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# Experimental Aging Research

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## **Impact of the physical activity level of master athletes on divided attention and binding processes in episodic memory: a virtual reality study**

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# **Impact of the physical activity level of master athletes on divided attention and binding processes in episodic memory: a virtual reality study**

Background: Master athletes are a model of successful aging as their high level of physical activity limits the age-related change of physiological functions. This model is used to investigate how a high level of physical activity impacts cognitive functioning.

Objective: We aim to study the effect of a high level of physical activity on the ability to manage interferences and binding processes in episodic encoding in an ecological situation.

Method: Fifty-five participants were recruited and separated into three groups: 18 master athletes (MA,  $M = 69.39$ ,  $SD = 1.13$  years), 18 young adults (YA,  $M = 22.44$ ,  $SD = 1.10$  years), and 19 older adults with a moderate level of physical activity (OA,  $M = 72.11$ ,  $SD = 1.10$  years). Participants performed an episodic memory task assessing binding processes by encoding under either full or divided attention using a virtual reality technique.

Results: After encoding under divided attention, MA outperformed OA in the interference task as well as in the binding score on both free and cued recall. After encoding under full attention, YA and MA did not differ in the number of events recalled in cued recall. Furthermore, significant correlations were found between weekly volume of physical activity and cognitive performance.

Conclusion: Binding and interference management, and probably the hippocampus along with prefrontal areas, benefit the most from a sustained and regular physical activity in master athletes.

Word count : 13 218

## **Introduction**

Physical activity is defined by the World Health Organization (WHO, 2022) as “any bodily movement produced by skeletal muscles that requires energy expenditure –

including activities undertaken while working, playing, carrying out household chores, travelling, and engaging in recreational pursuits” which includes exercising (“physical activity that is planned, structured, repetitive, and aims to improve or maintain one or more components of physical fitness”). A higher level of physical activity is associated with an increased life expectancy, about 3.5 additional years, than a lower level of physical activity (Woodcock et al., 2010). Physical activity reduces or delays the emergence of cardiovascular diseases or other pathologies such as type II diabetes (Tompkins et al., 2009), lung cancer (Sun et al., 2012) and breast cancer (Wu et al., 2013). In addition, physical activity induces a positive effect not only on mental health but also on cognitive health (Colcombe & Kramer, 2003; Blanchet et al., 2018 for a review). A crucial topic concerns the optimal dose of physical activity necessary to benefit from the positive gains of physical activity on cognition in order to remain in good cognitive health. Master athletes (MA) are elderly people who engage in sustainable and intense physical training (Lepers, 2019). They may therefore be a good model for countering the effects of age on different levels, such as physiological, cognitive, and mental health. The impacts of physical activity on cognition in master athletes have been less studied. The main purpose of the current study was to consider whether master athletes may be considered as a model of successful cognitive aging by analyzing the impacts associated with a high level of physical activity on cognitive and daily life functioning in elderly people.

Executive functions, attention and episodic memory are the cognitive functions that are the most vulnerable to normal and pathological aging with an increased risk of progressing to Alzheimer’s disease or other types of dementia (Blanchet et al., 2002). Fortunately, these processes are also the most sensitive to the benefits of physical activity on cognition (Blanchet et al., 2018 for a review). Episodic memory allows one

to remember events specific to individual experience in their subjective spatial and temporal context, and includes encoding, storage, and retrieval stages (Tulving, 1972, 1995). These stages involve not only episodic memory processes *per se*, but also related cognitive processes such as executive functions and attentional resources. The role of attention in episodic memory has been particularly investigated through memory paradigms performed under divided attention. A secondary task affects greater subsequent recall performance when this division of attention takes place during encoding rather than during retrieval, suggesting that encoding is particularly sensitive to interference ( Craik et al., 1996; Naveh-Benjamin, 2000; Troyer & Craik, 2000; Naveh-Benjamin et al., 2005; Blanchet, Belleville & Peretz, 2006). In aging, the executive control process which allows one to manage two tasks at the same time decreases, leading to a lower subsequent memory performance after encoding under divided condition ( Craik & Byrd, 1982; Park et al., 1989; Craik et al., 1996; Anderson et al., 1998; Naveh-Benjamin et al., 2005; Blanchet et al., 2006; Luo & Craik, 2008; Toczé & Taconnat, 2014; Blanchet, 2015). Executive control processes are also involved in encoding strategies such as linking items of information together during encoding or binding processes (Ranganath, 2010; Blanchet, 2015). Binding processes, which are solicited during episodic memory, enable one to combine the contextual features surrounding the information into a coherent whole during both encoding and storage ("what", "where", "when" and "how") (Plancher et al., 2010). Episodic memory decline in older adults may be explained, at least in part, by poorer abilities for binding contextual information (i.e. location, item, color, size) into a unique representation (Chalfonte & Johnson, 1996). These binding processes can be particularly well investigated in a relatively ecological situation using virtual reality paradigms.

Virtual reality is a technique that can be used to assess cognitive functioning in a controlled and safe environment, while simulating some aspects of the real world (Fuchs et al., 2006). Plancher et al. (2010) assessed the effects of aging on episodic memory, and specifically binding processes in full attention encoding and retrieval using virtual reality. Their experiment, conducted on a computer screen, consisted in driving through a virtual urban environment in which several events took place. Participants were then asked to recall as much contextual information as possible (time, location, perceptual details) in addition to the events. A similar number of events and perceptual details were recalled by both older and younger adults whereas spatial, time-related contextual information was significantly less well recalled by older adults compared to younger adults. This pattern can be explained in the light of the Associative Deficit Hypothesis (ADH, Naveh-Benjamin, 2000) which posits that age-related memory decline is due to difficulty in binding the contextual elements of a memory episode and retrieving bound units.

The attentional resources theory accentuates this pattern since binding performances depend on the availability of attentional resources and the ability to allocate attention efficiently (Blanchet, 2015, for a review). Binding processes performed in dual task conditions were studied using a virtual reality task by Jebara and colleagues (2014). Their experiment consisted in memorizing episodes while navigating in a virtual city in one of four modes of exploration: passive condition (memorize only, no interaction or itinerary control), itinerary control condition (memorize and choose the itinerary without driving), low navigation control (memorize and move the car on the rails with the gas pedal on a fixed itinerary), high navigation control (memorize and drive with a steering wheel and the gas pedal on a fixed itinerary). The study showed that binding performances were higher for participants in the passive condition and the

itinerary control condition than in the low and high navigation control conditions. The authors suggested that the latter two conditions were associated to a high attentional and executive load, which decreased the efficiency of binding processes. These findings are consistent with the fact that carrying out an interfering task during the encoding of an item and its contextual information has a greater impact on the creation of the link between the item and its context than the processing of the item itself (Kim & Giovanello, 2011).

Episodic memory as well as executive functions are highly sensitive to age-related effects ( Craik & Byrd, 1982; Park et al., 1989; Craik et al., 1996; Anderson et al., 1998; Blanchet et al., 2006; Luo & Craik, 2008; Toczé & Taconnat, 2014; Blanchet, 2015). These functions are also the most sensitive to the cognitive and health benefits induced by physical activity (Colcombe & Kramer, 2003; Blanchet et al., 2018; for reviews). The first meta-analysis to have revealed a positive effect of physical activity on cognition is the one by Colcombe and Kramer (2003) which found that executive functions, control processes, and processing speed were the most positively impacted by physical activity. Attentional resources are also improved by physical activity (Smith et al., 2010). For instance, older adults with a high level of physical activity outperformed those with a lower physical activity level in processing speed and the strategic control of attentional orienting (Condello et al., 2017). These results suggest that a high level of physical activity could moderate age-related decline in the ability to distribute attentional resources. Given the lower attentional resources and executive control of older adults and the involvement of these processes in different cognitive tasks, the gain related to physical activity could compensate for age-related differences in many types of cognitive tasks such as episodic memory tasks.

