorporating human factors considerations in the utilization of elements such as 360-degree videos and imaging. The inclusion of human factors in the scientific discourse surrounding 360-degree videos, imaging, and VR signifies a progressive comprehension of user-centered design and the escalating significance of these technologies across diverse industries. Moreover, it underscores the increasing interdisciplinarity of these fields as a result of their ongoing expansion and advancement.

In both instances, namely 360-degree videos and VR, there is a notable emphasis on integrating human factors, indicating an increasing acknowledgment of the necessity to enhance interactions with state-of-the-art technologies. The integration has resulted in the emergence of novel prospects for research and development. To ensure the ongoing availability, engagement, and satisfaction of diverse users, researchers can adopt a user-centric approach by acknowledging and accommodating the inherent human needs and limitations associated with immersive technologies.

According to Figure 9, there has been a notable surge in scholarly publications pertaining to 360-degree videos and images since the year 2015. This event coincided precisely with the onset of the new economic era, characterized by substantial investments in information technology. The accessibility of 360° technologies has significantly increased due to the advancements in consumer-oriented 360° cameras and VR headsets. As a result, an increasing number of industries, such as entertainment, education, tourism, marketing, and research, have adopted the utilization of 360-degree technologies.

Despite the increasing prevalence of 360° videos, they have not attained an equivalent level of success as VR. One factor to consider is the requirement of a specific type of viewer or headset in order to fully immerse oneself in 360° videos. Despite the increasing availability and affordability of VR headsets, a significant portion of the population continues to face limited access to the necessary technological resources. The potential viewership of 360-degree video content is limited. Furthermore, although 360° videos afford viewers the ability to visually survey a scene and explore its surroundings, they lack the capability to actively immerse individuals within the environment or facilitate interaction with characters and objects, as is possible in a comprehensive VR encounter. In contrast, individuals utilizing 360-degree videos were limited to modifying their viewing perspective exclusively, lacking the ability to actively engage with or manipulate the surrounding environment they were immersed in. Another potential factor that could have contributed to the limited impact on viewers is the inadequate quality of the 360° video content. The videos exhibited recurrent problems pertaining to subpar image quality, inconsistent camera stitching, and a lack of engaging or captivating content. In recent times, notable investments and advancements in VR technology have been made by prominent organizations such as Oculus and HTC. Consequently, there has been a proliferation of high-quality VR experiences and applications, which has overshadowed the comparatively static nature of 360° videos.

Overall, the field of 360° technologies faces numerous challenges, but also holds a promising future that requires thoughtful consideration. An important unresolved matter concerns the level of interactivity and user involvement in 360° experiences. At present, 360° videos have fewer options for interaction compared to VR experiences, highlighting the necessity to create inventive techniques for actively involving users in these environments (Mancuso et al., 2023).

Another notable obstacle involves guaranteeing a consistently elevated level of Quality of Experience (QoE) for users. The challenges of stitching artifacts, resolution limitations, and ensuring a high QoE across various platforms and devices remain unresolved. Content creation continues to be intricate, necessitating the development of more user-friendly tools and workflows for content creators. The difficulty lies in resolving problems associated with narrative construction and focus control in 360° settings, requiring inventive and user-centric remedies. Enhancing accessibility is a pertinent concern, necessitating the expansion of the reach of 360° content to a wider audience. This can be achieved by reducing hardware prerequisites or creating novel display technologies. Furthermore, the absence of uniformity and compatibility across platforms poses challenges for integration. Establishing industry standards is crucial to guarantee a smooth and consistent experience across different platforms and devices. Anticipated in the future is a rise in interactivity by incorporating cutting-edge technologies like tactile feedback and gesture control. Artificial intelligence (AI) has the potential to completely transform the creation of 360° content by implementing algorithms that automatically compose scenes, enable adaptive storytelling, and generate personalized content.

One important direction is the incorporation of 360° technologies with other extended reality (XR) components. This allows for the combination of augmented reality (AR) and VR elements to create hybrid and enhanced experiences.

360-degree videos offer several advantages compared to VR, particularly in terms of achieving a harmonious blend between authentic and digitally generated settings. The utilization of virtual reality can provide users with immersive experiences; however, it often depends on computer-generated graphics, which may not consistently possess the same level of authenticity as 360-degree videos. On the other hand, 360-degree videos provide viewers with a heightened sense of realism as they encompass real-world surroundings from all angles.

The enhanced realism offered by 360-degree videos has significant implications across various domains, notably in healthcare, education, and entertainment industries. This phenomenon facilitates a heightened level of engagement with the subject matter, leading to the potential for more profound emotional responses (Calogiuri et al., 2018; Chirico et al., 2018; Chirico & Gaggioli, 2019; Jun et al., 2020; Quesnel & Riecke, 2018)

One additional advantage of 360° videos lies in their non-immersive nature. For example, the accessibility of 360° videos is more convenient on tablets and smartphones compared to VR, as the latter often necessitates the use of specialized equipment that can be cumbersome for certain users.

Indeed, certain cohorts, such as individuals receiving medical care, may find the utilization of these specialized headsets to be impracticable. In contrast, 360° videos present a more viable alternative for these individuals due to their convenient accessibility and compatibility with various devices, such as tablets, which can be viewed without causing any discomfort or disruption (Borghesi et al., 2022; Mancuso et al., 2020; Pedroli et al., 2020, 2022; Stramba-badiale et al., 2020). The profitability of businesses can be enhanced by the ability to engage with 360° content without the requirement of complex equipment or burdensome setups, primarily due to reduced initial investments and ongoing maintenance expenses. When comparing VR with the utilization of 360° videos, it becomes evident that the latter provides immersive experiences to diverse audiences in a more cost-effective and efficient manner. 360-degree videos are highly versatile in their application due to the immersive and genuine environment they provide, as well as their adaptable implementation possibilities. These experiences possess several advantages compared to traditional VR experiences as they promote accessibility, engagement, and potential benefits across diverse industries.

Thinking about future directions of this technology, the increasing utilization of 360° technologies in education and training is anticipated to be a progressive trend, offering opportunities to develop virtual classrooms, immersive training simulations, and enhanced learning experiences using 360° content.

Industries like healthcare and therapy will witness a rise in the adoption of 360° technologies for virtual therapies, immersive patient encounters, and therapeutic interventions that leverage 360° videos for mental health and rehabilitation purposes. The advancement of live streaming and social interaction in 360° environments is expected to provide real-time collaborative experiences, interactive live events, and social platforms specifically designed for sharing 360° content. The utilization of 360° technologies will make a substantial impact by documenting and preserving cultural heritage and natural environments. This will be achieved through virtual tours of historical sites, immersive documentation of endangered ecosystems, and interactive experiences that contribute to cultural preservation.

The aforementioned findings underscore the significance of interdisciplinary research in the development and utilization of 360° video and image technologies. The acknowledgement of the influence of human factors on user interaction with emerging media formats remains imperative, despite the prevailing dominance of engineering and computer science in this domain. A comprehensive comprehension of the optimal utilization of 360° videos and images for diverse objectives in different sectors can be achieved by establishing a connection between technology-oriented disciplines and human-centered studies.

It is imperative to recognize the presence of numerous unpublished research studies, despite the fact that our manuscript is classified as published research. While the Web of Science (WoS) is widely recognized for its inclusion of influential scholarly articles, it is important to acknowledge that our study is limited by the existence of several other databases that hold substantial value for the scientific community. Notable examples include the IEEE Xplore Digital Library, ACM Digital Library, and various others.

6.2. Study 2: Mindscape: integrating psychology and technologies for building cognitive and behavioral tasks.

5.2.1. Introduction

Although standard neuropsychological measures have demonstrated sufficient predictive value, their ability to accurately predict real-world functioning may be compromised due to limited ecological validity. The conventional neurocognitive assessments may not accurately reflect the wide range of environmental factors that individuals encounter in their daily lives. Furthermore, conventional neurocognitive assessments often focus on individual aspects of neuropsychological functioning, potentially failing to accurately capture the diverse cognitive domains. Despite the widespread utilization of contemporary neuropsychological assessment procedures, professionals in the field of neuropsychology have exhibited a sluggish response in adapting to the influence of technology on their discipline. Although computer-based neuropsychological assessments have several advantages compared to traditional paper-and-pencil testing, such as improved standardization of administration, more accurate timing of presentation and response latencies, ease of administration and data collection, and reliable and randomized presentation of stimuli for repeat administrations, the emphasis on ecological validity of these measures is relatively low. As previously stated, a limited number of neuropsychological assessments have been created with the explicit purpose of assessing individuals' engagement in routine activities such as community navigation, grocery shopping, and other daily living tasks. Among the various developments that have been made, only a limited number of them utilize the advancements in computer technology.

VR is a sophisticated computer interface that enables individuals to experience a state of complete immersion within a computer-generated simulation. The recognition of the advancing technology has led to the acknowledgment of the potential utilization of VR in the assessment and rehabilitation of human cognitive processes. Virtual environments offer the ability to accurately present and manipulate various sensory stimuli (such as visual, auditory, olfactory, gustatory, ambulatory, and haptic conditions). As a result, they can facilitate ecologically valid assessments that integrate the meticulous control and scientific rigor of laboratory measures with a level of realism that closely resembles real-life situations. Moreover, the increased computational capacity enables the precise capture of neurobehavioral reactions within a perceptual environment that systematically exposes individuals to intricate stimuli. Simulation technology demonstrates a unique suitability for the creation of ecologically valid environments, characterized by the presentation of three-dimensional objects in a consistent and precise manner. Consequently, individuals possess the ability to manipulate objects in a three-dimensional virtual environment that offers a variety of potential tasks. According to the study conducted by (A. A. Rizzo & Galen Buckwalter, 1997), the utilization of VR in neuropsychological assessment holds particular significance as it offers the potential for more than a mere linear expansion of current computer technology for human utilization. Rizzo emphasizes the significance of VR going beyond mere automation of conventional paradigms. Virtual environments, on the other hand, offer a transformative shift in the trajectory of future developments. There exists a fundamental conflict between individuals who prioritize ecological validity and those who prioritize maintaining experimental control. Several researchers in the field of neuropsychology would concur with Neisser's viewpoint regarding the genuine apprehensions surrounding the verisimilitude, also known as ecological validity, of neuropsychological assessments. Nevertheless, despite the extensive discourse on the matter of ecological validity within the existing body of literature, there has been a notable lack of efforts to address and rectify this predicament. In contrast, efforts have been made to solely improve the external validity of neuropsychological assessments. The concepts of external validity and ecological validity are interconnected, yet they are not interchangeable. External validity pertains to the degree to which the results obtained from research studies can be applied to a diverse range of individuals, temporal contexts, and environments, as well as to specific individuals, temporal contexts, and environments. Considering the historical development of traditional paper-and-pencil neuropsychological measures, it is evident that their primary purpose was to identify specific brain regions and their functions. This approach was centered around the concept of double dissociation. However, contemporary efforts to improve these measures primarily aim to enhance their external validity. Therefore, experimental conditions are not typically necessary to replicate real-life conditions. Neuropsychological measures exhibit a rudimentary presentation and do not demonstrate a preoccupation with the degree of realism observed in virtual environments. On the contrary, their aim is to possess external validity, which entails the ability to consistently predict behavior demonstrated in real-life situations.

As previously stated, Banaji and Crowder argue that the ecological perspective in neurocognitive research holds little significance, asserting that scientific advancement requires a stronger focus on experimental control (Banaji & Crowder, 1991) . Regrettably, a significant portion of VR research provides evidence in favor of this division. The primary focus in research studies utilizing VR for psychology and neuropsychology is often on achieving verisimilitude, which refers to the degree of realism or similarity to the real world. However, there is comparatively less attention given to veridicality, which encompasses factors such as reliability, validity, and psychometric properties. One could posit that the primary task for neuropsychologists employing virtual environments is to cultivate methodologies that effectively address the requirements of internal validity, external validity, and ecological validity in a simultaneous manner. (Parsons, 2011b) argue that the creation of an ecologically valid virtual environment necessitates the incorporation of psychometric rigor, encompassing internal and external validity, alongside the principles of verisimilitude and veridicality, which pertain to ecological validity. To attain such standards, it is necessary to take into account various factors: 1) The tasks executed within virtual environments should align with the relevant aspects of real-world activities and environments. 2) The tasks designed should accurately represent individuals who are engaged in performing these tasks. 3) Research problems should have practical implications on real-world functioning in order to contribute to the authenticity and accuracy of the virtual environment. 4) Outcome measures should be pertinent to the practical problem under investigation (see figure 10).