The neurophysiological mechanisms underlying the relationship between physical activity, executive functions, and episodic memory can be understood through both direct and indirect pathways, as described by the Memory NEO-Structural Inter-Systemic model (MNESIS; Eustache & Desgranges, 2008; Eustache et al., 2016). Physical activity is proposed to directly enhance attentional resources by increasing arousal, improving executive function, and promoting neurogenesis in brain regions associated with attention, particularly the prefrontal cortex (Hillman et al., 2008; Voss et al., 2011). According to the MNESIS model, the frontal areas play a crucial role in executive functions and the regulation of attentional resources, which are essential for the effective encoding and retrieval of episodic memory (Eustache & Desgranges, 2008). Physical activity may enhance the brain's metabolic efficiency and energy availability, which is particularly important given the high energetic cost of neuronal activity and the brain's limited attentional resources (Blanchet, 2015; Lennie, 2003). Optimizing the functioning of the prefrontal areas, by recruiting more neurons or improving their efficiency, enables the brain to have a greater pool of attentional resources (Erickson et al., 2015, 2019; Xiong et al., 2021). This, in turn, supports tasks that require episodic memory (Bugajska et al., 2007; Toczé & Taconnat, 2014; Moutoussamy et al., 2024).

Improved executive functioning, which can be enhanced through physical activity, may play a mediating role in the relationship between physical activity and episodic memory. The MNESIS model suggests that the hippocampus and frontal regions operate in coordination, with the hippocampus being critical for the consolidation and retrieval of episodic memory, while the frontal cortex oversees the executive functions that guide these processes (Eustache & Desgranges, 2008). A study by Moutoussamy and colleagues (2024) supports this hypothesis, showing that the

protective effects of physical activity on episodic memory during aging are largely attributed to improvements in executive functioning. Enhanced executive functions, including inhibitory control, working memory, and cognitive flexibility, facilitate better allocation and utilization of attentional resources, thereby supporting more effective encoding, consolidation, and retrieval of episodic memory (Erickson et al., 2013; Blanchet et al., 2015).

Alternatively, physical activity may also have a direct impact on episodic memory through its effects on the hippocampus, independent of attentional resources. The MNESIS model emphasizes the hippocampus's role in the encoding and retrieval of episodic memory, with physical exercise known to increase hippocampal volume and improve its function (Erickson et al., 2009; 2011; Eustache & Desgranges, 2008). This direct effect of physical activity on the hippocampus occurs through mechanisms such as increased cerebral blood flow and neurogenesis, which directly support memory processes (Prakash et al., 2011). Notably, neurogenesis in the hippocampus is significantly influenced by the Brain-Derived Neurotrophic Factor (BDNF), which is upregulated by physical exercise (Colcombe et al., 2004). BDNF is crucial for supporting neurogenesis and hippocampal function, thereby enhancing memory processes (Colcombe et al., 2004; Klempin et al., 2013; Farrukh et al., 2023; Walsh et al., 2020; Dadkhah et al., 2023). Thus, physical activity contributes to improved episodic memory performance by enhancing the structural and functional integrity of the hippocampus, in conjunction with optimized executive functioning via the frontal areas. It is also important to note that these frontal regions are particularly sensitive to the effects of physical activity (Dupuy et al., 2018, 2019; Erickson et al., 2022; Raji et al., 2024). Exercise enhances the structural and functional integrity of the prefrontal cortex, crucial for executive functions such as attention and working memory, through

increased cerebral blood flow, angiogenesis, and synaptic plasticity (Hillman et al., 2008; Voss et al., 2011). BDNF, upregulated by exercise, further supports neuroplasticity in these regions as well (Leckie et al., 2014, Dupuy et al., 2019). For instance, a high level of physical activity has been shown to be associated with better relational memory and feature binding in preadolescent children (Chaddock et al., 2011), in young adults aged between 18 and 35 (Schwarb et al., 2017) and in the elderly (Hayes et al., 2015; Nagamatsu et al., 2012). In these studies, binding processes were assessed with verbal learning and face-name association tasks under full attention. It is relevant to assess how physical activity acts on binding processes in an ecological environment such as virtual reality. Given the role of these cognitive functions in the evolution towards dementia in aging and considering the significant gains of physical activity on cognition in aging, it appeared interesting, therefore, to investigate how these cognitive functions could benefit from a high level of physical activity, as in the case of master athletes who engage in sustained and intensive physical activity over a long period of time (Lepers, 2019).

Master athletes are defined as people with a high physical activity level, training several times a week and competing in sports events, maintaining their sustained and intense training routines like younger elite athletes, with the main difference being their greater age (Lepers & Stapley, 2016). In the present study, we focused on athletes aged 65 years old or above. To our knowledge, only a few studies have investigated the cognitive functions of master athletes. However, master athletes may offer a model for optimal aging and for counteracting the impact of normal, and even pathological, aging on cognition. Tseng et al. (2013) demonstrated that MA (medium age: 72.4 years old) showed higher executive functioning with higher performances in letter and category fluency tasks than their sedentary age-matched counterparts. An improvement in

attention-executive function (measured with Trail Making Test- B, COWAT, n-back and the Digital Span Subset from the WAIS-III) was also found for MA compared to sedentary elderly people (Schott & Krull, 2019; Tarumi et al., 2015). More recently, Dupuy and colleagues (2018) showed that master athletes with a high VO<sub>2</sub>max level succeeded better in a computerized dual task than less fit individuals with a lower VO<sub>2</sub>max level, indicating that they were better able to distribute their attentional resources in a dual task situation. Several authors have also found a beneficial effect of the high level of physical activity of MA on episodic memory as compared to sedentary elderly participants with medium ages respectively: above 75 years old, 52 years old and 57.3 years old (Tarumi et al., 2015; Zhao et al., 2015). To our knowledge, no studies have investigated, among MA, the effect of physical activity on both divided attention and binding processes in an ecological situation, although these kinds of situations often occur in daily life.

Cognitive functions, and especially episodic memory, are vulnerable to aging (Isingrini et al., 1990; Tulving, 1995; Anderson et al., 1998; Troyer & Craik, 2000; Blanchet et al., 2006; Toczé & Taconnat, 2014; Blanchet, 2015) and more specifically to binding performance (Spencer & Raz, 1995; Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000; Mitchell et al., 2000; Glisky et al., 2001), even when using an ecological task such as virtual reality (Plancher et al., 2010). Episodic memory performance also declines in older adults when encoding an item under divided attention conditions or when carrying out an interfering task because of the insufficient attentional resources available (Craik & Byrd, 1982; Craik, 1983; Park et al., 1989; Craik et al., 1996; Anderson et al., 2000; Fletcher & Henson, 2001; Naveh-Benjamin et al., 2005; Blanchet et al., 2006; Luo & Craik, 2008; Shing et al., 2010; Kim & Giovanello, 2011; Toczé & Taconnat, 2014; Blanchet, 2015). Jebara et al. (2014) also

showed the impact of an interference task during the memorization of events and their context through a virtual reality task, which led to poor binding performance due to high executive-attentional load. In contrast, physical activity has a beneficial, if not protective, effect on both cognition and the brain (Colcombe & Kramer, 2003; Erickson et al., 2009, 2011, 2022; Smith et al., 2010; Nagamatsu et al., 2012; Hayes et al., 2015; Blanchet et al., 2016; Condello et al., 2017; Schwarb et al., 2017; Blanchet et al., 2018). Therefore, MA, with their cognitive functioning, and especially their greater episodic memory, executive and attentional performance (Tseng et al., 2013; Tarumi et al., 2015; Zhao et al., 2015; Dupuy et al., 2018; Saillant et al., 2023) could provide an interesting research model for investigating optimal aging. However, these studies compared MA only to sedentary older adults (Tarumi et al., 2015; Zhao et al., 2015; Dupuy et al., 2018) and none used ecological tasks to measure cognitive performance.

In the current study, to assess the effect of a high level of physical activity in MA on the management of attentional resources in encoding and on binding processes in episodic memory, MA carried out an episodic memory task in which the allocation of attentional resources during encoding was manipulated and was compared to the performance of elderly individuals with a moderate level of physical activity and that of young adults. During this episodic memory test, participants were immersed in a virtual town as a pedestrian and had to memorize 12 events with their spatio-temporal context (location, time of onset, perceptive details) either in full attention (FA) or in divided attention (DA) before their delayed free recall followed by a cued recall with the spatio-temporal information. We expected greater binding performance in MA after encoding under divided attention than in older adults with moderate physical activity level. We expected that this ecological task would be more sensitive than standardized neuropsychological tests to assess the cognitive gains induced by a high and sustained

level of physical exercise. Lastly, the relationship between the number of hours of physical activity and cognitive functioning was explored to establish the optimal dose for inducing cognitive gains. We expected that the higher the weekly volume of physical activity, the better the performances among our three groups.

## **Materials and methods**

### ***Participants***

Fifty-five participants were enrolled in the protocol and were divided into three groups: 18 elderly MA, 19 older individuals with moderate physical activity (OA) and 18 young adults (YA). The sociodemographic characteristics and physical activity levels of the participants are summarized in Table 1. All participants were volunteers. They were recruited through sports or leisure associations as well as announcements in shops and stores in two different French regions: Ile-de-France and Burgundy. All the older individuals had to be 65 years old or more. The inclusion criteria for the MA were to have practiced endurance training in a sport such as running, cycling, or swimming in a club and to have participated in competitions for at least two years. The two-year minimum for competitive participation must have occurred during their older adulthood (from age 50 onwards). This ensures that both the endurance training and competitive participation are recent and relevant to their current physiological status, as well as to the period of life being studied, allowing for accurate assessment of the athletic activities' benefits and effects. The level of physical activity was considered moderate for older individuals obtaining a score between 11 and 20 on the Dijon Physical Activity Score (SAPD; Robert et al., 2004). This questionnaire is composed of nine questions with answers on a Likert scale ranging from 0 to 3, or 0 to 4. The rating is divided into three categories: a score of 0 to 10 reflects a low level of physical activity,

a score of 11 to 20 reflects a moderate level of physical activity, and a score of 21 to 30 reflects a high level of physical activity. This score was developed by the authors to be as precise as a field test without having to compel participants to undertake real exercise testing. The score obtained by a population of elderly people and the peak of VO<sub>2</sub>max are correlated, proving that effortful VO<sub>2</sub>max testing can be substituted by this scale, thereby making physical activity level assessment easier and quicker. The inclusion criteria for all participants were to be a French native speaker and to have normal or corrected-to-normal vision and hearing. Exclusion criteria for both older and young individuals included motor disability of the hands, a history of head trauma, neurological impairment or stroke, depressive symptoms (cut-off above 10 on the Geriatric Depression Scale), alcoholism or drug abuse as well as psychiatric history, medication intake that could interfere with cognitive functioning (antidepressants, sleeping pills, anxiolytics) and general anesthesia in the preceding six months. The elderly groups were screened using the Mini Mental State Examination (MMSE; Folstein et al., 1975) to avoid the presence of cognitive deficits (MMSE cut-off above 27/30). During the first meeting, individuals signed a consent form in accordance with the Helsinki ethical agreements.

[Table 1 near here]

The three groups did not differ in educational level. OA and MA did not differ in age ( $p > .05$ ). The level of physical activity level on the SAPD and the weekly volume of physical activity differed between the three groups: OA had the lowest scores compared to MA and YA ( $p < .001$ , for both scores). Lastly, MA and YA did not differ in level of physical activity or in the weekly volume of physical activity ( $p > .05$ , for both scores).

## ***Procedure***

The neuropsychological assessment and virtual reality task were conducted in two different sessions (approximately one week apart), each one lasting about 2 hours. The sessions were held in a quiet environment. For the virtual reality task, participants experienced one condition (full attention versus divided attention) per session, with the order of conditions counterbalanced. Therefore, participants who were assigned to the full attention condition in session 1 were assigned to the divided attention condition in session 2, and those who were assigned to the divided attention condition in session 1 were assigned to the full attention condition in session 2.

### *Memory task performed in full or divided encoding using a virtual reality environment*

Participants had to memorize events that occurred during a trip through the streets of a virtual city, either with full attention or divided attention, before a recall phase (free recall and cued recall). The virtual reality environment consisted of a typical French city similar to Paris, generated with the Simulamem software. The environment was designed to look as much as possible like a real French city and included shops, trees, cars, trashcans, and traffic lights. The usual city sounds could be heard (car engines, trains, birds chirping, etc.). There were 12 landmarks in the environment (newsstand, church, town hall, playground, train station, tobacco shop, post office, pantheon, fountain, kebab trucks, medical and psychological center, and office building) which remained the same regardless of the condition of attention (full or divided). Participants had to follow a road indicated by arrows, navigating with the computer joystick, and memorize 12 animated events (featuring animals or humans) that occurred during the trip. A first-person perspective was adopted to enhance the feeling of immersion in the virtual environment (Tuena et al., 2017). Participants had to stay in the middle of the

road and moved at a constant speed equivalent to 8 km/h. The encoding phase was followed by a delayed recall phase (free recall and cued recall).

In the divided attention condition, forty sounds were heard during the learning phase. For each sound, participants had to indicate if it corresponded to a living sound (animal or human) or to a not-living sound (noise of a car, clock, phone...). After a filled delay with the Brown-Peterson paradigm or the Paced Auditory Serial Addition Test, both lasting about fifteen minutes, participants were asked to provide a free recall during five minutes of the events they had previously seen, mentioning as many events as possible along with their context (perceptual details, location in space and temporality). This was followed by a cued recall of five minutes using a slide show of the events seen during the experimental phase in a random order (without any clue allowing participants to identify their location or details concerning the color of the items for example). For each event presented, participants had to recall as many details as possible. In the divided attention condition, after the two recall modes, participants also had to recall all the sounds they remembered, followed by an identification of each sound previously heard during the learning phase.

Before beginning the experimental memory task, participants underwent a training session to familiarize themselves with the setup. They were seated at a desk, with a flight stick joystick connected to the computer, positioned in front of them and a computer screen displaying the virtual environment. The joystick was used to navigate within the environment, allowing participants to move freely and interact with the virtual space during the task. The training phase allowed them to explore the environment. Participants had to memorize the different landmarks during this trip. They had to recall 8/12 landmarks in order to be allowed to follow the experimental task. If this threshold was not reached, they had to begin the training phase again. The

duration of each phase was about 7 minutes (familiarization and learning). Parallel versions of the list of events were used between the two conditions. These versions were counterbalanced between participants.

### *Scoring*

*Memory task.* Analyses of the virtual reality task were carried out on memory response indices based on previous research using this virtual environment (Plancher et al., 2010), in addition to three response indices for the interfering task. For each encoding condition under full attention or divided attention, different memory indices were calculated for both free and cued recall.

*Number of events recalled (clue “what”).* This index corresponds to the overall number of events recalled after each encoding condition, no matter how many details are associated with each event. For each encoding condition, it was calculated for both free and cued recall, with a maximum of 12 recalled events.

*Binding score (clues “where”, “when” and “perceptive details”).* This score was calculated taking into account all the spatio-temporal and perceptive details given by the participants for each event recalled. The binding score corresponds to the recall of three kinds of details (clues “where”, “when” and “perceptive details”) associated to each event recalled.

### *Indices obtained in the interference task*

*Sound classification score during divided encoding.* This index corresponds to the number of sounds heard during encoding and correctly categorized as "living" or "non-

living". The score was established by counting one point for each sound correctly classified (maximum score of forty points).

*Sound delayed free recall score.* Once the free and cued recall of the virtual reality task had been completed, participants were asked to recall as many sounds as possible from the forty sounds previously heard during the learning phase of the encoding condition in divided attention. The score corresponds to the number of sounds correctly recalled (maximum score of forty points).

*Sound identification score.* After the delayed free recall of sounds, a soundtrack containing the forty sounds heard in the study phase was presented to the participants who had to name them. Each sound correctly identified was awarded one point (maximum of forty).

#### *Standardized neuropsychological tests*

A battery of standardized neuropsychological tests was administered to all participants to draw their cognitive profile. Episodic memory was assessed using the Doors & People Test (Baddeley et al., 1994). This test includes two subtests: the Doors Test and the People Test. The Doors Test is a visual recognition test, divided into two parts. Participants were shown 12 photographs of different types of doors for a few seconds. The same target doors were then presented immediately afterwards with three distracter doors from the same category. Participants were asked to identify the target door. In part A, the distracters were from different categories of doors to the target door whereas in part B, the distracters were the same type of doors but differed in certain details. One point was awarded for each correct response. The People Test measures the binding processes of episodic memory. The photographs of four characters with their names and

occupations printed below were presented for a few seconds each. Once the four pictures had been shown, participants were given each character's occupation and were asked to recall the associated name. One point was awarded for each first name and surname correctly recalled. If the participant succeeded at the first attempt, the maximum score was automatically awarded. Otherwise, two more presentations, the same as the previous one, were conducted. The maximum score per trial was 12 and the maximum score for the immediate recall test was 36. Lastly, delayed recall of the names was assessed after administration of the visual recognition subtest.