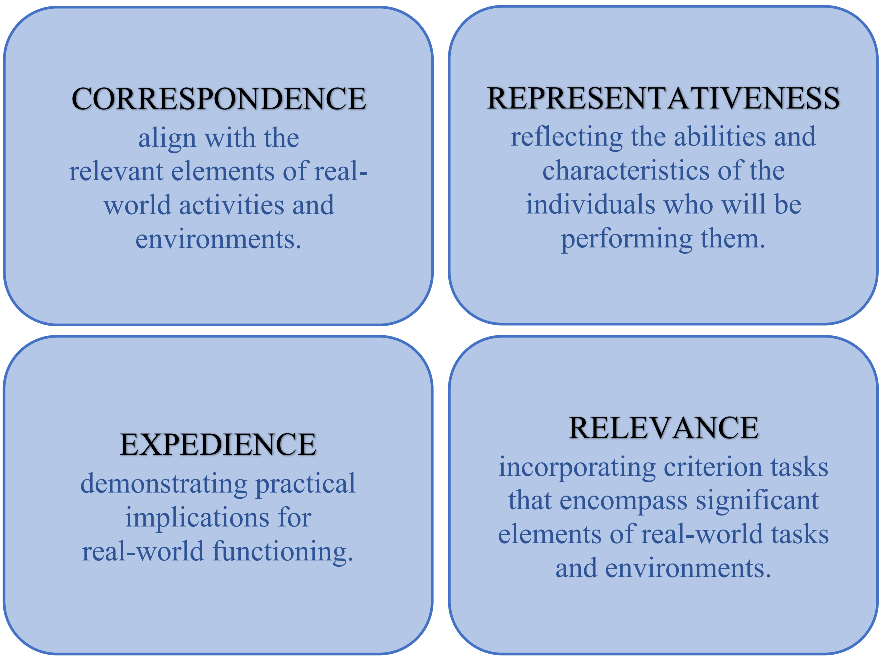

Figure 10: characteristics of ecologically valid virtual environments

Correspondence: The tasks executed within virtual environments should align with the relevant elements of real-world activities and environments. Virtual environments offer the potential to systematically administer cognitive tasks that target various domains of performance, surpassing the limitations of traditional methods. The verisimilitude of cognitive assessment in VR can be improved through the implementation of various measures. These measures include better management of the perceptual environment, ensuring a more consistent presentation of stimuli, and employing more precise and accurate scoring methods. The enhancement of the validity of neuropsychological measurements using VR can be achieved by quantifying more distinct behavioral responses, which enables the identification of cognitive domains that are more specific. There is also the potential for VR to facilitate neuropsychological assessments that offer greater ecological validity by testing neurocognition in more realistic situations. Participants can undergo evaluation within a simulated real-world setting, as opposed to an artificial testing environment. The integration of VR technology into neuro-psychological evaluations has the potential to enhance the authenticity of synthetic experiences, thereby increasing their verisimilitude. The concept of verisimilitude underscores the importance of aligning the data collection method with real-life tasks conducted in an open environment. Neuropsychologists with an interest in VR measures will develop immersive experiences that offer engaging interactive narratives, aiming to simulate real-world scenarios.

Representativeness: The tasks that have been developed should accurately reflect the abilities and characteristics of the individuals who will be performing them. In addition to the careful consideration of tasks and outcome measures, it is imperative to also take into account the subject populations involved in the study. It is crucial to guarantee that these populations accurately represent individuals who are engaged in the tasks. Authors of VR-based neuropsychological studies must ensure that they provide sufficient details regarding the sampling strategy employed. This is essential to enable readers to evaluate the extent to which the sample under investigation accurately represents the intended population. The importance of study design lies in its impact on the generalizability and validity of the study, particularly when sampling bias is introduced. In order for the study findings to possess generalizability to the entire population, it is imperative that the sample selected is representative of the population from which it is derived. Therefore, it is imperative that the assessment of ecological validity incorporates cultural sensitivity and a design that incorporates appropriate language. This includes interventions that prioritize the use of language that is culturally appropriate and promotes a deeper understanding of cultural knowledge. Furthermore, the visually mediated environments present in virtual reality underscore the imperative for researchers in the field of VR to create environments that effectively utilize symbols and concepts that are commonly understood by the specific population under investigation. The topic at hand holds significant importance for researchers in the field of VR within a multicultural society. Hence, it is imperative that neuropsychological evaluations effectively incorporate cultural factors, such as values, customs, and traditions. In addition to the advancement of forthcoming virtual simulations, there may arise a necessity to modify existing treatment manuals to encompass cultural values and affirm the distinctiveness of the specific ethnic cohort. The user did not provide any text to rewrite. Although conventional neuropsychological tests strive for generalizability, an ecologically valid assessment involves aligning the neurocognitive evaluation with the sociocultural context of the target population or the individual being assessed.

Expedience: For research problems to be considered integral to veridicality, they must demonstrate practical implications for real-world functioning. In order for the neuropsychological measure to exhibit veridicality, it is imperative that the outcomes of the test accurately reflect and have the ability to predict real-world phenomena. Research problems should be regarded as pragmatic tools whose value is assessed based on criteria beyond the mere adherence to a standard of plausibility, wherein the concepts and theories are expected to accurately reflect the real world. The matter of determining accuracy is primarily a concern of pragmatic instrumentalism, wherein the effectiveness of VR-based neuropsychological assessment results in explaining and predicting future neurocognitive performance and daily activities serves as the criterion for evaluating their significance. One commonly employed approach to ascertain the accuracy of VR-based neuropsychological measures involves the utilization of the multitrait-multimethod matrix. This method entails the measurement of a particular construct through multiple methods, resulting in the development of a matrix that outlines the relationship between the construct and the measures employed (Campbell & Fiske, 1959). The multitrait-multimethod matrix provides a means of evaluating the convergent and divergent validity of a measurement instrument through the analysis of its correlation patterns with other measures. In the context of a neuropsychological study utilizing VR, it is worth noting that the scales employed in such research endeavors often aim to assess the construct of memory. However, it is important to acknowledge that these scales may differ in terms of the degree of memory impairment they measure or the specific aspect of memory they evaluate. The assessment of convergent validity coefficients, specifically in the memory domain, can involve comparing the correlations between the memory scores obtained from VR technology and those obtained from traditional neuropsychological measures of memory. This comparison aims to determine whether these correlations are statistically significant and greater in magnitude than the correlations observed between different measures assessing domains other than memory within the same set of measures. Discriminant validity can be established by observing lower correlations between scales assessed using different measures, compared to the coefficients of convergent validity.

Relevance: In order to achieve neurocognitive assessment questions that yield ecologically valid answers pertaining to real-world functioning, it is imperative to incorporate criterion tasks that encompass substantial elements of real-world tasks and environments. Although computerized assessments are valuable for evaluating performance on laboratory tasks, they prove inadequate in providing solutions to real-world problems. It is imperative to acknowledge that contemporary neuropsychological assessments, encompassing both traditional pen-and-paper tests and computerized evaluations, play a significant role in elucidating the origins and characteristics of variations in individual performance. Nevertheless, it is uncommon for neuropsychologists to solely rely on laboratory measures as a means to fully comprehend the challenges they face when presented with a referral for a neuropsychological assessment. Therefore, in order to address the ecological concern of relevance in VR-based neuropsychological assessments, it is imperative for neuropsychologists to recognize that experience encompasses both individual elements and the interconnections between these elements. Hence, it is imperative to include both the specificities of the neurocognitive domains and the interconnections between these domains that arise from interactions in the real world within our explanatory frameworks. The adequacy of any neuropsychological measure that is based on VR is compromised if it solely focuses on evaluating a neurocognitive domain without providing an explanation for the emergence of meaning, values, intentionality, and activities of daily living from that domain.

As previously mentioned, VR is a viable technology that has the potential to encompass all four essential features necessary for the development of a robust ecological assessment tool.

A recent innovation in VR technology, 360° immersive images and videos, presents an additional avenue for conducting neuropsychological assessments. 360° cameras have the capability to capture a fisheye view of the surrounding environment. This captured view can then be presented to the user through a head-mounted display or by manipulating the viewpoint using a mouse or finger. The ability to select the specific location for observation is granted, however, direct engagement with the narratives is precluded due to the manner in which they are actualized. Moreover, the possibility for users to customize their own interpretation of the narrative, commonly known as personalization, has become increasingly prevalent. The researcher has the ability to design an immersive experience for the audience, aiming to provide explicit instructions for their focus. However, ultimately, it is the audience's prerogative to determine their own points of interest and allocate their time accordingly. Hence, agency, which plays a significant role in the generation of presence, the subjective experience of being immersed in a virtual environment, stands out as a prominent distinction between 360-degree and two-dimensional video formats. In alignment with VR, 360-degree videos have the capacity to elicit profound emotional responses by creating a sense of physical presence and facilitating user engagement and reactions akin to real-world experiences. The concept of a sense of presence refers to the perceptual experience of "being there" within a virtual environment. In the context of 360° videos, individuals have the ability to select their preferred perspective, which typically falls into one of two categories: first-person or third-person. The narrative perspective in which a character is perceived by the audience as if they were experiencing events firsthand is commonly known as the "first person point of view." The concept of "third-person point of view" characterizes the reader's role as an observer rather than an active participant in the narrative. The utilization of this approach offers certain benefits in comparison to the utilization of the first-person perspective, as it reduces the likelihood of experiencing a complete loss of presence.

The various attributes of 360° videos and images render them a highly suitable instrument for constructing innovative cognitive tasks. Indeed, individuals have the capacity to encounter photorealistic surroundings from a first-person viewpoint through immersive 360° scenarios. This characteristic has the potential to enhance the precision of medical procedures and is of utmost importance for the assessment of various memory-related variables. Furthermore, the incorporation of photorealistic aesthetics in 360° technologies enhances their ecological significance. This is due to the profound influence that the level of immersion and realism has on the encoding processes of memory. Despite the perceived lack of interactivity in 360° videos when compared to VR, it is feasible to modify the environment by incorporating links or hotspots on a door. This alteration creates an illusion of transitioning between rooms, albeit without the intended capacity for comprehensive interaction. 360-degree videos have the potential to enhance viewers' sense of presence by creating the illusion of being able to navigate and interact with objects within the video. Moreover, due to the absence of manual control requirements, a broader demographic can be effectively engaged by these technologies, encompassing individuals with motor impairments. Furthermore, it is feasible to investigate the immediate environment or make item selections by directing one's attention towards the designated hotspots using visual perception.

Although there have been promising findings in the field of memory and executive function testing, their utilization in neuropsychological evaluation remains relatively uncommon. One potential challenge that may arise is the complexity associated with the development of tools or the editing of 360-degree videos in order to align with clinical specifications.

Presently, in contrast to previous times, the predominant concern regarding VR lies in the financial aspect, specifically pertaining to the software rather than the hardware. Indeed, at a cost of less than $1,500 USD, one can acquire the essential hardware components required for this purpose. These components encompass a computer equipped with a high-quality graphics card, a head-mounted display (HMD), and a Kinect device. Nevertheless, the process of programming a personalized protocol or creating an experimental design incurs substantial expenses, amounting to thousands of dollars per experiment. This is primarily due to the involvement of a multidisciplinary team comprising engineers, user specialists, and psychologists who collaborate to develop innovative technologies. The primary concern associated with the utilization of novel technology and VR pertains to the aspect of customization. In order to effectively utilize VR technology, researchers must possess a high degree of flexibility and adaptability. As the level of flexibility demanded increases, the corresponding complexity of the system also escalates, necessitating more intricate programming, expertise in computer graphics, specialized user design, considerations for usability and ergonomics, integration of software developer kits, engineering proficiency, knowledge of 3D architecture, and other related factors.

The objective of this study is to introduce MindScape, an advanced platform designed by clinicians specifically for clinicians. The platform enables the creation of ecologically valid and controlled environments, incorporating standardized multimodal stimulation, precise feedback on performance, and automated tracking of outcomes. This software provides individuals with the opportunity to utilize fully customizable virtual environments for any desired objective. Enhancing the efficacy of the devised scenarios can be achieved through the utilization of photographs depicting familiar objects and individuals with whom the patient regularly engages. The study will administer two memory assessments: an object recognition task and a spatial memory task. The primary objective is to assess visual memory through the simulation of a realistic scenario that could potentially arise in

everyday circumstances. Participants are required to encode and subsequently retrieve specific objects that have been displaced within a virtual living room environment. During the second phase, participants are required to navigate through a series of apartment rooms and accurately identify the floor plan of the house from a set of four different maps.
The utilization of 360° immersive photos and videos does not necessitate expertise in advanced technical skills, and the equipment required for capturing and subsequently displaying 360° content is also more cost-effective compared to conventional VR setups. Moreover, 360-degree environments provide an elevated degree of visual authenticity as they serve as visual depictions of real-life scenarios, thereby enhancing participant engagement to a greater extent.

In particular, the capacity to engage with 360° environments from an immersive egocentric standpoint, coupled with the provision of high visual fidelity, which is linked to enhanced encoding of visual memory, renders 360°-VR a viable instrument for investigating memory processes. The potential of these novel virtual environments appears to be promising in the development of ecological assessment tools for memory processes, as they have the ability to evoke visual exploration mechanisms that closely resemble those observed in real-world settings.

6.2.2. MINDSCAPE: a novel platform for building cognitive tasks

The recently developed platform seeks to transform the field of neuropsychological assessment by incorporating pre-existing software capable of playing 360° media, in addition to a personalized architecture that comprehend JavaScript and HTML extensions that provide supplemental features to the software. The platform offers researchers a distinctive tool for constructing virtual environments, which enables users of all levels of expertise to easily create a virtual scene that optimally fulfills the demands of experimental design and clinical protocols. The aforementioned characteristic renders the platform highly advantageous for the purpose of conducting research.
MindScape has the capability to integrate 360-degree images and videos with questionnaires, thereby generating novel tasks and assessments that can be employed to examine and gain insights into individuals' cognitive processes. The aforementioned tasks and tests can be employed for the purpose of assessing and gaining further insights into individuals' cognitive processes. The platform's user-friendly design and easy accessibility make it suitable for utilization by both researchers and clinicians. The software offers a unique and captivating method for conducting neuropsychological tests, thanks to its user-friendly interface and smooth incorporation of 360-degree media. Through the utilization of 360-degree media, the platform facilitates a heightened level of immersion for users, concurrently offering a more precise depiction of real-life situations. Furthermore, the platform offers a diverse array of questionnaire options, enabling clinicians and researchers to customize assessments according to the unique needs of specific populations. Due to its versatile nature, the platform exhibits suitability for implementation across various contexts, encompassing educational settings, clinical trials, and research investigations.
Several significant features of the platform encompass Hotspots, Animated Panorama, Hosting, Live Panorama, 3D Transition Effect, Social Sharing, Maps, Floor Plans, Virtual Reality Hotspots, and 360-Site Streams. Furthermore, users possess the capability to generate personalized virtual tasks, and the software exhibits compatibility with a diverse array of operating systems. The utilization of the editor module facilitates a straightforward procedure for researchers to generate protocols. Users have the capability to import a diverse range of 2D and 3D objects, images, and videos. These

imported elements can be manipulated using the drag-and-drop technique to facilitate actions such as importing, moving, rotating, and scaling. These objects can then be utilized in time- or space-specific events. The integration of 360-degree photos and videos in the context of neuropsychological testing has the potential to enhance the precision and ecological validity of cognitive process assessments. This represents a potential outcome in a general sense. This technology facilitates a more extensive comprehension of an individual's cognitive capacities and holds the potential to ultimately yield more efficient interventions and treatments by creating an environment that is simultaneously more immersive and authentic.