The Paced Auditory Serial Addition Task (PASAT; Gronwall & Sampson, 1974) was used to investigate information updating skills in addition to information manipulation and sustained attention skills. An audio recording is needed to carry out this test: a number is spoken audibly every 4 seconds. Participants must add up the last 2 digits heard and formulate their answer orally as the series of digits unfolds. The sums to be made never exceed 15. The score can vary from 0 to 60. The Brown-Peterson Paradigm (Belleville et al., 2002) assesses working memory in double task. This paradigm consists in memorizing several trigrams of letters which are not phonologically similar. Participants were assessed on their immediate recall of the trigrams (0 delay interference) or delayed recall after a backward counting during 10, 20 or 30 seconds.

Executive functions were evaluated with three tests: the *Trail Making Test A and B* (Reitan, 1956), the French adaptation of *Stroop Victoria* (Bayard et al., 2009), and verbal fluency (Cardebat et al., 1990). Trail Making Test (TMT): In part A which measures processing speed, participants were asked to draw a line connecting the digits in ascending order (e.g., 1, 2, 3, etc.). In part B, which measures cognitive flexibility, participants were asked to draw a line alternately connecting letters in alphabetical order

and digits in ascending order (e.g., 1, A, 2, B, 3, C, etc.). Time in seconds taken for performance was measured. Stroop Victoria was used to assess initiation capacity, processing speed and inhibition among the elderly. This version of the Stroop has 3 cards: in the first one called “Dot”, several lines of dots in four different colors (blue, green, red and yellow) were presented; in the second one called “Word”, short words were written in a random order in one of the four colors mentioned; in the third one called “Interference”, the names of the four colors were written in a different color from the written word (e.g. the word blue was written in red). For the Dot and Words cards, participants were asked to give the color of the ink as quickly as possible without error. The shorter the response time, the better the processing speed. For the Interference card, the fewer the errors, the better the participant's inhibitory capacity. To test lexical access ability, *Letter fluency and Category fluency* were used. For letter fluency, participants were asked to say as many words as possible starting with a given letter (letter P). For category fluency, the participant had to state as many words as possible for a given semantic category (animals). Participants were given two minutes for each of the two tasks.

Several questionnaires were also administered to the participants. The *Self-Assessment of Memory Questionnaire* (QAM; Van der Linden et al., 1989) was also administered to assess subjective memory complaints in everyday life. The QAM comprises 62 items with responses on a 7-point Likert scale ranging from 0 “never” to 6 “always”. A high score on this questionnaire indicates a high memory complaint. Lastly, the level of anxiety was assessed with the French version of the *State Trait Anxiety Inventory A and B* (STAI; Spielberger, 1983). Part A assesses the anxiety state when the participant completes the scale while part B assesses the anxiety trait, i.e., the level of anxiety usually felt by the person in daily life. Each part includes 20 statements

that participants must rate on a scale from 1 to 4 based on their feelings. This scale makes it possible to distinguish five levels of anxiety: very low (less than 35), low (36 to 45), moderate (46 to 55), high (56 to 65) and very high (score above 66).

### ***Data analysis***

To examine the effect of physical activity level on binding score according to the attentional availability in encoding, an ANOVA with encoding conditions (Full attention, Divided attention) as within-subject factors and groups (MA, OA, YA) as between-subjects factors was conducted for each memory index. Significant interactions were decomposed by post-hoc analysis using a Scheffé test. Following these post-hoc analyses, a Bonferroni correction was applied to avoid Type II errors. When comparing the encoding conditions (full attention and divided attention), the threshold chosen for the Bonferroni correction was .025 (since only two conditions were compared) to analyze the results of the different memory indices for both free and cued recall and interference task indices. To analyze the impact of physical activity levels on the scores obtained in the interference task of the virtual memory task and the standardized neuropsychological tests, a one-way ANOVA was applied with the three groups as between-subject factors. Significant effects were decomposed thanks to post-hoc analyses using a Scheffé test to differentiate the effects between the three groups. For all the latter analyses, the threshold chosen for applying the Bonferroni correction was .016 as three groups of participants were compared.

Additionally, we conducted a post hoc power analysis using G\*Power (version 3.1.9.7) to determine the effect size for a repeated measures ANOVA examining the interaction between a between-subjects factor (Physical Activity Level: MA, OA, YA) and a within-subjects factor (Attention Condition: full, divided) for the interferent sound classification score. The analysis, with an effect size  $f = 1.175$ , a total sample size of 55,

and a significance level of 0.05, resulted in a noncentrality parameter  $\lambda = 303.7375$ , a critical F value of 3.175, and achieved a power of 1.000, indicating a high probability of detecting a significant effect if one exists. While this analysis suggests a highly robust study with a reliable ability to detect meaningful effects, we acknowledge the limitations of this approach (Lakens, 2022).

Lastly, we analyzed the relationship between the number of hours of physical activity practiced and cognitive functioning. For this purpose, Pearson's correlation analyses were applied between the weekly volume of physical activity (in hours) and the different scores obtained in the virtual reality task as well in the standardized neuropsychological tests. This correlational analysis was conducted on the data of all participants ( $N = 55$ ) in order to increase the statistical robustness of the analysis.

## **Results**

### ***Memory performances in the virtual reality task***

#### *Free recall mode*

[Figure 1 and Figure 2 near here]

The ANOVA with encoding conditions (Full attention, Divided attention) as within-subject factors and groups (MA, OA, YA) as between-subjects factors on the number of recalled events in free recall mode showed a significant group effect,  $F(2, 52) = 25.69$ ,  $p < .001$ ,  $\eta^2 p = .49$ . These results are illustrated in Figure 1. Post-hoc analyses indicated that YA recalled more events ( $M = 11.03$ ,  $SD = 0.25$ ) than OA ( $M = 8.63$ ,  $SD = 0.24$ ,  $p < .001$ ) and MA ( $M = 8.58$ ,  $SD = 0.25$ ,  $p < .001$ ). MA and OA did not differ ( $p > .05$ ). There was also a significant condition effect,  $F(1, 52) = 29.11$ ,  $p < .001$ ,  $\eta^2 p = .36$ . The number of events were greater after encoding under FA ( $M = 10.09$ ,  $SD = 0.20$ ) than under DA ( $M = 8.74$ ,  $SD = 0.20$ ). The condition x group interaction was not significant,

$F(1, 52) = 2.88, p < .06, \eta^2p = .099$ ].

The binding score highlighted a significant group effect,  $F(2, 52) = 31.08, p = .000, \eta^2p = .544$ ]. These results are illustrated in Figure 2. Post-hoc analyses indicated that MA ( $M = 5.86, SD = 0.44$ ) performed significantly better than OA ( $M = 3.53, SD = 0.43, p = .001$ ). However, YA ( $M = 9.39, SD = 0.44$ ) outperformed both MA ( $M = 5.86, SD = 0.44, p < .001$ ) and OA ( $M = 3.53, SD = 0.43, p < .001$ ). A significant condition effect,  $F(1, 52) = 14.03, p = .004, \eta^2p = .21$  was also found: the binding score was higher after encoding under FA ( $M = 6.92, SD = 0.35$ ) than under DA ( $M = 5.59, SD = 0.35$ ). The interaction between conditions and groups was significant,  $F(2, 52) = 3.32, p = .04, \eta^2p = .11$ , although this interaction lost significance after the Bonferroni correction.

#### *Cued recall mode*

The ANOVA on the number of recalled events for the cued recall mode showed only a significant condition effect,  $F(1, 52) = 4.34, p = .042, \eta^2p = .077$ . The number of events recalled was greater after encoding under FA ( $M = 11.95, SD = 0.25$ ) than DA ( $M = 11.66, SD = 0.10$ ). No other significant interaction or main effect was found.

The ANOVA on the binding score highlighted a significant group effect,  $F(2, 52) = 45.54, p < .001, \eta^2p = .93$ . These results are shown in Figure 2. Post-hoc analyses indicated that MA ( $M = 6.44, SD = 0.39$ ) obtained a significantly higher binding score than OA ( $M = 4.26, SD = 0.38, p = .001$ ) even if they were outperformed by YA ( $M = 10.39, SD = 0.30, p < .001$ ). YA also outperformed OA ( $p < .001$ ). The condition effect was also significant,  $F(1, 52) = 17.63, p < .001, \eta^2p = .25$ , revealing that the binding score was higher after encoding under FA ( $M = 7.74, SD = 0.31$ ) than DA ( $M = 6.32, SD = 0.31$ ). The interaction between group and condition of attention was significant,  $F(1, 52) = 5.18, p < .009, \eta^2p = .166$ . Post-hoc analyses showed that OA performed

worse after encoding in full attention than both YA ( $p < 0.001$ ) and MA ( $p = 0.035$ ). This last comparison lost significance after Bonferroni correction. After encoding in divided attention, YA outperformed both MA ( $p < .001$ ) and OA ( $p < .001$ ).

### ***Interference task scores in the divided encoding condition***

[Figure 3 near here]

The data showing the group effect on the three interfering tasks of sounds are illustrated in Figure 3. The one-way ANOVA on the sound classification score performed during the divided encoding condition showed a group effect  $F(2, 52) = 34.89, p = .0001, \eta^2p = .58$ . Post-hoc analyses indicate that MA ( $M = 37.61, SD = 0.45$ ) correctly classified significantly more sounds in the divided encoding condition than OA ( $M = 34.21, SD = 0.44, p < .0001$ ). YA ( $M = 39.39, SD = 0.45$ ) also classified more sounds than OA ( $p < .0001$ ). A difference was also observed between YA and MA ( $p = .027$ ), but lost significance after Bonferroni correction ( $p > .016$ ).

The ANOVA on the sound delayed recall score also highlighted a group effect,  $F(2, 52) = 6.59, p = .003, \eta^2p = .21$ . Post-hoc analyses revealed that MA ( $M = 13.67, SD = 0.86$ ) recalled as many sounds as YA ( $M = 16.06, SD = 0.86, p > .05$ ) and did not differ from OA ( $M = 11.68, SD = 0.84, p > .05$ ). In contrast, OA recalled significantly fewer sounds than YA ( $p = .0029$ ) even after applying Bonferroni correction.

Finally, a significant group effect was found for the Sound identification score,  $F(2, 52) = 18.17, p = .0001, \eta^2p = .41$ . Post-hoc analyses indicated that YA ( $M = 37.44, SD = 0.45$ ) correctly identified more sounds than both MA ( $M = 34.83, SD = 0.45, p = .0008$ ) and OA ( $M = 33.68, SD = 0.44, p = .000002$ ) than (even after Bonferroni correction), and that these two elderly groups did not differ ( $p > .05$ ).

### ***Data obtained in the standardized neuropsychological tests and questionnaires***

The scores (mean  $\pm$  standard deviation) obtained on the standardized neuropsychological tests and questionnaires on both mental health and cognitive complaints in daily life are shown in Table 2.

[Table 2 near here]

Performances between MA and OA did not differ ( $p < .05$ ), but YA outperformed MA and OA ( $p < .004$ ). MA did not differ from YA and OA in immediate recall and delayed recall on the People Test (Baddeley et al., 1994), assessing visual and verbal episodic memory. In contrast, OA performed less well than YA on the People Test for immediate recall and delayed free recall, but these differences lost significance after Bonferroni correction ( $p < .016$  for both). Performances between MA and OA did not differ ( $p < .05$ ) on another test assessing visual and verbal memory recall either (Doors Test, Baddeley et al., 1994), but YA outperformed MA and OA ( $p < .004$ ).

MA did not differ significantly from YA and OA ( $p < .05$ ) on a test assessing sustained attention and working memory (Paced Auditory Serial Addition Test) but YA performed significantly better than OA ( $p = .02$ ). On other tests assessing inhibition processes (Stroop) and cognitive flexibility (Trail Making Test), performances between MA and OA did not differ ( $p < .05$ ), but YA outperformed both OA and MA (respectively, TMT A,  $p = .0008$  and  $p = .0035$ ; TMT B,  $p = .0001$  and  $p = .0004$ ; Stroop Dot,  $p = .00089$  and  $p = .00089$ ; Stroop Word,  $p = .000729$  and  $p = .00011$ ; Stroop Interference,  $p = .0002$  and  $p = .0012$ , respectively).

Lastly, the three groups did not differ significantly ( $p > .05$ ) on tests assessing working memory (Brown Peterson Paradigm), lexical access ability (Letter Fluency and Category Fluency) and anxiety levels (State-Trait Anxiety Inventory). The scores of the

three groups on the questionnaire evaluating memory complaints did not significantly differ ( $p > .05$ ) (Memory Self-Assessment Questionnaire).

***Correlational analyses between cognitive performances and weekly volume of physical activity***

To assess whether sustainable and intense physical activity may enhance cognitive performance, we analyzed the relationship between the number of hours of physical activity practiced and cognitive functioning for all pooled groups.

*Correlation analyses between performances on the virtual reality memory task and weekly amount of physical activity*

[Figure 4 near here].

The number of events recalled after encoding either in full or divided attention was positively correlated to the weekly volume of physical activity for both the free recall mode [respectively,  $r(53) = .452, p = .$  and  $r(53) = .25, p = .01$  for both] and the cued recall mode [respectively,  $r(53) = .31$  and  $r(53) = .38, p = .01$  for both]. These results are presented in Figure 4. As the weekly volume of physical activity increased, the number of events recalled increased whatever the encoding condition and recall mode. As the weekly volume of physical activity increased, the binding score obtained after either encoding in full or divided attention was positively correlated to the weekly volume of physical activity for both the free recall [respectively,  $r(53) = .65$  and  $r(53) = .49, p = .01$ ] and cued recall [respectively,  $r(53) = .59$  and  $r(53) = .48, p = .01$  for both]. As the weekly volume of physical activity increased, the binding score increased whatever the encoding condition and recall mode.

*Correlation analyses between performance on the interference task of the virtual reality memory task and weekly amount of physical activity*

[Figure 5 near here].

The weekly volume of physical activity was positively correlated to the Sound classification score [ $r(53) = .59, p = .01$ ], the Sound delayed free recall score [ $r(53) = .35, p = .01$ ] and the Sound identification score [ $r(53) = .36, p = .01$ ]. These correlations are illustrated by the data in Figure 5. The more the weekly volume of physical activity increased, the better the performance for the three interference scores was.

*Correlation analyses between performance on standardized neuropsychological tests and weekly amount of physical activity*

Correlational analysis between cognitive performance on different response indices obtained in the standardized neuropsychological tests and weekly volume of physical activity showed that almost all correlational analysis coefficients reached significant levels. As the weekly volume of physical activity increased, the performance improved in the immediate recall of the Doors Test [ $r(53) = .37, p = .01$ ], the immediate and delayed recall of the People Test [respectively,  $r(53) = .22, p = .05$  and  $r(53) = .28, p = .01$ , for both], the Paced Auditory Serial Addition Test [ $r(53) = .40, p = .01$ ], the Brown Petersen Paradigm [ $r(53) = .23, p = .05$ ], the Category Fluency [ $r(53) = .33, p = .01$ ], the Mini Mental State Examination [ $r(53) = .44, p = .01$ ], except the Literacy Fluency test [ $r(53) = .13, p > .10$ ]. The higher the weekly volume of physical activity, the shorter the processing time in both part A [ $r(53) = -.32, p = .01$ ] and part B [ $r(53) = -.37, p = .01$ ] of the Trail Making Test as well as in the Stroop test [Dots part:  $r(53) = -.22, p = .05$ ; Words part:  $r(53) = -.20, p = .01$ ; Interference part:  $r(53) = -.25, p = .01$ ].

## **Discussion**

The main objective of the current study was to assess the effect of physical activity level on cognitive functioning through the master athlete model. In other words, the study investigated whether sustained and intense physical activity would contribute to protecting against age-related neurocognitive decline. In order to reach this goal, the effect of a high level of physical activity was assessed on the ability to manage interferences on binding processes during episodic encoding using a virtual ecological environment. Our main results showed that MA had better binding performance than OA on free recall whatever the encoding condition (divided or full attention), but this difference no longer existed on cued recall. MA also performed better than their less active counterparts and did not differ from YA in the interfering task performed during encoding in the divided attention condition.