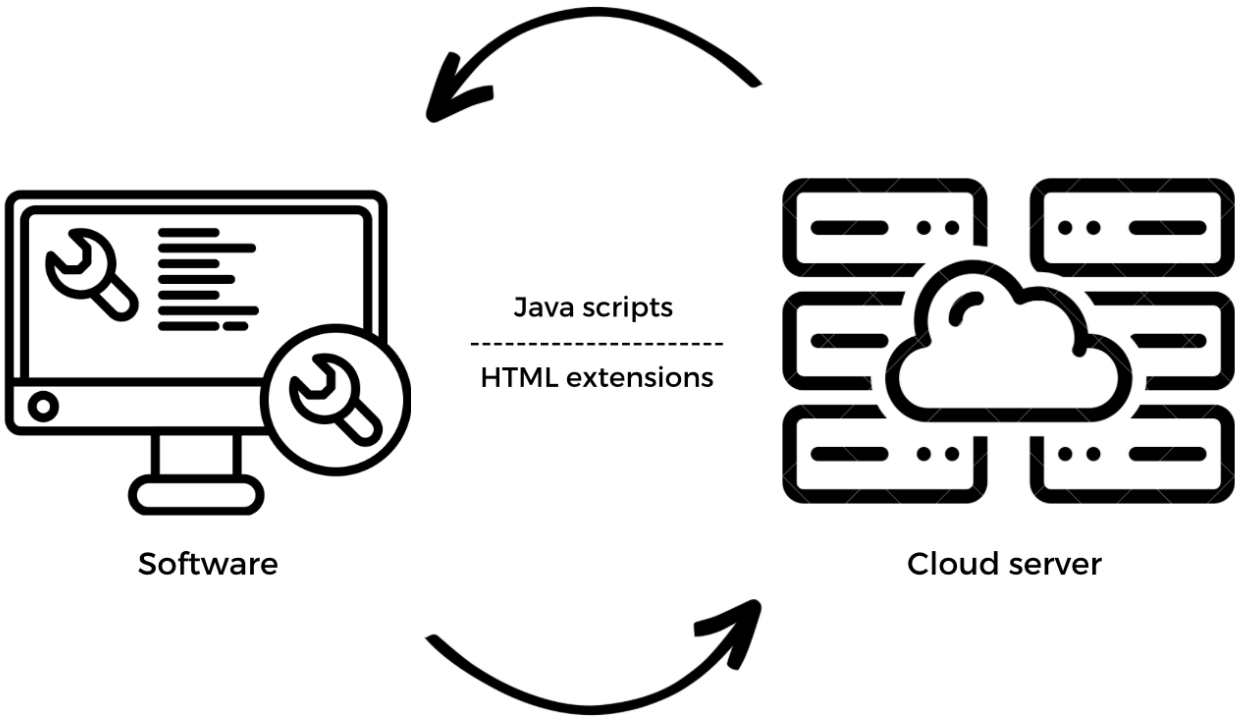

Fig. 11. Illustration of the interaction between the software and the cloud server

As a result of these characteristics, researchers and healthcare professionals are now afforded the opportunity to utilize, replicate, disseminate, analyze, adapt, and enhance any form of content (including objects and environments) for the betterment of the virtual reality community. One additional feature offered by the platform is the ability to navigate and engage with the virtual environments, while concurrently generating hotspots that establish connections between various panoramas. During the execution of simulations on the system, users are provided with a range of inherent functionalities that, when integrated, enhance the realism of the environment. The aforementioned features encompass collision detection for regulating movement within the environment, lifelike walking motion, three-dimensional audio, sophisticated lighting techniques to enhance image quality, and advanced lighting techniques. The user is presented with a choice between two fundamental configuration options: an immersive visualization mode and a non-immersive visualization mode. The visual representation can be observed in either monoscopic or stereoscopic mode, contingent upon the utilization of a Head-Mounted Display (HMD) and the adoption of an immersive modality. Furthermore, there exists provision for the incorporation of head-tracking sensors. Within the non-immersive mode, the virtual environment has the capability to be visually presented on either a desktop monitor or a wall projector, contingent upon the user's individual inclination. The user possesses the capability to engage with the virtual environment through the utilization of various input devices, such as the keyboard, mouse, or joy-pad commands, contingent upon the specific hardware configuration that has been chosen. At the onset of the experiment, the researcher has the ability to strategically place the camera within the editor, thereby influencing the users' initial perception of the environment.

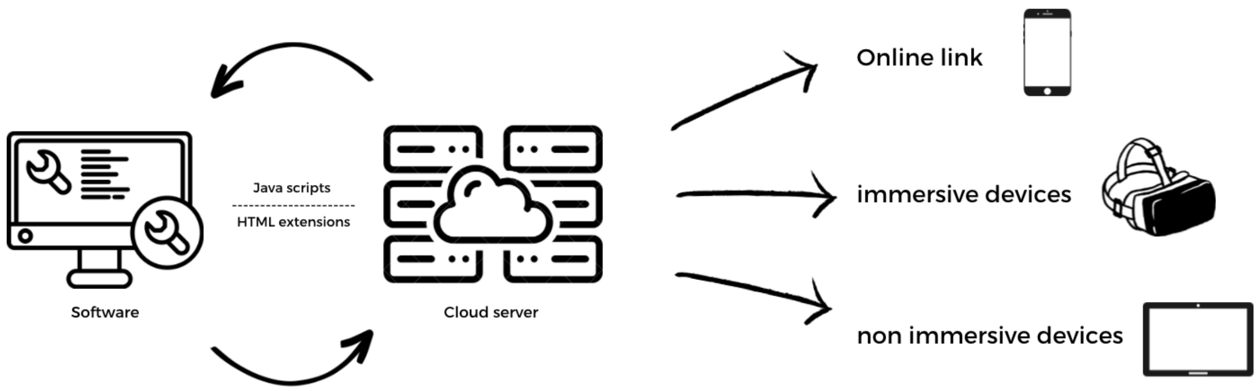

Fig. 12. A depiction of the results generated by Mindscape. This platform's product can be accessed via a hyperlink on a mobile device or uploaded to a head-mounted display on a non-immersive device such as a tablet.

Furthermore, after incorporating an object into a 360-degree panorama, it becomes feasible to activate it and issue a command for it to execute an action in reaction to a specific trigger-based event. This enables the object to engage with the panorama in a manner that was previously unattainable. One instance of this phenomenon can be observed when a user interacts with a simulated environment and approaches a specific entity, such as a car, wherein an auditory cue may be triggered. The configuration of the trigger and action can be easily customized using a user-friendly graphical interface. The implementation of an interactive video segment, which incorporates pre-recorded narratives, holds potential for effectively immersing users in virtual reality experiences. This approach leverages real video content within virtual environments to enhance user engagement and exposure to virtual reality. The achievement of this objective can be facilitated through the establishment of a virtual environment.

6.2.3. Two novel memory tasks from MindScape

Episodic memory assessment

Virtual environment. The virtual house in question is composed of several distinct areas. These include a kitchen area equipped with a refrigerator, a closet, a table, and various other essential kitchen fixtures. Additionally, there is a living room area furnished with two sofas, a small table, a central shelf, a lamp, a television, and a chimney. Furthermore, there is a bedroom area featuring a bed and a wardrobe. Lastly, the bathroom is visible through a door within the house. The environment lacks any characters.

This environment has the capability to operate on tablet devices as well as in immersive modalities. In the latter case, a basic cardboard device is utilized, enabling the user to rotate their head and have a complete 360◦ view. Additionally, interaction with the environment is facilitated through the use of gaze-based controls.

Virtual objects. A total of forty-five objects were generated with the purpose of populating the Virtual Shop, serving as either targets or distractors. It should be noted that these objects possess the versatility to be utilized in any alternative virtual setting. Various variables were systematically manipulated, examined, and evaluated throughout the process of their development in order to guarantee that the objects possess comparable characteristics and lack any ambiguity. Initially, four distinct semantic categories were identified, namely kitchen items, living room items, musical instruments, and home decor items. All the objects mentioned were tangible items that are typically encountered in residential dwellings.

The utilization of clear and unequivocal stimuli is of utmost importance in psychological assessments to effectively control for confounding variables, such as the accurate or inaccurate encoding of semantic information associated with the object.

Familiarization. Prior to commencing the memory VR task, participants underwent a familiarization phase in which they were introduced to the virtual devices within a simulated household setting. During this phase, participants were instructed to navigate through the virtual environment and adhere to the provided instructions. According to the instructions provided in the tablet version, users are instructed to horizontally swipe their finger to the right and subsequently tap on the green circle. Upon selecting the green circle, the subsequent instruction materializes, prompting the user to horizontally swipe their finger and subsequently select the green circle. This directive is employed to establish the comprehensibility of the environment's navigability in a complete circle of 360 degrees, as well as to indicate that the objects within said environment possess the capability of being interacted with through clicking. In the concluding directive of this phase of familiarization, participants are requested to select the door in order to move to a different room. Consequently, the participants find themselves situated within the bathroom environment, wherein they are presented with an instruction to interact with the drawer to ascertain its contents. The final instruction serves to convey the concept of interactivity within the environment, emphasizing that the act of clicking on the doors enables the transition between rooms. This functionality is integral to the execution of the spatial memory task.

Encoding. In the initial phase, the objective entailed the categorization of 15 distinct entities enclosed within various boxes distributed in the house' environments, with each object being easily recognizable. In order to carry out the task, participants were provided with instructions to open each of the boxes and verbally identify the objects contained within. Specifically, they were instructed to imagine themselves entering Marco's new residence. Please engage in a thorough examination of the room, meticulously selecting each box and audibly articulating the identity of the item it contains. Fifteen distractors, which shared a semantic category with the target items, were strategically positioned in comparable locations. Upon activation, the object is visually rendered in a two-dimensional format against a white backdrop for a duration of three seconds per appearance. Subsequently, the identical object is positioned within the confines of its respective container (see figure 13). The task concluded upon the completion of opening all the boxes. Located in the upper left corner of the screen is a numerical display that provides a count of the quantity of boxes that have been opened. At this juncture, it is advised that participants proceed to select the primary entrance by clicking on the designated area labeled "as soon as you finish, click here." A neutral gray environment is presented, accompanied by the following prompt: "Reflect upon the contents of the boxes that were previously opened and record any items that you remember" This phase is referred to as the **free recall phase.** The variable labeled as "Correct Items" is assessed based on the participant's ability to accurately identify the types of items contained in the boxes.

Following an interval of ten minutes of interference with visuo-spatial tasks, individuals subsequently resume their engagement in the task. Within the confines of the aforementioned dwelling, one can observe the presence of various objects that are dispersed throughout the space. These objects are comprised of the contents of the boxes, as well as an additional set of 15 distractors that were initially introduced during the encoding phase. Furthermore, an additional 15 objects, belonging to the same semantic categories as the distractors, have been included. The following are the provided instructions: You are revisiting Marco's recently acquired residence. To navigate the apartment, utilize touch screen functionality by swiping your finger across the screen. Click on the objects that have been previously extracted from the boxes by tapping on them.

Upon selecting an object, a luminous outline emerges, serving as a form of feedback for the user. The task concludes when the participant indicates that they have chosen all of the objects. In this particular instance, the platform provides users/clinicians with the option to determine whether or not to display the score. The variable labeled as "Correct Items" is assessed based on the participant's ability to accurately identify those objects previously seen in the boxes.

Fig. 13. (a) encoding phase: patients have to explore the 360° panorama, click on each box, and label the object that appears; (b) retrieval phase: patients have to explore the 360° panorama and click only the objects they previously saw in the boxes.

Table 5. The descriptions of scores of the episodic memory task.

Score	Description	Method
Encoding	The quantity of accurately encoded items that participants successfully completed during the initial phase of the task.	Each object successfully identified within the box will receive one point. The highest attainable score is 15, indicating complete recognition of all elements in this stage.
Free Recall	The participant's capacity to retrieve information without any external signals or prompts following the encoding phase.	Participants are instructed to retrieve as many objects as they can without any special prompts. Each accurately remembered item contributes to the score, with a maximum score of 15 for complete and precise recall.
Retrieval of target	The participant's capacity to recognize objects that were previously stored in memory throughout the task (target objects) when they are once again immersed in the virtual environment.	Participants are exposed to the identical setting in which the encoding took place. In this case, the items that were previously encoded are intermingled with distractors. The score is determined by the accuracy of identifying the correct items among the distractors, which consist of 15 known items and 15 unknown items. The highest attainable score is 15.
Retrieval of known distractors	The count of objects that were mistakenly identified as targets. These things are classified as "known" distractors due to their initial presence outside the boxes in the virtual environment during the encoding phase.	Participants may erroneously attribute items as being part of the encoding phase, despite these items being present in the initial house setting. Every wrong identification results in a deduction from the score.
Retrieval of unknown distractors	The number of objects that were mistakenly recognized as targets. The "unknown" distractors refer to novel objects that were not initially present in the boxes or the house environment during the task.	Participants may erroneously classify entirely unfamiliar items as if they were included in the initial encoding process. Every wrong identification decreases the total score.

Spatial Assessment task

Virtual environment: The virtual environment refers to a tangible living space that has been captured through the utilization of the Insta One X 360-degree camera configuration. The present configuration, which exists in three dimensions, encompasses separate functional areas that collectively contribute to the generation of a visually and spatially captivating encounter. The residence encompasses a kitchen area that incorporates a centrally positioned table, along with intricate elements such as appliances, shelves, and furnishings. The spatial configuration encompasses the living room, which includes the placement of an extra table amidst various pieces of furniture, such as a sofa and a stove. In addition to the primary ingress, there exists an alternative portal that grants access to a passageway. The corridor is bordered by six doors, each leading to separate rooms, including the living room, two bedrooms, and two bathrooms.

The familiarization phase is the same as described above in the episodic memory task.

Prior to commencing, the participants were presented with the subsequent instructions displayed on the tablet screen: "You are entering an apartment." Examine the various rooms while considering their spatial arrangement within the dwelling. Please select the different doors to enter and exit the various rooms.

The task starts from the dining room and kitchen area. The participant is afforded the freedom to engage in interactions by clicking on the different doors in order to transition between rooms (see figure 14 and 15).

Once the participants believe they have completed their examination of all the rooms, specifically after having opened the remaining five doors, the clinician instructs them to return to the main room to continue with the testing process. Upon activating the main entrance, a set of instructions appears, presenting four distinct maps depicting the layout of the previously explored domicile. "Look through the available options and identify the appropriate one". The first option is displayed on the screen in an allocentric perspective, accompanied by a small arrow indicating the possibility to proceed to the subsequent option. Following the presentation of the fourth and final option, it becomes apparent that all four maps are amenable to comparative analysis. In order to make a selection, the participant is required to click on the designated symbol labeled "click here to answer". This feature provides users with the opportunity to either revisit and examine the maps or proceed with a multiple-choice question, wherein they can choose a number ranging from 1 to 5.

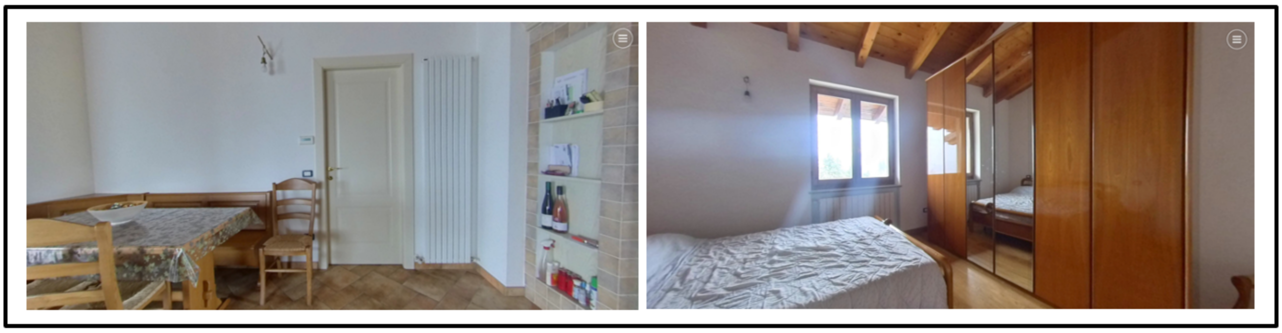

Figure 14. Encoding phase: patients have to explore the 360° panoramas, clicking on the doors to move from one room to another.

Figure 15. Retrieval phase: patients have to choose the map that represents the house they have just explored.

For this task, navigation can be done in the virtual environment by using a non-immersive device, like a tablet. The process is engaging with the virtual environment by selecting different doors to move between different places. Every room relates to a distinct section of the virtual house. Navigation is facilitated by selecting doors, which mimic real-world physical movements in the virtual environment and offer a user-friendly and intuitive mode of interaction. If a head-mounted display is used, navigation can be accomplished by using the joystick to control the direction. By either clicking on doors or fixating their attention on the doors, users can navigate between various places inside the virtual environment, depending on the type of head-mounted display.

6.2.4. Discussion

The incorporation of immersive technologies has recently surfaced as a potentially promising avenue to investigate in the field of cognitive assessment and rehabilitation. In light of the aforementioned shift in paradigm, it is crucial to establish accessible platforms that facilitate the development of cognitive tasks by researchers and clinicians, regardless of their level of expertise in engineering. The utilization of user-friendly platforms can enhance the accessibility and influence of immersive technologies, thereby maximizing their potential to significantly transform cognitive assessment and rehabilitation.
The demonstrated potential of immersive technologies to revolutionize cognitive assessment and rehabilitation is noteworthy. This is achieved by creating an environment that is distinguished by its immersive and authentic characteristics. As a result, individuals have the capability to engage in interactions that closely mimic real-life experiences, thus promoting a heightened sense of

authenticity in their engagement. By employing this methodology, a more thorough understanding of cognitive capabilities is achieved. The emergence of user-friendly platforms has streamlined the process of task creation, resulting in an increased adoption of these advanced technologies by a larger cohort of clinicians and researchers.

MindScape functions as a conduit for cognitive innovation. This platform exemplifies a notable instance of a software that is both accessible and user-friendly. The inclusion of drag-and-drop functionality in the interface obviates the need for researchers and clinicians to possess specialized engineering expertise. This functionality allows users to easily generate engaging tasks and environments. The inherent user-friendliness of this system not only accelerates the process of task creation, but also presents innovative opportunities for cognitive rehabilitation. The effectiveness of immersive environment exercises in the treatment of neurological conditions, such as stroke and traumatic brain injury, has been well-documented.

Moreover, MindScape not only facilitates the empowerment of clinicians and researchers, but it also engenders a comprehensive transformation in the way patients navigate the clinical process. The integration of virtual environments and interactive activities can contribute to the improvement of patient engagement in cognitive and motor rehabilitation. There exists a potential for this intervention to augment adherence to treatment protocols, thereby expediting the recuperation process.

However, the integration of immersive technologies in the realm of cognitive assessment and rehabilitation presents various challenges that need to be overcome before any progress can be made in this area. The assurance of the dependability and precision of research outcomes has emerged as a prominent field of inquiry, resulting in the acknowledgment of standardized procedures as a critical concern. A potential constraint of the initiative lies in the requirement for specialized tools and information, which could hinder certain demographics from fully leveraging its benefits. Additional research is necessary to evaluate the effectiveness of immersive technologies in these fields and to support their efficacy through the implementation of interventions based on empirical evidence.

In conclusion, the integration of immersive technologies demonstrates considerable promise in the field of cognitive assessment and rehabilitation. Platforms such as MindScape play a crucial role in fostering engagement between individuals possessing advanced technological skills and those who lack technical expertise. Consequently, these platforms contribute to the advancement of innovation and the promotion of inclusivity. Notwithstanding the existence of numerous obstacles, the potential benefits linked to the improvement of rehabilitation outcomes and cognitive functions highlight the significance of continuous research and development in this field.

This work also presents two novel tests for the assessment of episodic and spatial memory. The design of these two tasks has been formulated with the intention of adhering to the guidelines for constructing an assessment tool, taking into consideration both practical and diagnostic requirements (Jin et al., 2020). In particular, (i) the examination is of short duration; (ii) the test questions are built to avoid inducing emotional distress in the patient, (iii) the examination refrains from engaging the patient's family members and collateral individuals; (iv) the administration of the test is straightforward, necessitating only minimal training for both delivery and evaluation; (v) the test exhibits a minimalistic approach with regards to the necessary materials; (vi) the test exhibits a high degree of sensitivity and specificity, indicating its ability to consistently produce accurate and reliable results when repeated; (vii) multiple parallel versions with varying objects are accessible.

6.3. Study 3: Convergent and divergent validity of two memory tasks built with 360-degree technologies: a psychometric study.

5.3.1. Introduction

One typical aim of neuropsychological evaluation is to assess memory function. The concept of memory is widely acknowledged within the field of neuropsychology as encompassing a range of cognitive processes that pertain to the ability to encode, store, and retrieve information. In light of the essential cognitive processes implicated in memory and its consequential effects on everyday functioning, researchers in the field of memory aim to elucidate the neural underpinnings associated with memory. Moreover, the cognitive processing of information stored in memory necessitates that the neural connections engage in the analysis of observations across multiple levels in a coherent manner. Contemporary perspectives on the neurobiology of hippocampal function strive to incorporate additional dimensions of analysis, namely anatomical, physiological, and plasticity-related aspects. Although standard neuropsychological measures have been determined to possess sufficient predictive value, their ability to accurately predict real-world functioning may be compromised due to limitations in ecological validity. The conventional neurocognitive assessments may not accurately reflect the wide range of environmental conditions in which individuals reside. Moreover, conventional neurocognitive assessments often focus on analyzing individual aspects of neuropsychological functioning, potentially failing to capture the full range of distinct cognitive domains. The accurate assessment of memory impairments is of utmost importance, especially in populations that are more prone to developing dementia. The importance of identifying potential impairments, especially among cohorts affected by MCI, is emphasized by this imperative. Individuals with MCI are at a crucial stage, as they face an increased likelihood of progressing into clinically evident dementia. Therefore, conducting a thorough evaluation of memory functions is an essential undertaking. This effort is crucial as it has the potential to reveal subtle cognitive differences that may indicate the onset of more severe cognitive decline. As a result, these thorough memory assessments play a crucial role as diagnostic tools that aid in early intervention and the implementation of suitable therapeutic approaches to mitigate cognitive decline patterns within this vulnerable population.

Amnestic mild cognitive impairment (aMCI) is distinguished by memory impairments that exceed the typical decline associated with aging. These impairments can manifest as either selective deficits in memory (referred to as single-domain aMCI) or as deficits in memory along with impairments in other cognitive domains, such as language, attention, executive function, or visuospatial skills (known as multiple-domain aMCI). Importantly, aMCI is linked to an increased likelihood of developing Alzheimer's disease (Petersen, 2004). The prevalence of this condition ranges from 5.8% to 18.5% in the elderly population aged 50 to 95 years (Bowen et al., 1997; Mitchell & Shiri-Feshki, 2009; Petersen et al., 1999; Tierney et al., 1996). Therefore, the identification of this transitional phase as a clinical condition that lies between typical cognitive aging and dementia holds significance in terms of preventing relapse and the advancement towards Alzheimer's disease (AD)(Petersen et al., 1999). Patients with aMCI typically exhibit intact overall cognitive abilities and are able to engage in daily activities. However, the diagnosis of aMCI is typically established by considering both objective memory complaints and subjective memory decline (Ganguli et al., 2004; Petersen et al., 2001). The symptoms of aMCI typically manifest as difficulties in the processes of encoding and retrieving contextual memory. These individuals exhibit difficulties in recalling the association between objects or the connection between an object and its surrounding context, commonly referred to as associative memory (Troyer et al., 2008). The cognitive condition of certain individuals in this patient cohort seems to remain stable or potentially revert back to a normal state. However, it is noteworthy that over fifty percent of these individuals experience a progression to AD within a timeframe of three to six years (Fisk et al., 2003; Fisk & Rockwood, 2005).

Moreover, individuals diagnosed with aMCI frequently report experiencing spatial deficits, specifically difficulties in navigating their physical surroundings (referred to as "topographical disorientation" in the literature) (De Renzi et al., 1977). The impairment of spatial navigation is a characteristic that manifests early in the progression of AD (Henderson, Mack, & Williams, 1989; Hort et al., 2007). This impairment may be attributed to the atrophy of the hippocampus, a phenomenon that is also observed in individuals with amnestic mild cognitive impairment (Shi, Liu, Zhou, Yu, & Jiang, 2009). Two primary categories of spatial navigation are allocentric and egocentric references. Allocentrism, also known as object- or environment-centered perspective, pertains to the capacity to perceive the world from an impersonal standpoint and within a familiar environment. On the other hand, egocentrism, or ego- or body-centered perspective, involves the ability to perceive the world from a personal viewpoint, which plays a crucial role in maintaining a stable perception from moment to moment (Barry et al., 2006; Keefe & Nadel, 1978). Research conducted on the neural mechanisms underlying spatial navigation has provided evidence suggesting that the hippocampus and medial regions of the temporal lobe play a role in the formation of allocentric representations. Conversely, the parietal and striatal regions have been found to be crucial for egocentric processing (N. Burgess et al., 2002; Eichenbaum, 1999).

Thus far, within clinical environments, the Mini-Mental Status Examination (MMSE) and the Montreal Cognitive Assessment (MoCA) have been employed for the purpose of differentiating older individuals with MCI from their cognitively intact counterparts(J.-H. Park et al., 2018)The MMSE has demonstrated both validity and reliability in its application as a screening tool for cognitive impairment, with the added advantage of being time-efficient, as it can be administered within a 10-minute timeframe. Nevertheless, its sensitivity to MCI is believed to be limited due to its susceptibility to the influence of factors such as the educational attainment and age of the individuals being assessed. A previous study has indicated that the MMSE is not suitable for assessing cognitive impairment in older adults with Mild Cognitive Impairment (MCI) (Hoops et al., 2009). However, while the MoCA was originally designed as a supplementary tool to the MMSE, it is worth noting that the MoCA places less emphasis on items related to episodic memory testing. Consequently, this reduced emphasis on episodic memory items leads to lower sensitivity in distinguishing MCI when compared to the MMSE (J.-H. Park et al., 2018). Furthermore, it is worth noting that both the MMSE and the MoCA may be susceptible to the influence of the tester's proficiency and the test environment(Wouters et al., 2011).

Given the potential benefits of early therapeutic interventions for patients with cognitive impairment, it is imperative to employ an evaluation method that accurately assesses functional impairment in dementia by testing cognitive performance in real-world scenarios (Tangen et al., 2015). Furthermore, it is essential to utilize advanced diagnostic techniques to identify functional cognitive impairment and determine the extent to which the disease affects functionality.