Regardless of the attention condition during the learning phase, our study showed better binding performances in MA compared to their less active counterparts. The number of contextual elements recalled in free recall by MA was significantly higher than those of OA; they were outperformed, however, by YA. The binding score reflects the capacity to recall three kinds of contextual details (time, location, and perceptual details) related to each event recalled. These processes are very vulnerable to age-related effects (Spencer & Raz, 1995; Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000; Glisky et al., 2001; Balota et al., 2000; Bender, Naveh-Benjamin & Raz, 2010). Our results revealed that high-level physical activity in the elderly has a beneficial effect on binding processes and could reduce age-related decline in those processes. Our findings suggest that there is a reduction in age-related decline in binding processes, and even a preservation of these processes, thanks to intense and sustained physical activity. These gains in MA on binding processes can be well

explained at a neural level. Our findings align with the notion that enhanced executive functions and attentional resources, facilitated by physical activity, support better spontaneous retrieval of episodic memory. Specifically, the prefrontal cortex, which is crucial for executive functions, benefits from increased metabolic and neuronal efficiency due to physical activity (Blanchet, 2015; Erickson et al., 2015). This enhanced efficiency likely aids in better organization and retrieval of information, as reflected in the superior free recall scores of MA. Moreover, physical activity in aging populations exerts a protective effect on brain areas underlying episodic memory and binding, such as the hippocampus and prefrontal region by limiting age-related declines in hippocampal and prefrontal volume (Erickson et al., 2009, 2011, 2022; Dupuy et al., 2019; Raji et al., 2024). Furthermore, physical activity increases neuronal regeneration of the hippocampus through release of the Brain-Derived-Neurotrophic Factor (BDNF) in humans (Colcombe et al., 2004) or even serotonin liberation such as demonstrated in aged mice models (Klempin et al., 2013; Park et al., 2020; Illesca-Matus et al., 2023, for a review).

However, the lack of significant differences in cued recall on the binding score, regardless of attention conditions, suggests that while physical activity improves spontaneous memory retrieval, its effect is mitigated when cues are provided. This outcome implies that the provision of cues equalizes the conditions for both MA and OA, as both groups can use other strategies for retrieval to access stored information effectively. This observation underscores the role of attentional resources and executive functions in free recall but also highlights that cued recall is less dependent on these resources, as cues help compensate for any differences in retrieval efficiency. Physical activity therefore acts on these structures involved in binding, as well as on elaboration strategies solicited for binding different items of contextual information during

encoding. It also impacts the retrieval capacity of these contextual elements when no cues (free recall) or a few recall elements (cued recall) are provided. The capacity to encode and recall information with its spatiotemporal contextual details solicits a distributed network including the hippocampal and surrounding areas connected to the prefrontal areas (Shing et al., 2010). This means that the strategic components of executive functions and attentional resources with memory performance are interdependent at both functional and neuronal levels. The weaker binding performances of the elderly compared to their younger counterparts could also be explained by the strategies used during the learning phase of events. The elderly's proactive control strategy is less efficient than in young individuals (Braver et al., 2007) because of their weakened executive functions. As a result, the age-related changes in executive functions may reduce older persons' ability to initiate the encoding of target information effectively for a lasting and explicit representation, especially when the targeted information to be encoded is accompanied by numerous contextual details (Erickson et al., 2007). Although previous researchers have argued that age induces a change in strategy use (Braver et al., 2007; Bugajska et al., 2007), the age-related change in memorization strategies could be reduced by high physical activity. Therefore, MA may apply an efficient proactive strategy as YA do in order to actively retain contextual information.

Our findings indicate that MA are less sensitive to interference than OA, as they correctly classified significantly more sounds in the divided encoding condition than older adults with moderate physical activity. This supports our assertion through the MNESIS model that physical activity improves executive functions, which, in turn, manage attentional resources and interference better (Erickson et al., 2015, 2019; Xiong et al., 2021; Moutoussamy et al., 2024). Master athletes were therefore less sensitive to

interference while carrying out the sound classification task (interference task during encoding). The fact that MAs' performance in the primary interference task was comparable to that of YA further supports the idea that physical activity can maintain or enhance executive function levels across the lifespan, mitigating the impact of interference on cognitive tasks. These results suggest an improvement in interference management in elderly people having a high level of physical activity. The sound classification score benefits the most from the gains of sustained and intense physical activity. These results agree with the hypothesis that attentional abilities improve with structured physical activity (Smith et al., 2010; Moutoussamy et al., 2024) and previous research demonstrating a decreased sensitivity to interference in older adults following aerobic training compared to sedentary older people (Guiney & Machado, 2012). In addition, Smiley-Oyen and colleagues (2008) reported that this decrease in interference sensitivity was greater with the duration of the aerobic-type training program, the sensitivity to interference after 10 months of training being significantly lower than after 5 months of training. At the neurophysiological level, this decrease in sensitivity to interference could be explained by an increased recruitment of prefrontal and parietal cortices (Prakash et al., 2011). In addition, aerobic-type physical activity is associated with reduced activations in the anterior cingulate cortex (Colcombe et al., 2004). A decreased activation of this region, known for its role in the adaptation of control processes, may explain an increase in the efficiency of attentional resources (Colcombe et al., 2004). Overall, the results of these previous studies support the idea that regular exercise of aerobic-type physical activity in older adults improves their ability to precisely select and inhibit distractors. It may also reflect better neuronal plasticity and BDNF production, associated with a higher performance, in older adults with a high level of physical activity than less active counterparts. Given the regular and sustained

physical activity practiced by MA, the results of this study support this model of successful aging for cognitive and particularly executive and attentional performance.

Nevertheless, a high level of physical activity does not seem to compensate for the age-related decline in binding between MA and YA when exacerbated in the divided encoding attention condition. A divided attention situation has a detrimental impact in the elderly (Craik & Byrd, 1982; Verhaegen & Cerella, 2002), causing difficulty in using intentional encoding strategies as well as difficulty dividing attentional resources efficiently between two tasks (Blanchet et al., 2006; Staub et al., 2013), making it more challenging for older adults to successfully encode information. Our findings are consistent with those of Craik et al. (1996), who demonstrated that encoding a list of words in a divided attention condition leads to performance degradation in both the main task and in the interfering task in aging.

Lastly, in all three groups, our study emphasizes the importance of a sustainable and high level of physical activity to enhance cognitive performances such as binding performance (virtual task), visual and verbal memory performance (Doors and People Test), processing speed and cognitive flexibility (Trail Making Test), as well as sustained attention and working memory (PASAT). A level of high physical activity also helps to decrease sensitivity to interference (sound interference tasks). When considering the weekly volume of physical activity, high binding processes (binding score) benefited the most from a sustainable and intense volume of physical activity among our three groups, in contrary to weak binding processes, suggesting again that regular and intense training enhances binding performance quality in aging. These effects can be explained on a neurobiological level. Rasmussen and colleagues (2009) found that with aerobic physical activity there was an increase in the levels of BDNF release, a protein which plays an essential role in neurogenesis as well as in learning

and memorization capacities (Pang, 2004). Thus, the increase in BDNF release with a very high physical activity level in master athletes is likely to increase their learning and memorization capacities. Furthermore, Erickson et al. (2009) found an association between BDNF levels and changes in anterior hippocampal volume. The increased dendritic branching from BDNF increases hippocampal volume through exercise (Erickson et al., 2009). This increase in BDNF release is crucial because the anterior hippocampus plays a key role in the encoding of contextual information (Eichenbaum, 1999; Davachi, 2006). In short, this neurogenesis underlies the cognitive gains induced by physical activity. Binding capacities may therefore be preserved for a longer period thanks to a high level of physical activity. In addition, aerobic-type physical activity is thought to contribute to reversing the loss of hippocampal volume in late adulthood and to improving memory performance (Erickson et al., 2009). As a result, MA benefit from a slowing of the age-related decline in hippocampal volume, thus preventing or even slowing down the cognitive disorders encountered during aging. The results of the correlational analysis between the weekly volume of physical activity and the three scores of the interference tasks of sounds also indicate an enhancement of attentional resources management during dual tasks. The sound classification score performed during encoding benefited the most from sustained and intense physical training. This reinforces our claim, grounded in the MNESIS model, that physical activity enhances executive functions, leading to more effective management of attentional resources and interference (Erickson et al., 2015, 2019; Xiong et al., 2021; Moutoussamy et al., 2024). Therefore, the greater the weekly activity volume is, the lesser the interference sensitivity, even in daily life situations such as those assessed by a virtual reality paradigm.