Therefore, at present, researchers have employed hippocampal-dependent episodic memory tasks as a means to address these challenges. Multiple studies have indicated that cognitive tasks designed to assess episodic memory have demonstrated superior discriminatory ability in distinguishing older adults with MCI from their cognitively normal counterparts (J. H. Park & Ah Lee, 2021). In particular, within the sub-components of episodic memory, it has been observed that spatial location memory and temporal order memory exhibit a greater ability to predict MCI compared to traditional neuropsychological evaluations, such as verbal learning tests (J. H. Park & Ah Lee, 2021; Plancher et al., 2012). In contrast to neuropsychological assessments that solely evaluate object memory through the process of recalling previously presented information, cognitive tasks that involve remembering sub-elements of episodic memory within spatiotemporal contexts have demonstrated a greater capacity for prediction (J. H. Park & Ah Lee, 2021; Plancher et al., 2012). Hence, the assessment of spatial memory, which relies on the functioning of the hippocampus, may serve as a viable method for detecting MCI. Nevertheless, the assessment of spatial memory in a two-dimensional array is reliant on brain regions other than hippocampal function, leading to its limited ability to make accurate predictions (Farias et al., 2003). Consequently, to assess the spatial memory that relies on the hippocampus, it is necessary for the cognitive tasks to incorporate a multifaceted navigational scenario within a three-dimensional setting. In recent times, the emergence of VR technology has led to its widespread utilization in various cognitive tasks.
The main aim of this research is to thoroughly investigate the convergent and divergent validity of two distinct memory assessment tasks, both developed using advanced 360-degree technologies. The aforementioned tasks are conducted on two separate cohorts, consisting of individuals who have been diagnosed with MCI and older adults who do not have any cognitive impairments. This study seeks to clarify the effectiveness and suitability of these innovative memory assessment tools in distinguishing between cognitive states among the various participant groups.
The assessment of convergent validity will involve an examination of the extent to which the results of memory assessment tasks align with established neuropsychological measures that are specifically designed to evaluate cognitive functions related to memory. This study aims to determine the degree of alignment between the performance outcomes of 360-degree memory tasks and the cognitive constructs that are assessed through traditional neuropsychological evaluations. The study aims to emphasize the validity of the 360-degree tasks in assessing memory-related cognitive functioning by demonstrating a strong positive correlation between the outcomes of these tasks and established measures.

On the other hand, the examination of divergent validity seeks to determine the extent to which the 360-degree memory assessment tasks can differentiate between separate cognitive domains, thereby assessing their efficacy in accurately measuring particular memory-related cognitive processes. The study aims to establish the distinctiveness of the targeted cognitive domain from unrelated cognitive functions by utilizing neuropsychological measures that evaluate non-memory cognitive functions for comparative purposes. This assessment aims to provide empirical evidence supporting the distinctiveness of the 360-degree tasks in assessing memory capabilities, while controlling for potential interference from other cognitive functions.

6.3.2. Methods

Participants

The research encompassed a cohort of 66 patients over 60 years old (mean age=73.8, SD=7.29; mean education= 13.2, SD=3.84, 33 males and 33 females). 29 of these patients were diagnosed with MCI based on the criteria established by Petersen (Petersen, 2016). The age of this group ranged from 61 to 68 years, with a mean age of 76 years (SD=7.58) and a mean education of 13.3 (SD=3.81). The other 37 patients were recruited as controls from the geriatrics Department of Istituto Auxologico Italiano in Milan, Italy, and represented the control group (healthy controls, HCs). The age of the control group ranged from 62 to 90 years, with a mean age of 72 years (SD=6.65) and a mean education of 13.2 (SD=3.92). The data collection was carried out from April 2023 to September 2023. The HCs group consisted of 21 female subjects, while the aMCI group included 12 female subjects. All participants underwent comprehensive neuropsychological assessments. All participants' neuropsychological test scores were calculated using the appropriate age and education corrected norms. All participants demonstrated intact functioning, as evidenced by their Activities of Daily Living (ADL) scores. The scale was directly administered to the participants. The diagnostic process involved the utilization of scores, medical history, and a clinical interview to determine the presence of mild cognitive impairment MCI or HCs. The clinical interview effectively ruled out other neurological and psychiatric disorders. Table 5 provides a summary of the general and clinical characteristics exhibited by the groups.

Apparatus

The administration of the two memory tests involved the utilization of an iPad. Participants engaged directly with the device's screen using their hands for tactile interaction. The utilization of a practical approach to interaction ensured a seamless and instinctive testing experience, enabling participants to navigate the assessments effortlessly. The two tests have been developed using the Mindscape platform previously described.

Neuropsychological assessment

The neuropsychological assessment comprised several standardized tests, including the Mini-Mental State Examination (MMSE)(Magni et al., 1996), the Italian Version of the Frontal Assessment Battery (FAB) (Spinnler & Tognoni, 1987), the Italian Version of the Babcock Story Recall Test (BSRT) by (Spinnler & Tognoni, 1987), the Rey–Osterrieth complex figure (ROCFT) as described by (Carlesimo et al., 1996), the Attentive Matrices test by Spinnler and Tognoni (1987), the digit span, the Trail Making Test (TMT) as described by Amodio et al. (2002), the Corsi Test. In addition, the participants engaged in the Picture Recognition sub-test, which was a component of the RBMT-III Italian Version (Beschin and Urbano, 2013). The Picture Recognition sub-test is a component of the RBMT-III assessment. The process can be divided into two distinct phases, namely the encoding phase and the recognition phase. During the encoding phase, participants are presented with a series of 15 images that depict both living and non-living objects (e.g., a clock, a chicken). They are then instructed to identify and label each image accordingly. During the recognition phase, participants are instructed to visually examine a collection of 30 images, which consist of both target items (i.e.,

the 15 images previously shown during the encoding phase) and distractors (i.e., 15 images that were not included in the encoding phase). For each image, participants are required to indicate whether they recall seeing it before by responding with a "yes" or a "no" accordingly. During the Recognition task, various measures are gathered: The HR, which refers to the proportion of affirmative responses to previous items, The False Alarm Rate, which refers to the proportion of affirmative responses to distractors, and the False Alarm Unknown, which pertains to the proportion of affirmative responses to unknown distractors, were identified by Snodgrass and Corwin in 1988. The raw score achieved in the sub-test refers to the quantity of pictures accurately identified. Additionally, prior to the Recognition Phase, a Free Recall task was administered to the participant, wherein they were instructed to recall all the objects that were presented during the encoding phase. The raw score is determined by the quantity of objects accurately identified.
One additional subtest that has been administered within the RBMT is the "Route - Immediate Recall" subtest. The purpose of this subtest is to evaluate an individual's capacity to recall and replicate a straightforward pathway promptly following its presentation. The typical route is generally straightforward and may entail traversing the room on foot or adhering to a designated path comprising six distinct points of interest.
The examiner illustrates the pathway to the examinee. The procedure entails the examiner traversing the designated pathway in the room, clearly indicating each point of cessation and corresponding action necessary for the successful completion of the route (involving the selection and elevation of two objects at two out of the six designated stops).
Following the completion of the demonstration, the examinee is promptly instructed to replicate the route they have recently observed. Participants are anticipated to recollect and replicate the path with utmost precision, devoid of any supplementary cues or reminders.
Scoring: The evaluation of the examinee's performance is typically conducted by assessing the degree of accuracy with which they can replicate the given route. Points can be allocated for every accurate step or action executed during the journey. The Route - Immediate Recall subtest is designed to evaluate the examinee's immediate memory capacity and their cognitive aptitude in processing and reproducing spatial information. Additionally, it offers valuable insights regarding their aptitude for adhering to instructions and retaining information within a limited timeframe.

Memory assessment using 360° technologies.

In the episodic memory test, participants are immersed in a virtual house with a kitchen, a living room, a bedroom, and a bathroom. The environment is characterless. 45 objects were created to populate this virtual house as targets or distractors.
Familiarization. Participants were familiarized with the virtual devices in a simulated household before starting the memory VR task. Participants were instructed to navigate the virtual environment and follow instructions during this phase. Tablet users should horizontally swipe their finger right and tap the green circle, according to the instructions. After selecting the green circle, the user is instructed to horizontally swipe their finger and select it. This directive establishes the environment's navigability in a 360-degree circle and indicates that its objects can be clicked. In the final directive of this familiarization phase, participants must choose the door to move to another room. Thus, the participants are instructed to open the drawer in the bathroom to determine its contents. The final

instruction emphasizes environmental interactivity by showing how clicking on doors switches rooms. This functionality is essential for spatial memory.
Encoding. The initial goal was to categorize 15 easily recognizable entities in boxes scattered throughout the house. Participants were instructed to open each box – clicking on it - and verbally identify the contents. They were told to imagine entering Marco's new home. Examine the room carefully, selecting each box and clearly identifying its contents. The target items and 15 semantically similar distractors were strategically placed. Upon activation, the object appears in two dimensions against a white backdrop for three seconds. Then, the same object is placed in that spot without the box. The task ended when all the boxes were opened. A numerical display in the upper left corner of the screen counts the number of boxes opened. Participants should click "as soon as you finish, click here" to go on. A neutral gray environment is shown with the prompt "Reflect upon the contents of the boxes that were previously opened and record any items that you remember". This is the free recall phase. The participant's ability to identify the boxes' contents determines the "Correct Items" variable.
After ten minutes of visual-spatial interference, people resume the task. One can see various objects scattered throughout the dwelling. These objects include the boxes and 15 distractors introduced during encoding. An additional 15 objects from the same semantic categories as the distractors have been added. Here are the instructions: You're visiting Marco's new home. Swipe your finger across the touch screen to navigate the apartment. Select only the objects extracted from the boxes by clicking on them. The task is complete when the participant selects all objects. This platform lets users/clinicians choose to display the score. The "Correct Items" variable measures the participant's ability to identify objects in the boxes.

In the spatial memory assessment test, participants are immersed in a novel house with 6 rooms: a kitchen and living room, 2 bedrooms, 2 bathrooms, and an antechamber. Participants were given the following tablet instructions before starting: "You are entering an apartment. Consider how the rooms fit together in the house. Select the doors to enter and exit rooms". The task begins in the kitchen and dining room. The participant can interact by clicking on doors to switch rooms. After opening all five doors, the clinician instructs participants to return to the main room to continue testing. After activating the main entrance, instructions appear with four maps of the previously explored domicile. "Check the options and choose the right one". The first option is shown in an allocentric perspective with a small arrow indicating the next option. The fourth and final option shows that all four maps can be compared. Participants must click the "click here to answer" symbol to choose. This feature lets users revisit and examine the maps or answer a multiple-choice question from 1 to 4.

6.3.3. Results

Clinical and demographical features in MCI patients and HC

The demographic and cognitive profile of groups are summarized in Table 1. The two groups statistically differed for Age (F (1, 56.1) = 4.972, p = 0.030), Corsi Block test (χ^2 = 4.254, p = 0.039), ROCFT_IR (χ^2 = 4.963, p = 0.026) and ROCFT_DR (F (1, 62.7) = 23.851, p <0.001), phonemic (F (1, 50.2) = 15.862, p<0.001) and semantic (F (1, 61) = 11.063, p <0.001) fluency, TMT_A (χ^2 = 16.424, p<0.001), Attentional matrices (F (1, 45.4) = 5.622, p = 0.022), the free recall (F (1, 58.3) =

5.947, p = 0.018) and retrieval (χ^2 = 6.947, p = 0.008) of RBMT. The other measures did not significantly differ.
Overall, MCI patients displayed lower performance than HC in the executive function (phonemic and semantic fluency, attentional matrices, TMT A and TMT B) and memory domain (immediate and delayed recall of ROCFT, the free recall and retrieval of RBMT, and the Corsi Block test). The two groups did not differ in terms of general cognitive status as assessed by the MMSE.

	Measure	**Total sample (N=66)**	**MCI (N=29)**	**HC (N=37)**	**Group difference**
Demographic	Gender (female)	33 (50%)	12 (41.4%)	21 (56.8%)	
	Age	73.77 (7.291)	76.00 (7.578)	72.03 (6.648)	p=0.030
	Education	13.24 (3.843)	13.31 (3.809)	13.19 (3.922)	n.s.
	ADL	5.92 (0.404)	5.86 (0.581)	5.97 (0.164)	n.s.
Cognitive	MMSE	27.15 (1.820)	26.76 (1.606)	27.45 (1.938)	n.s.
	Babcock	9.96 (3.187)	9.55 (3.046)	10.27 (3.297)	n.s.
	Digit span	6.09 (1.127)	5.84 (1.291)	6.29 (0.950)	n.s.
	Corsi block	4.90 (1.081)	4.50 (0.769)	5.21 (1.194)	p=0.039
	ROCFT_IR	33.14 (5.452)	30.77 (7.011)	34.94 (2.876)	p=0.026
	ROCFT_DR	16.46 (6.910)	12.42 (5.235)	19.52 (6.481)	p<0.001
	Flu_fon	33.11 (11.215)	27.35 (11.615)	37.63 (8.628)	p<0.001
	Flu_sem	45.56 (11.140)	40.78 (10.206)	49.31 (10.498)	p= 0.001
	TMT_A	39.12 (25.145)	53.62 (29.168)	27.76 (13.336)	p=0.005
	TMT_B	92.94 (108.117)	140.72 (144.258)	55.49 (40.484)	n.s.
	TMT_B-A	54.85 (93.015)	88.10 (127.873)	28.78 (36.254)	n.s.
	FAB	16.16 (1.810)	15.65 (2.267)	16.55 (1.272)	n.s.
	AM	36.51 (8.649)	33.62 (10.168)	38.77 (6.532)	p=0.022
	RBMT_enc	14.82 (0.389)	14.72 (0.455)	14.89 (0.315)	n.s.
	RBMT_free recall	6.70 (2.536)	5.86 (2.532)	7.35 (2.371)	p=0.018
	RBMT_retrivial_raw	13.79 (2.173)	13.00 (3.000)	14.41 (0.798)	p=0.008
	RBMT_retrivial	8.85 (3.962)	8.14 (4.138)	9.41 (3.782)	n.s.
	RBMT_PI_raw	8.55 (3.039)	7.93 (3.217)	9.06 (2.828)	n.s.
	RBMT_PI	8.39 (3.407)	7.97 (3.386)	8.74 (3.433)	n.s.
	RBMT_mess_raw	4.47 (1.984)	4.14 (2.574)	4.74 (1.291)	n.s.
	RBMT_mess	7.09 (3.882)	6.79 (3.959)	7.34 (3.857)	n.s

Table 5. Means (SD) for demographics and cognitive tests of the sample. P-values for comparison between the two groups are derived from one-way Anova for Age, Babcock, Digit span, ROCFT_DR, phonemic fluency, semantic fluency, attentional matrices (AM), free recall of RBMT except for education, ADL, MMSE; Corsi Block Test, ROCFT_IR, TMT_A, TMT_B, TMT_B-A, FAB and the other measures of RBMT which reflects Kruskal-Wallis Anova.