In conclusion, by comparing a moderate level with a high level of physical activity among the elderly, we showed that physical activity induces benefits on binding performance in episodic memory and attentional processes in an ecological situation such as the one assessed with a virtual reality task. This study provides new findings with respect to previous studies comparing the cognitive performance of master athletes to sedentary elderly people (Tseng et al., 2013; Tarumi et al., 2015; Zhao et al., 2015; Dupuy et al., 2018). In addition, only a few studies selected master athletes from the age of 65 years old and above (Tseng et al., 2013). In contrast to these previous studies on master athletes, our methodology uses virtual reality, allowing an immersive and interactional setting to evaluate episodic memory in daily life functioning. This virtual reality paradigm was particularly sensitive in highlighting the effect of physical activity compared to standard neuropsychological tests administered in full attention. Furthermore, this study recorded the participants' volume of physical activity, which makes it possible to assess the optimal amounts of physical activity in order to benefit from the induced gains. Thus, the performance of binding in episodic memory, the ability to distribute attentional resources, processing speed, cognitive flexibility, sustained attention and working memory are also cognitive functions improved by regular and sustained physical activity, both in YA and in elderly people either with a moderate level of physical activity or MA. Despite an age effect that subsists between YA and the two groups of older adults, the binding performance and interference management of MA are for the most part superior to those of older adults. This study contributes to research on the model of successful aging by demonstrating the benefits of physical activity with a view to preventing and protecting from the effects of normal and abnormal aging on the physical level but above all on cognitive and psychological health. Regular and sustained physical activity helps to protect against the

neurocognitive decline associated with normal aging, while promoting successful aging both physically and cognitively.

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#### Consent to Participate

Prior to enrollment, written informed consent was obtained from each individual participant.

#### Data availability statement

The data sets that were used and/or analyzed in the current study are available from the corresponding author, SB, upon reasonable request.

#### Disclosure statement

The authors report no potential conflicts of interest.

#### Ethics approval

This study was approved by the Ethical Committee of the University Paris Cité (N° 2022-76) in accordance with the ethical standards of the Declaration of Helsinki (1964) and its subsequent amendments. Ethical research approval was granted to both Indra Maurisse and Sophie Blanchet, Ph.D.

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Table 1. Socio-demographical characteristics and physical activity levels of participants (mean  $\pm$  standard deviation)

	Master Athletes <i>N=18</i>	Older Adults <i>N=19</i>	Young Adults <i>N=18</i>	<i>F</i>	<i>p</i>
Male/Female	15/3	7/12	8/10	-	-
Age	69.39 $\pm$ 1.13	72.11 $\pm$ 1.10	22.44 $\pm$ 1.10	650.01	.000
Education (years)	14.22 $\pm$ 0.64	13.68 $\pm$ 0.62	15.39 $\pm$ 0.63	1.93	.155
Dijon Physical Activity Scale	25.00 $\pm$ 0.48	18.32 $\pm$ 0.47	25.94 $\pm$ 0.53	64.24	.000
Weekly volume of physical activity	7.89 $\pm$ 0.61	2.76 $\pm$ 0.60	8.61 $\pm$ 0.68	23.07	.000

Table 2. Performances on the battery of standardized neuropsychological tests and questionnaires on mental health and cognitive daily life functioning (mean  $\pm$  standard deviation)

Neuropsychological Tests	Master Athletes	Older Adults	Young Adults	<i>F</i>	<i>p</i>	<i>partial <math>\eta^2</math></i>
Doors Test	17.00 $\pm$ 0.64	15.68 $\pm$ 0.62	20.17 $\pm$ 0.64	13.17	.000 <sup>c,d</sup>	.33
People Test						
Immediate recall	21.78 $\pm$ 1.47	20.95 $\pm$ 1.43	26.78 $\pm$ 1.47	4.65	.014 <sup>g</sup>	.15
Delayed free recall	8.83 $\pm$ 0.72	8.42 $\pm$ 0.70	11.11 $\pm$ 0.72	4.06	.023 <sup>g</sup>	.13
Trail Making Test (TMT)						
Part A (s)	29.50 $\pm$ 2.04	30.79 $\pm$ 1.98	19.28 $\pm$ 2.04	9.70	.000 <sup>c,e</sup>	.27
Part B (s)	73.00 $\pm$ 6.23	76.11 $\pm$ 6.07	35.44 $\pm$ 6.23	13.33	.00002 <sup>b,d</sup>	.34
Stroop						
Dots (s)	12.78 $\pm$ 0.58	13.32 $\pm$ 0.56	9.50 $\pm$ 0.58	12.98	.00003 <sup>b,d</sup>	.33
Words (s)	16.39 $\pm$ 0.66	15.79 $\pm$ 0.64	12.06 $\pm$ 0.66	12.89	.00003 <sup>a,e</sup>	.33
Interference (s)	26.61 $\pm$ 1.62	27.74 $\pm$ 1.57	17.67 $\pm$ 1.62	11.80	.00006 <sup>b,e</sup>	.31
Paced Auditory Serial Addition Test (PASAT)	53.44 $\pm$ 1.99	49.89 $\pm$ 1.93	57.94 $\pm$ 1.99	4.23	.020 <sup>f</sup>	.14
Brown Peterson Paradigm	30.67 $\pm$ 0.90	29.74 $\pm$ 0.88	31.22 $\pm$ 0.90	0.72	.494	.04
Fluency						
Letter	23.67 $\pm$ 1.24	23.16 $\pm$ 1.21	26.67 $\pm$ 1.24	2.37	.103	.08
Category	31.72 $\pm$ 1.85	32.26 $\pm$ 1.80	36.94 $\pm$ 1.85	2.42	.099	.09
State Trait Anxiety Inventory (STAI)						
State	26.33 $\pm$ 1.55	29.00 $\pm$ 1.51	28.61 $\pm$ 1.55	0.88	.421	.03
Trait	35.06 $\pm$ 2.21	38.74 $\pm$ 2.15	41.50 $\pm$ 2.21	2.15	.127	.07
Memory Self-Assessment Questionnaire (QAM)	132.11 $\pm$ 6.96	149.89 $\pm$ 6.78	147.56 $\pm$ 6.96	1.95	.152	.07
Late Life Leisure Activities (EAM)	16.94 $\pm$ 2.07	17.84 $\pm$ 2.01	22.57 $\pm$ 2.07	2.15	.127	.08

a\_Significative difference between Master Athletes and Young Adults at  $p < .0001$

b\_Significative difference between Master Athletes and Young Adults at  $p < .001$

c\_Significative difference between Master Athletes and Young Adults at  $p < .016$

d\_Significative difference between Young Adults and Older Adults at  $p < .0001$

e\_Significative difference between Young Adults and Older Adults at  $p < .001$

f\_Significative difference between Master Athletes and Young Adults at  $p < .016$

g\_No significative difference between groups,  $p > .016$

Figure 1. Effect of physical activity level on the number of events recalled for the free recall