Performance on the virtual episodic memory task

A series of non-parametric analyses of variance were computed with Group ("MCI" vs. "HC") as between variables to investigate differences in the performance of the VR-based episodic memory task. The outcome measures were: (i) the number of objects encoded (out of 15); (ii) the number of objects freely recalled (out of 15); (iii) the number of objects (out of 15) recognized among (iv) 15 known distractors and (v) 15 unknown distractors.

The results showed that MCI patients encoded (M=14.621, SD=1.860 vs M= 15.054, SD=0.524), freely recalled (M=6.793, SD=2.258 vs M=7.865, SD=2.311), retrieved (M=12.655, SD=2.567 vs M=13.417, SD=2.143) less objects than the HC group and retrieved more known (M=0.241, SD=0.786 vs M=0.194, SD=0.525) and unknown (M=0.552, SD=0.783 vs M=0.361, SD=0.543) distractors as shown in figure 15.

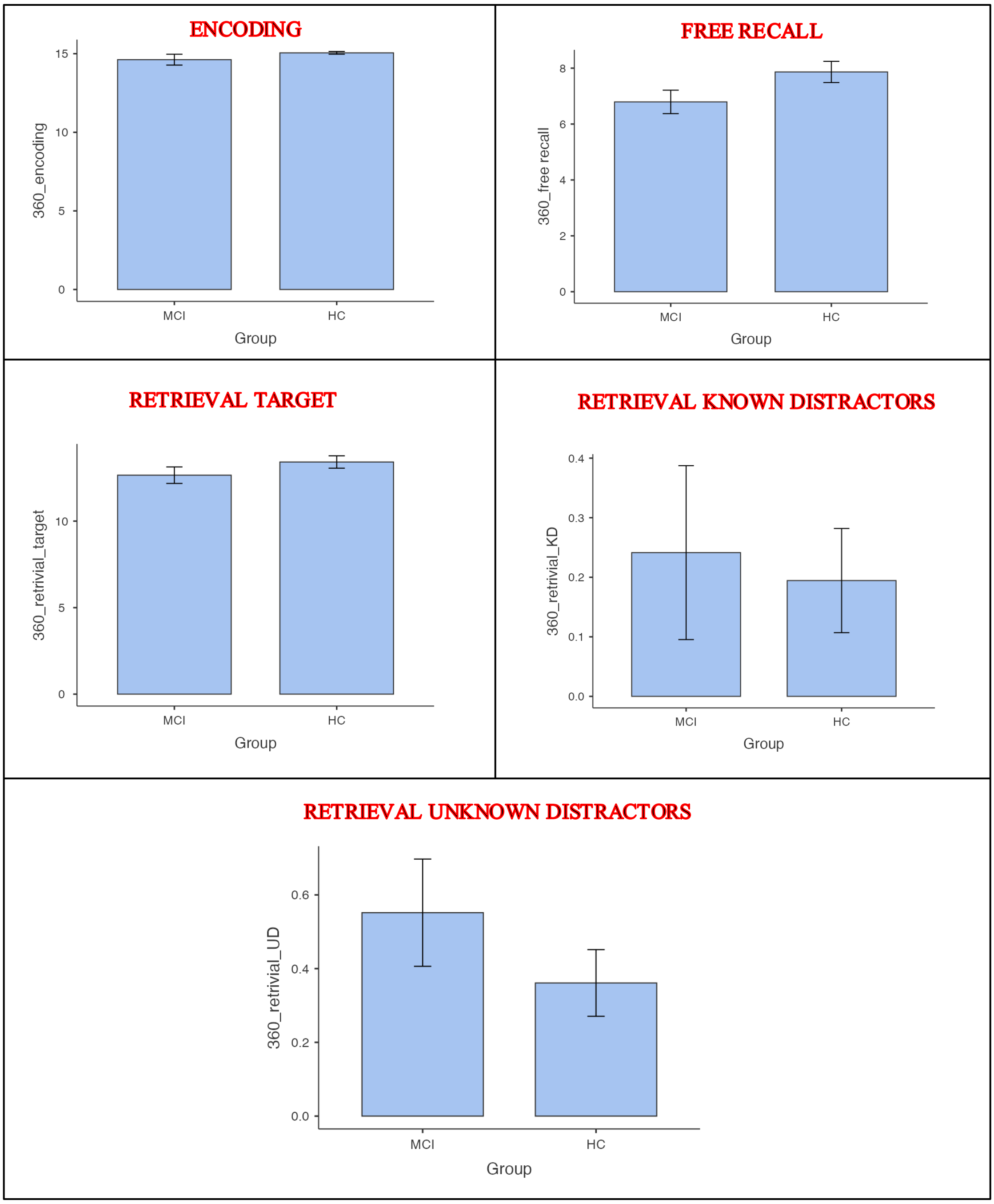

Fig. 15. Comparison of the two groups in the virtual episodic memory test.

However, none of these differences were statically significant according to Anova analyses as shown in table 6.

Table 6. Kruskal-Wallis

	χ^2	gdl	p
360_encoding	1.300	1	0.254
360_free recall	2.698	1	0.100
360_retrivial_target	1.844	1	0.175
360_retrivial_KD	4.84e-4	1	0.982
360_retrivial_UD	0.718	1	0.397

Performance on the virtual spatial memory task

The only measure used to assess performance in the spatial memory task was the identification of the accurate house map from a pool of four possible options (the right one is the number four). A chi-square analysis was conducted to evaluate potential group differences in map selection performance between participants diagnosed with MCI and HC. The findings of this analysis produced a result that lacked statistical significance, suggesting that there were no notable differences between the MCI and HC groups in their capacity to correctly choose the appropriate house map as shown in table 7 and 8.

Table 7. Contingency table.

	360_map				
Group	1	2	3	4	Tot
MCI	13	5	2	9	29
HC	16	7	2	12	37
Tot	29	12	4	21	66

Table 8. Test χ^2

	Value	gdl	p
χ^2	0.104	3	0.991
N	66		

Correlations of the virtual-based episodic task with neuropsychological measures.

The construct validity of the study was evaluated in the second part by calculating Spearman bivariate correlations (two-tailed) to examine the association between performance on the VR task and memory measures obtained from conventional tasks, thereby assessing convergent validity. Given the lack of distinctions between the two groups, we proceeded to perform the analyses on the entire sample. Furthermore, the assessment of construct validity is conducted by evaluating the extent to which the

VR task demonstrates sensitivity to the age-related effect commonly observed in tasks involving episodic memory.

Table 9. Correlations between the outcomes of the virtual reality based episodic memory test and neuropsychological measures.

	360_encoding	360_free recall	360_retrivial_target	360_retrivial_KD	360_retrivial_UD
360_encoding	—				
360_free recall	0.285*	—			
360_retrivial_target	0.029	0.369**	—		
360_retrivial_KD	-0.128	-0.271*	-0.333**	—	
360_retrivial_UD	-0.186	-0.383**	-0.159	0.308*	—
RBMT_enc_raw	0.267*	0.371**	0.150	-0.247*	-0.340**
RBMT_free recall_raw	0.289*	0.445***	0.408***	-0.146	-0.118
RBMT_retrivial_raw	0.356**	0.355**	0.114	-0.112	-0.402***
Babcock	0.141	0.177	0.089	-0.148	-0.020
Digit span	-0.018	0.129	0.033	0.021	-0.111
Corsi block	-0.140	-0.156	0.019	0.180	-0.182
ROCFT_imm	0.103	0.065	0.258*	0.185	0.040
ROCFT_diff	0.167	0.253*	0.133	0.204	-0.216
MMSE	-0.005	-0.201	-0.001	0.010	0.113
ADL	-0.028	-0.056	0.161	-0.120	-0.034
Flu_fon	-0.050	0.328**	0.186	-0.165	-0.274*
Flu_sem	0.175	0.458***	0.385**	-0.149	-0.263*
TMT_A	-0.073	-0.311*	-0.317*	0.063	0.224
TMT_B	-0.060	-0.393**	-0.402***	0.112	0.379**
TMT_B-A	-0.044	-0.362**	-0.367**	0.161	0.356**
FAB	0.137	0.081	0.042	-0.135	0.106
AM	-0.135	0.114	0.455***	-0.065	-0.150

Nota. * p < .05, ** p < .01, *** p < .001

The findings from the correlation analyses demonstrate a significant and meaningful association between the memory measures based on virtual reality technology and the conventional neuropsychological assessments. Our study found notable associations between the virtual assessments of encoding, free recall, and retrieval, and the corresponding measures in the Rivermead Battery. This indicates a convergence in memory evaluation between virtual and traditional methods. Moreover, our research outcomes expand to include correlations with other widely recognized neuropsychological assessments. It is worth mentioning that the virtual free recall and retrieval tasks displayed substantial associations with the Immediate and Delayed Recall aspects of the Rey-Osterrieth Complex Figure Test, providing additional evidence to support their congruence with traditional memory evaluations. Furthermore, our observations revealed strong correlations with executive functions. Specifically, both virtual free recall and retrieval demonstrated significant associations with the three indices of the Trail Making Test and measures of semantic fluency. In addition, the virtual free recall task exhibited significant associations with phonetic fluency, whereas the virtual retrieval task demonstrated correlations with attentional matrices. The results of this study highlight the agreement and distinction between different measures, supporting the reliability and accuracy of our memory assessment using virtual reality technology.

Effects of gender, age, and education level on the episodic virtual reality-based memory measures

The results of this study suggest that gender does not have a statistically significant impact on the encoding ($F(1)= 2.05$, $p= 0.157$), free recall ($F(1)= 0.176$, $p= 0.676$), and retrieval ($F(1)= 0.807$, $p= 0.372$) measures.

Furthermore, we investigated the potential impact of educational attainment on the virtual memory metrics in our research. To our surprise, the findings of our study revealed that there were no statistically significant correlations between the number of years of education and the measures of encoding, free recall, or retrieval. Due to the lack of substantial correlations between the duration of education and the aforementioned memory outcomes, we opted not to pursue additional analyses regarding educational attainment. The results of this study indicate that, in the specific context of our research, formal education did not significantly contribute to the observed differences in virtual memory performance among the participants.

Correlation analyses were then performed to examine the association between age and the virtual memory measures of encoding, free recall, and retrieval. The findings indicated statistically significant inverse relationships between age and each of the memory measures. The obtained correlation coefficients were as follows: the correlation between age and encoding was $r = -0.253$, $p < 0.05$; the correlation between age and free recall was $r = -0.413$, $p < 0.001$; and the correlation between age and retrieval was $r = -0.530$, $p < 0.001$. In order to provide a more comprehensive understanding of these associations, we performed regression analyses to investigate the extent to which age can predict virtual memory measures. The results of the regression models indicate a significant relationship between age and all three memory measures, namely encoding ($encoding=18.195 – 0.045*age$, $p<0.05$, $R=0.25$), free recall ($free\ recall=17.131-0.132*age$, $p<0.001$, $R=0.41$) and retrieval ($retrieval=25.852-0.173*age$, $p<0.001$, $R=0.53$). The collective findings suggest that there is a significant decrease in performance on the memory task as individuals age. This finding implies that the decline in memory abilities is linked to increasing age, as indicated by the virtual memory assessments utilized in this research.

Given the significant impact of age on memory measures, we employed partial Spearman correlations to control for the potential confounding influence of age. The utilization of an analytical approach facilitated the examination of the associations between the measures of 360-degree virtual memory and diverse cognitive assessments, while simultaneously accounting for the potential influence of age through statistical control. The findings indicate the presence of statistically significant partial correlations, which emphasize the strong connections between the 360-degree virtual memory measures and various cognitive assessments. These associations remain significant even after controlling for the influence of age. In particular, upon adjusting for age, a statistically significant positive association was observed between the virtual encoding and the retrieval measure of the Rivermead Battery of Memory Test (RBMT) ($r = 0.325$, $p < 0.01$). In a similar vein, the virtual free recall measure demonstrated significant positive partial correlations with both the encoding ($r = 0.268$, $p < 0.05$), free recall ($r = 0.317$, $p < 0.05$) and retrieval ($r = 0.286$, $p<0.05$) of the Rivermead Battery, as well as with scores on semantic fluency ($r = 0.332$, $p < 0.01$), TMT B ($r = -0.306$, $p < 0.05$), and TMT B-A ($r = -0.287$, $p < 0.05$).

Moreover, several executive function assessments demonstrated noteworthy partial correlations with the virtual retrieval measure. The results indicate that there is a negative partial correlation with the

TMT B score ($r = -0.306$, $p < 0.05$), TMT B-A ($r = -0.289$, $p < 0.05$), and with attentive matrices correlation ($r = 0.337$, $p < 0.01$).

Effect of neuropsychological variables on virtual spatial memory task

We employed binary logistic regressions to examine the impact of neuropsychological variables on performance in virtual spatial memory tasks. The dependent variable in these analyses was the scoring obtained from the virtual spatial memory assessments. The study incorporated neuropsychological variables as independent variables, while utilizing the "group" variable as a categorical factor.

The findings of the binary logistic regressions yielded interesting insights. Of the various neuropsychological predictors examined, only phonemic fluency demonstrated a statistically significant association (estimate = -0.0555, $Z = -1.970$, $p < 0.05$) with virtual spatial memory performance. This finding suggests that individuals with higher phonemic fluency scores were less likely to exhibit lower performance in virtual spatial memory tasks. It is worth mentioning that the categorical variable "group" did not demonstrate statistical significance as a predictor. The indicators of the model's goodness of fit consisted of a deviance value of 78.4, an Akaike Information Criterion (AIC) value of 84.84, and an R-squared (R^2) value of 0.0504.

6.3.4. Discussion

As previously discussed, there is ongoing development and testing of VR applications that specifically target various cognitive processes, such as attention, spatial abilities, memory, and executive functions. The inclusion of VR scenarios in neurocognitive batteries can enhance ecological validity, thereby facilitating differential diagnosis and treatment planning.

In the context of a virtual environment, it is feasible to methodically introduce cognitive tasks that aim to enhance memory performance beyond the capabilities offered by conventional approaches (N. F. Gould et al., 2007; Matheis, Schultheis, Tiersky, Deluca, et al., 2007; Parslow et al., 2005; Phelps et al., 2004). The enhancement of memory assessment reliability in VR can be achieved through improved control of the perceptual environment, ensuring more consistent stimulus presentation, and employing more precise and accurate scoring methods. Virtual environments have the potential to enhance the measurement of validity by quantifying discrete behavioral responses, thereby enabling the identification of more precise cognitive domains. Moreover, VR has the potential to facilitate memory assessment in contexts that closely resemble real-world environments, thereby enhancing ecological validity. Participants can undergo evaluation within a simulated real-world setting rather than an artificial testing environment (Borghesi et al., 2022).

The objective of the current study was twofold: firstly, to examine the patterns of episodic and spatial memory in both healthy older adults and individuals with MCI through the utilization of a realistic VR memory test; and secondly, to explore the correlation between these memory patterns and conventional neuropsychological assessments. The study initially examined these relationships separately for the two groups in order to investigate the underlying neuropsychological factors contributing to age-related differences in memory processes.

The results of our study revealed little disparities in performance between the two groups. There is evidence suggesting that individuals diagnosed with MCI exhibit a tendency towards diminished encoding capacity, as they demonstrate a lower ability to encode objects when compared to individuals without cognitive impairments. The aforementioned pattern was also observed in the quantity of items that were recalled and retrieved by individuals with MCI, who, on the whole, demonstrated inferior performance when compared to the HC group. Nevertheless, it is crucial to acknowledge that although the observed variations in performance indicate potential indications of cognitive decline in the MCI group, none of these disparities attained statistical significance. The absence of statistical significance suggests that, given the parameters of our study and the size of the sample analyzed, the observed differences in performance did not reach a level of confidence that would allow us to draw definitive conclusions.

However, we demonstrated the typical age-related effects that are commonly observed through the utilization of traditional memory tests or laboratory assessments (Paolo et al., 1997), as outlined below: older age is associated to diminished encoding abilities, as well as reduced capacity for free recall. However, older adults demonstrate a greater advantage in recognition tasks when compared to free recall. Conversely, age is associated to lower accuracy in recognition tasks and a heightened vulnerability to false recognitions (Constantinidou & Baker, 2002; Craik & McDowd, 1987b; Pierce et al., 2005). This finding suggests that the VR task is responsive to the common cognitive decline associated with memory impairment. It is noteworthy that both groups exhibited a comparable quantity of false recognition errors. Therefore, individuals with MCI exhibit a higher tendency to exclude certain items compared to HC, but they do not make errors in selecting semantically related distractors. This finding contradicts previous research that suggests a correlation between cognitive impairments and a tendency towards a more liberal response bias (Dodson et al., 2007; Huh et al., 2006). However, it aligns with other studies that have found no age-related differences in response bias (e.g., Bastin & Van der Linden, 2003). It is worth noting that Bastin and Van der Linden (2003) discovered that a yes-no recognition format, similar to the one employed in this study, resulted in a lower rate of commission errors in comparison to a forced-choice recognition format. The likelihood of false-recognition errors in forced-choice recognition is increased when concurrent alternatives are present. Hence, the observed equivalence in the occurrence of false recognition between older and younger adults could potentially be attributed to the absence of a recognition format that is conducive to facilitating this error.

The primary measure utilized to evaluate performance in the spatial memory task involved identifying the correct house map from a set of four options, with the accurate choice labeled as "number four." The findings of this analysis, however, indicated a lack of statistical significance in the outcome. This finding suggests that there were no significant differences observed between the two groups in their ability to accurately select the correct house map. The lack of statistical significance indicates that the MCI and HC groups demonstrated comparable performance levels in the specific spatial memory task. However, it is crucial to interpret these results considering the overall context of our study. Spatial memory tasks inherently involve multiple cognitive processes, and our evaluation primarily concentrated on a singular aspect, namely the identification of the correct house map. Hence, it is conceivable that additional aspects of spatial memory, which were not evaluated in this research, might demonstrate distinct patterns between the two groups. Furthermore, it is important to consider that the lack of statistical significance in our findings may be attributed to various factors, including but not limited to the size of our sample, the complexity of the task, or the specific characteristics of the groups of participants involved in the study. Additional investigation utilizing larger sample sizes and incorporating more extensive evaluations of spatial memory could yield a more nuanced

comprehension of potential disparities in this cognitive domain between individuals with MCI and HC.
The second objective of this research was to investigate the degree of convergence and divergence between our VR-based memory assessment and conventional neuropsychological measures. This investigation aimed to provide insights into the complex and diverse aspects of cognitive evaluation. Significantly, a strong correlation was observed between our virtual memory task and the Rivermead Battery of Visual Memory Tests, a well-established assessment tool known for its ability to accurately measure memory function in an ecological way. The aforementioned convergence highlights the capacity of our virtual task to accurately measure components of memory performance that correspond to real-life situations. Additionally, our research sheds light on the dimension of cognitive evaluation. The virtual memory task conducted in our study exhibited significant correlations with conventional memory assessments. This finding aligns with prior research that suggests VR has the capability to assess comparable constructs to those assessed by clinical or experimental measures (Armstrong et al., 2013; Parsons & Barnett, 2017; Parsons & Rizzo, 2008; Serino et al., 2015). Additionally, we observed noteworthy connections between the virtual memory task and measures of executive function. This intricate relationship highlights the notion that cognitive tasks are not limited to individual constructs, but rather can encompass various cognitive domains. In our endeavor to achieve ecological validity, we adhere to the current viewpoint that neuropsychological assessments should not solely be driven by theoretical constructs, but rather should accurately reflect the diverse range of cognitive functions observed in real-world situations (A. Benton, 1985; Franzen & Wilhelm. K.L., 1996).

The adoption of an integrated approach to cognitive assessment is indicative of the increasing acknowledgement that cognitive processes are intricately interconnected. In fact, while traditional memory tasks have the ability to isolate specific memory processes, VR tasks offer a means to observe how memory functions in real-world scenarios, where various processes interact to produce intricate behaviors. Consequently, a thorough evaluation should encompass a wide range of cognitive functions. The findings from our virtual memory task demonstrate that there are significant associations not only between memory but also executive function measures. This highlights the significance of taking into account comprehensive cognitive profiles, especially in clinical environments where an individual's cognitive abilities are typically multifaceted. The findings of our study provide evidence in favor of the idea that cognitive assessments should not be limited to specific cognitive domains, but rather should be designed to accommodate the intricate and multifaceted nature of cognitive processes in real-world settings. We assert that adopting a holistic approach is crucial in order to achieve a more comprehensive comprehension of cognitive function and its ramifications in both clinical and everyday settings.

Results must be interpreted within the context of some limitations. The study employed limited sample sizes and disparate participant numbers between the MCI and HC groups. Consequently, it would be valuable to replicate the study with a larger sample size to potentially address any concerns regarding statistical power. Additionally, individuals were considered MCI in relation to potential deficits observed in at least one neuropsychological test. Further studies are expected using a wider range of questionnaires and scales to assess cognitive complaints. Thirdly, it is important to acknowledge certain limitations of our virtual reality-based spatial memory task, despite the valuable insights it has offered into cognitive performance. One of the main constraints pertains to the exclusive dependence on a solitary outcome measure, namely the discernment of the accurate house layout from a range of alternatives. The constrained extent of evaluation, although enlightening, might not encompass the entirety of spatial memory functionality. Spatial memory is a complex cognitive domain that requires a comprehensive assessment using a wide range of measures in order to gain a more nuanced comprehension.

A potential augmentation to our task could entail incorporating metrics pertaining to the temporal duration required by participants to navigate the virtual house, as well as the number of rooms accessed during the exploratory phase. These supplementary measures might have the potential to provide insights into the efficacy and tactics employed by individuals in comprehending the spatial arrangement of a residential dwelling. As an illustration, an extended duration of exploration may indicate increased challenges in spatial orientation, whereas a greater quantity of rooms explored could suggest a more comprehensive grasp of the architectural layout of the house.

7. Discussion

Within the framework of neuropsychological assessment, the primary aim is to acquire a comprehensive comprehension of an individual's cognitive functioning and identify any potential deficits. Traditional assessment tools have been instrumental in this undertaking, providing standardized tests and clinical interviews for the purpose of diagnosing cognitive impairments. Nevertheless, a notable critique of numerous clinical assessments pertaining to episodic memory is their limited ecological validity, as highlighted by Sbordone and Long (1996). The characteristics of everyday episodic memory, which are often difficult to assess using clinical tests, encompass the recollection of long-term memories pertaining to distinct events within their specific spatiotemporal framework. These memories encompass the details of what occurred, where it transpired, and when it took place. According to Pause and colleagues (Pause et al., 2013), the encoding of information typically occurs incidentally, and its retrieval is often spontaneous, without the presence of any cues associated with the initial event. Laboratory tests typically exhibit certain characteristics, although it is uncommon for them to encompass all these attributes. For instance, certain assessments such as the R-AVLT focus on the retrieval of information from long-term memory, specifically within a 30-minute timeframe. In this particular test, participants are required to recall a list of words without the need to remember any spatial or temporal context. However, it is worth noting that an optional temporal-order trial can be included if desired (Vakil & Blachstein, 1994). Additionally, the learning process for this test involves intentional acquisition of the information followed by repeated rehearsal. Additional assessments, such as the Object Relocation task as described by Kessels et al. (1999), focus on the association between objects and their respective spatial positions. These assessments typically involve brief periods of retention and employ recognition processes to evaluate item-related information, while not applying the same approach to spatial location information. Furthermore, intentional encoding of the information is once again incorporated into these assessments. One notable benefit of employing these tests is that the experimenter or clinician possesses precise knowledge regarding the accuracy of each response, as they have control over the information that needs to be retained. When employing ecologically valid measures of episodic memory, such as the unrestricted recollection of actual personal experiences, the evaluation of these memories must necessarily depend on the level of detail recalled, rather than the accuracy of the memories. This is due to the absence of an objective record of the original event in most cases (Irish et al., 2011). Furthermore, it is worth noting that the episodes that are remembered tending to be those that have been repeatedly narrated in the past, potentially resulting in a higher presence of semantic information rather than genuine episodic recall (Pause et al., 2013). Notwithstanding these critiques, it is evident that current assessments of episodic memory have proven to be valuable (e.g., Bäckman et al., 2001). However, it is possible that these tests fail to capture certain dimensions of episodic memory as it occurs in real-life scenarios. The aforementioned limitation highlights the need for novel assessment techniques that provide enhanced ecological validity and a deeper comprehension of cognitive functioning.

The utilization of immersive technologies, specifically VR, has emerged as a significant advancement in the realm of neuropsychological assessment. VR possesses the capacity to replicate cognitive environments found in the real world and simulate genuine scenarios, thereby enabling more comprehensive assessments of cognitive abilities. This viewpoint is consistent with the current understanding that neuropsychological evaluations should shift from tests that are driven by theoretical constructs to ones that prioritize the examination of cognitive functioning in practical contexts. VR, especially when incorporating 360° videos and images, provides controlled and customizable environments that can be personalized to meet individual requirements, thereby improving the precision of cognitive assessments.

360° videos, also known as spherical videos or immersive videos, represent a dynamic and engaging form of media that offers viewers an all-encompassing, panoramic perspective of a scene or environment. Typically, these videos are captured utilizing omnidirectional cameras, which have the capability to record footage from all directions simultaneously. Consequently, spectators have the ability to thoroughly examine the entirety of the surrounding milieu through the mere manipulation of their perspective, thereby engendering an immersive and interactive encounter (Borghesi et al., 2022).

Nevertheless, the advent of VR technologies offers psychologists a promising prospect to enhance the ecological validity of a task within a context that concurrently upholds the essential experimental control required to consistently assess a specific psychological construct. More specifically, the integration of VR into an experiment holds the capacity to improve the study in terms of its fidelity to real-life situations, thereby imposing comparable cognitive demands on participants. Additionally, it has the potential to enhance the accuracy of experimental results, ensuring they effectively reflect and/or predict the psychological phenomenon under investigation. Virtual environments have the capacity to simulate an extensive range of scenarios, theoretically limitless in number, in a manner that often proves significantly more economically viable compared to the creation of their real-world counterparts. This technology offers researchers the opportunity to integrate tasks that would be unfeasible to reproduce within the controlled confines of a laboratory setting, irrespective of financial constraints. An example of such tasks includes large-scale navigational challenges, such as maneuvering through an urban environment.

The present doctoral thesis undertakes a comprehensive exploration within the domain of neuropsychological assessment with these research questions:

1. What can we learn from analyzing clusters and networks of 360° technologies in scholarly publications, and how does this analysis help us understand the main research areas, subtopics, and interdisciplinary interactions in this field?
2. How can the construction of a user-friendly platform like Mindscape help researchers overcome the challenge of complicated software needs, allowing them to easily develop immersive cognitive exercises in virtual reality without requiring extensive technical expertise?
3. To what degree do memory tasks utilizing 360° technologies, particularly in the context of the episodic and spatial memory assessments developed using Mindscape, accurately evaluate memory impairments in older individuals, by comparing those with mild cognitive impairment to older adults without cognitive impairment?