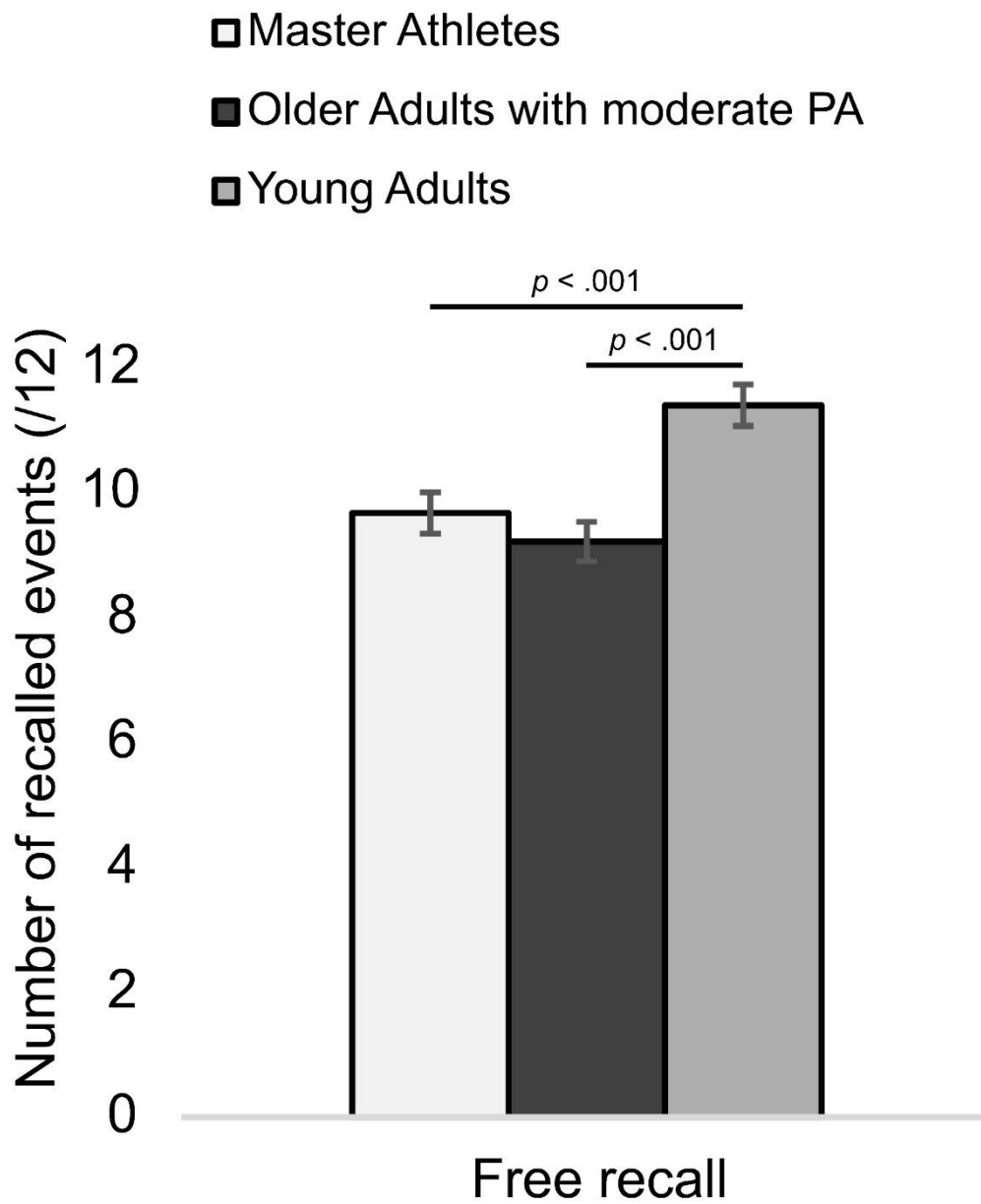


Figure 2. Effect of physical activity level on the binding score for the free and cued recall

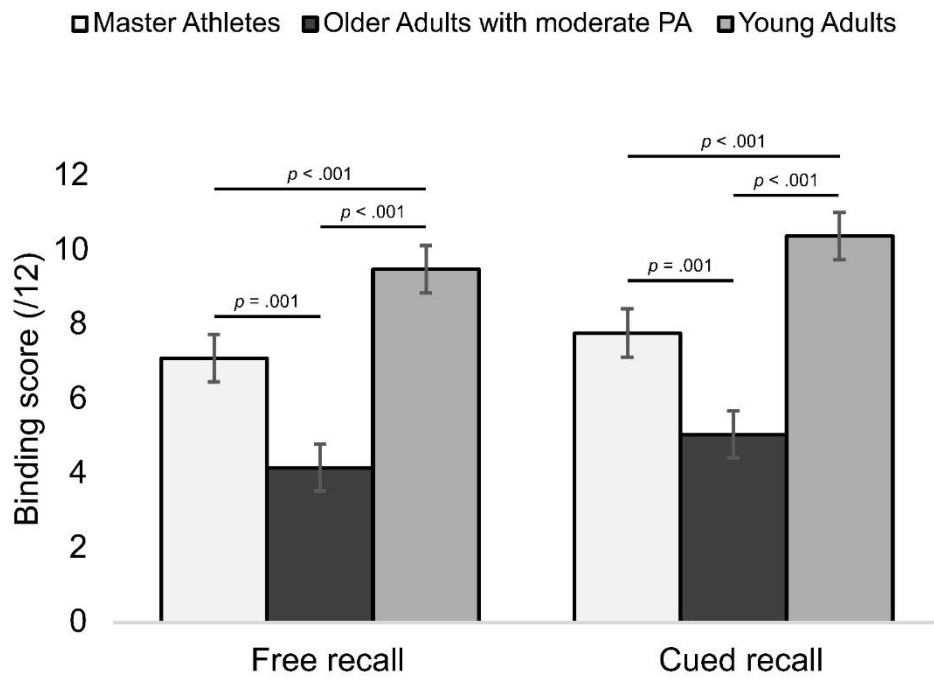


Figure 3. Effect of physical activity level on the interfering tasks of sounds

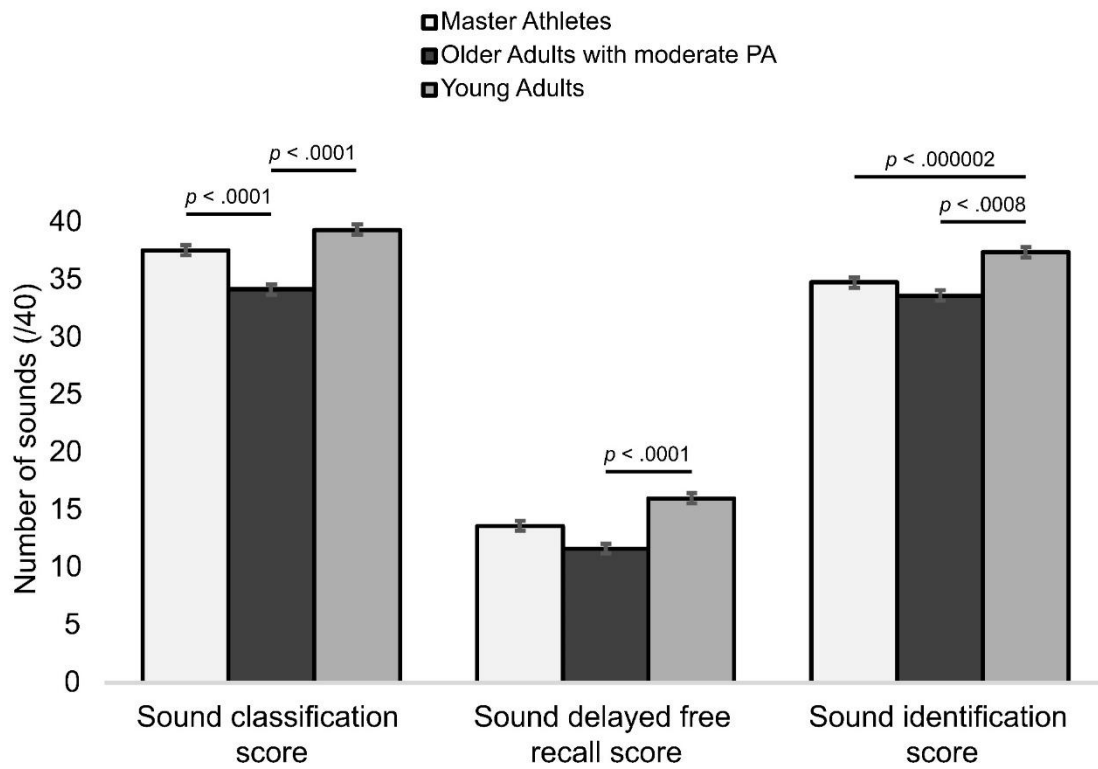
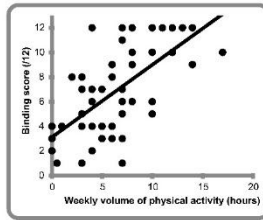
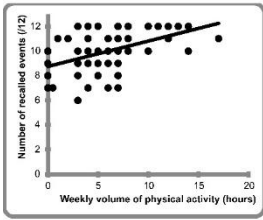


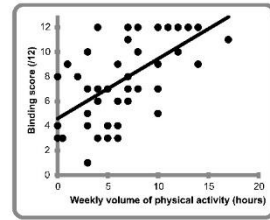
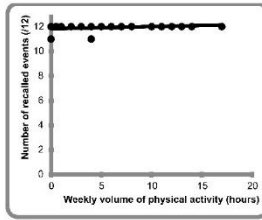
Figure 4. Scatterplots showing the relationship between weekly volume of physical activity and performance at the virtual reality task

**Full attention**

Free recall

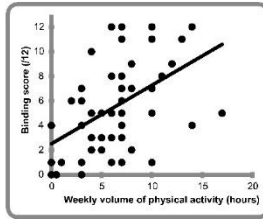
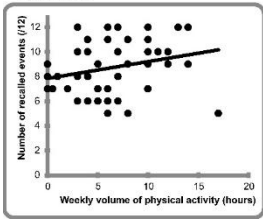


Cued recall



**Divided attention**

Free recall



Cued recall

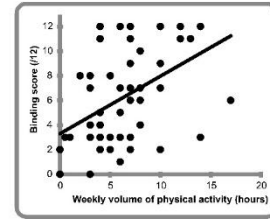
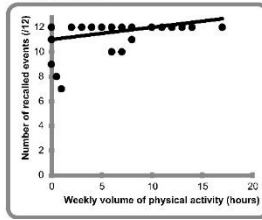


Figure 5. Scatterplots showing the relationship between weekly volume of physical activity and performance at interferent tasks of sounds