Therefore, the primary goals of this study are to investigate the potential benefits of immersive technologies, specifically 360° videos, in improving memory assessment. The thesis commences by providing a comprehensive overview of the current virtual reality tools that have been developed specifically for the purpose of evaluating memory. The study undertakes an in-depth analysis of these tools, thoroughly examining their convergence with traditional neuropsychological tests, and evaluating their ability to accurately simulate ecologically realistic situations.

In the subsequent analysis, the present thesis endeavors to examine the extensive domain of 360° videos by employing cluster and network analysis techniques. The proposed methodology classifies

and establishes connections between 360° videos by considering their content, context, and applications. This analysis plays a crucial role in deciphering the complex network of 360° video content, offering valuable insights into the various potentialities and uses of this emerging medium.
The thesis presents a novel platform aimed at addressing the longstanding challenge of developing virtual cognitive tasks within immersive environments, with the goal of narrowing the technological gap. The primary objective of this platform is to enhance the accessibility of task creation for a broader community of clinicians and researchers, thereby removing the need for advanced programming proficiency.
The thesis reaches its apex through the psychometric validation of two memory tasks that have been specifically developed for the purpose of evaluating episodic and spatial memory. The tasks are designed utilizing a platform that prioritizes ease of use for the user. The individuals diagnosed with Mild Cognitive Impairment and Healthy Controls undergo a thorough validation process. The validation process is responsible for ensuring that these tasks demonstrate the essential qualities of reliability, validity, and sensitivity in accurately differentiating cognitive impairments.

The results obtained from the cluster and network analysis have provided valuable insights into key areas of interest within the domain of 360° technology. Additionally, this analysis has identified specific subtopics that have received differing levels of scholarly consideration. This information holds significant value for researchers seeking to advance their studies or projects, as it enables them to expand on existing knowledge and address any existing gaps within the scholarly literature. Furthermore, the application of cluster and network analysis methodologies has significantly enhanced our comprehension of the complex network of interrelationships among diverse subjects pertaining to 360° technology. This methodology enabled us to comprehend the evolving nature of these interconnections throughout the course of time. The act of visualizing these connections provided a distinct opportunity to acquire a deeper understanding of the fundamental dynamics and structural framework of research on 360° technology. Moreover, it identified potential areas for interdisciplinary collaboration and innovation. Our analysis enables the integration and collaboration among scholars in different subfields of the discipline by identifying and acknowledging the interrelationships and shared patterns across diverse research domains. It is worth mentioning that the domains of engineering, computer science, and information systems have garnered significant scholarly focus, which is consistent with the interdisciplinary characteristics of 360° video and image technology. The development of hardware and systems required for capturing and processing immersive visuals is rooted in engineering principles. The aforementioned principles are essential for the advancement and production of the necessary hardware for the acquisition and visualization of this particular form of media. Computer science plays a crucial role in the development of algorithms, software frameworks, and data processing methods that are essential for effectively managing high-resolution images and videos. A thorough comprehension of the integration of various software and hardware components to ensure smooth operation in 360° media platforms is contingent upon a solid understanding of system information. Nevertheless, it is important to acknowledge a developing tendency that centers on the study of human factors within this particular domain. This phenomenon aligns with the trajectory of technological advancement and its subsequent adoption by the market. In general, individuals who engage in innovation tend to place a high emphasis on obtaining patents for their concepts prior to initiating the commercialization process. As a result, the practical application of technology can be utilized for commercial endeavors and subsequently becomes the focus of scholarly publications. The accessibility and rapid advancement of 360° technology has led

to its widespread adoption across various domains. The comprehension of human perception and engagement with technology has gained significant importance in enhancing user experiences. The integration of human factors in 360° video and image research has become more prominent in recent years, coinciding with the increasing utilization of VR and its expansion into clinical applications. The proliferation of immersive media has resulted in swift technological advancements and its extensive integration across diverse sectors, underscoring the significance of comprehending human factors.
Moreover, the incorporation of VR technology within clinical settings has heralded a notable transformation, commonly known as the clinical-VR era. This shift prioritizes areas like rehabilitation, neurosurgery, novel therapeutic approaches, and the development of laparoscopic skills. The correlation between the surge in applications and published articles in recent years can be attributed to the parallel progressions in VR technology, particularly in the domains of hardware and software. VR has undergone a transformation from its original emphasis on engineering components, including hardware and software development, to a multidisciplinary field that takes into account the needs and preferences of its users. As the technological advancements in VR extended beyond their initial scope, there emerged a growing emphasis on user-centered design in order to accommodate the diverse demographic of users. The incorporation of VR technology within the medical domain serves as a notable manifestation of this prevailing pattern.

The undeniable importance of incorporating immersive technology into neuropsychological assessments is evident. Nevertheless, the application of this technology has faced obstacles due to the requirement for extensive technical knowledge or substantial financial means, thereby limiting its accessibility to numerous clinicians and researchers. Historically, the development of cognitive tasks in virtual environments has necessitated expertise in programming or substantial financial resources to engage technical professionals. The challenge at hand has been effectively tackled in our study, Study 2, through the creation of a user-friendly platform. This platform enables clinicians and researchers to generate cognitive tasks without requiring extensive programming expertise. Consequently, the utilization of immersive technology in neuropsychological assessments is made accessible to a wider range of individuals, thus promoting inclusivity and democratization.

Researchers in the field of experimental psychology frequently encounter the challenge of designing a study that effectively balances ecological validity and experimental control (Kvavilashvili & Ellis, n.d.). While it is important to have control over variables in order to carefully and systematically manipulate them during research, tasks that do not possess sufficient ecological validity may not accurately represent the phenomenon being studied. This can potentially undermine the ability to generalize the results beyond the laboratory setting.

The impetus behind the creation of our memory assessment tests, which are integrated into the Mindscape platform, was the objective of designing ecologically valid instruments that proficiently evaluate two fundamental dimensions of human memory: episodic memory and spatial memory. In order to accomplish this, we utilized established cognitive paradigms in conjunction with innovative, ecologically pertinent components. The episodic memory test is based on the well-known picture recognition task found in the Rivermead Battery, which is a widely acknowledged and ecologically valid assessment battery. Nevertheless, we improved the ecological validity of the study by incorporating it into a genuine real-life setting. However, the spatial memory test draws upon not only the spatial memory assessment utilized in the Rivermead, but also incorporates findings from our previous research (Bruni et al., 2022, 2023; Pieri et al., 2022), thereby integrating established neuropsychological principles with contemporary advancements in the discipline. By integrating conventional and modern components, these memory assessments provide a comprehensive appraisal of memory performance that corresponds to real-life situations, thus augmenting their ecological validity and precision in evaluating memory abilities.

Most of the published literature pertaining to cognitive assessment utilizing virtual environments has primarily focused on exploratory investigations. However, there is a scarcity of research examining the psychometric properties of tests administered within simulated environments. Various studies (e.g., Rizzo et al., 2004; Rose, Brooks, & Rizzo, 2005) have provided evidence for the viability of developing tests that are both acceptable to patients with neurological impairments and possess a strong face validity. Moreover, substantial evidence supports the notion that VR assessments possess a high degree of sensitivity in detecting deficiencies in memory, attention, learning, and executive functions among individuals with cognitive impairments. As an illustration, the study conducted by Matheis et al. (2007) provided evidence that their recall test, administered in a virtual office setting, effectively differentiated individuals with traumatic brain injury (TBI) who experienced memory impairments from those who did not exhibit such difficulties. Additionally, the researchers discovered supporting evidence for the convergent validity of their memory assessments through the examination of correlations between indices derived from their VR tests and scores obtained from traditional neuropsychological measures (Matheis et al., 2007; Parsons & Rizzo, 2008).

In order to evaluate the psychometric validity of the two newly developed tasks, a comprehensive validation study was undertaken. This study involved the participation of individuals diagnosed with Mild Cognitive Impairment (MCI) as well as a control group consisting of individuals classified as Healthy Controls (HC). The objective of this study was to evaluate the reliability, validity, and sensitivity of our immersive cognitive assessments in effectively distinguishing individuals with cognitive impairments from those without. The present study employed a non-immersive setup for the purpose of validation. In fact, considering the financial implications associated with numerous head-mounted displays (HMDs) presently, the availability of a desktop/tablet version of the task that does not appear to hinder participants in terms of performance offers researchers a valuable alternative for investigating spatial learning and memory. In addition to the potential occurrence of motion sickness, HMDs may present practical limitations that render them unsuitable for certain populations. For instance, research examining the viability of immersive virtual VR systems in hospital environments has indicated that older individuals encounter greater challenges when utilizing HMDs and also exhibit a lower inclination to engage in such activities (Mosadeghi et al., 2016).

In brief, the third study examines the convergence of VR technology and cognitive assessment, with a particular focus on the possibility of augmenting ecological validity in cognitive evaluations. The primary focus of our research was twofold: firstly, to assess episodic and spatial memory in individuals with MCI and healthy older adults using a realistic VR memory test; and secondly, to investigate the correlations between these memory patterns and conventional neuropsychological assessments. While there were observed variations in performance between the groups with MCI and the control group consisting of healthy individuals, it is important to note that none of these differences were found to be statistically significant. This implies that the outcomes may have been influenced by factors such as the size of the sample or the specific parameters employed in the study.

Nevertheless, our VR task exhibited a capacity to adapt to prevalent age-related memory alterations, thereby mirroring the cognitive deterioration commonly witnessed in older individuals.
The spatial memory task, which involved identifying the correct house map, did not result in statistically significant differences between the groups with MCI and the healthy control group. The potential explanation for this phenomenon could be attributed to the complex and multifaceted characteristics inherent in spatial memory, as our evaluation specifically targeted a particular facet of this cognitive process. In order to enhance the depth of analysis, it may be advantageous to consider supplementary variables such as the duration of exploration and the quantity of rooms accessed. This would contribute to a more refined assessment.
Notwithstanding these constraints, our investigation unveiled noteworthy associations between the VR-based memory evaluations and traditional neuropsychological assessments, underscoring the interconnectedness of cognitive processes. This implies that it would be beneficial for cognitive assessments to incorporate a comprehensive perspective, taking into account various cognitive domains in both clinical and real-world contexts.
The findings of the study demonstrate the potential of VR technology in enhancing the ecological validity of cognitive assessments. However, in order to deepen our understanding in this area, it is imperative that future research endeavors employ larger sample sizes and conduct more comprehensive evaluations of spatial memory. The incorporation of an interdisciplinary approach is of utmost importance in ensuring the advancement of cognitive assessment, as it recognizes the complex interaction between cognitive processes within authentic environments.

The existing body of neuropsychological literature contains a plethora of tests and measures that have been developed and demonstrated to possess potential utility. Only a small number of these tests are ever developed to a level of psychometric sophistication that allows them to be widely accepted and used in clinical settings. This phenomenon can be attributed, at least in part, to the fact that the process of test development necessitates a sustained dedication to a structured program of development. However, this commitment may not be adequately recognized or incentivized in terms of securing research funding or garnering academic prestige. Numerous tests commonly employed in neuropsychology can be traced back to experiments conducted during the nascent stages of psychology as a laboratory-based discipline. It is crucial to acknowledge that the integration of assessment protocols is a gradual undertaking, often impeded by substantial resistance from clinicians actively engaged in the field. The tendency to resist change is frequently grounded in practicality, as the potential benefits of acquiring new knowledge or skills must outweigh the associated costs.

Overall, this doctoral dissertation represents a significant scholarly contribution to the domain of neuropsychological assessment, with the objective of establishing a connection between sophisticated immersive technology and accessible, user-friendly platforms for evaluating cognitive abilities. This study addresses the persistent constraints and difficulties that have historically impeded the incorporation of immersive technology in cognitive evaluations. The primary emphasis on improving ecological validity, usability, and practicality in cognitive assessment instruments is in line with the changing viewpoint in the field of neuropsychology. The current viewpoint is characterized by an increasing focus on functional and practical evaluations, acknowledging the necessity to move away from assessments solely based on theoretical constructs towards more inclusive and ecologically sound assessments.

The application of immersive technology in cognitive assessments holds the promise of fundamentally transforming our comprehension and quantification of cognitive functions. This doctoral thesis addresses the urgent need for assessments that are more practical, applicable, and holistic by implementing user-friendly platforms and immersive cognitive tasks.

Moreover, this study acknowledges its inherent limitations and recognizes the necessity for further research in order to comprehensively investigate the extensive possibilities of immersive cognitive assessments. The utilization of immersive technologies presents a flexible and adaptable approach for evaluating different cognitive domains. However, there remains a significant amount of knowledge to be gained regarding the specific capabilities and limitations of these technologies. Continued research will be crucial in order to reveal the full range of potential applications and to enhance the precision of these emerging assessment instruments.

Moreover, the discoveries and contributions of this doctoral dissertation align with a wider range of scholarly works that underscore the movement towards ecologically valid assessments of cognitive processes. The aforementioned transformation has been prompted by the increasing acknowledgment that cognitive functions cannot be compartmentalized into inflexible and separate constructs. Instead, these processes are characterized by their dynamic nature and interdependence, as they function within the contexts of the real world. Hence, the incorporation of practical, task-based evaluations is imperative in order to offer a more precise and all-encompassing comprehension of an individual's cognitive capacities.

In summary, this work represents a significant milestone in the continuous pursuit of cognitive assessments that are both practical and user-friendly, while also maintaining ecological validity. By adopting immersive technologies and user-friendly platforms, this approach expands the limits of conventional cognitive assessments and foresees the transformative possibilities of comprehensive and purpose-oriented evaluation methods in the field of neuropsychology. This study demonstrates the continuous development of the discipline, acknowledging the necessity of examining and assessing intricate cognitive processes within dynamic and environmentally diverse contexts.

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