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The Interplay Between Visuospatial Working Memory and Spatial Orientation in Dynamic Environments: Developing a Virtual Reality Paradigm for Realistic Assessment

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Abstract

Cognitive functioning is essential for how we navigate and interact with our surroundings, and it is significantly influenced by external factors. This thesis examines the role of visuospatial working memory (VSWM) in navigation and how it is impacted by external factors. VSWM is essential for spatial awareness and effective navigation, and various environmental influences can significantly affect its function.

The first chapter reviews existing research on the relationship between environmental factors and cognitive functioning, focusing on how these factors shape cognitive development and performance. Chapter two delves into theoretical and methodological approaches to assessing VSWM, advocating for more ecologically valid methods. It introduces a novel tool developed to assess VSWM in children and highlights the potential of virtual reality (VR) to simulate real-world navigation challenges in controlled environments.

The third chapter applies the concept of VSWM to spatial navigation, using a VR version of the Radial Arm Maze (RAM). This innovative approach addresses limitations of traditional RAM paradigms by offering a more dynamic and immersive representation of real-world navigation. The study presents new performance metrics and analytical techniques, exploring how procedural strategies and working memory interact during complex spatial tasks.

Ultimately, this thesis emphasizes the importance of ecological validity in cognitive assessments, linking controlled experimental conditions to real-world applications. The findings provide insights into how environmental factors influence VSWM and suggest potential interventions for individuals facing challenges with spatial memory and awareness.

Table of Context

Introduction

Cognitive functioning plays a pivotal role in our ability to navigate and interact with the world around us (Brown, 2018). Understanding how external factors influence cognitive processes is crucial, especially in dynamic environments that demand adaptability and responsiveness. All these environmental influences—particularly those arising from motor experiences like physical activity and sport practice—have garnered significant attention in the cognitive neuroscience field. Engaging in sports and other physical activities is not only beneficial for physical health but also enhances cognitive functions, including attention, memory, and executive functions (Mandolesi et al., 2018).

In particular, visuospatial working memory (VSWM) stands out as a crucial component of cognitive functioning, enabling individuals to process and manipulate visual and spatial information effectively (Van der Stigchel & Hollingworth, 2018). VSWM is essential for navigating complex environments, making it critical for success in both daily tasks and competitive settings. As individuals interact with their surroundings, their ability to encode, maintain, and update spatial information is continuously challenged, requiring a nuanced understanding of VSWM's dynamic nature (Barker et al., 2010).

The present thesis aims to examine the role of cognitive functioning in navigation and how it is influenced by environmental factors, with a particular focus on visuospatial working memory (VSWM). The first chapter explores the influence of motor experiences like physical activity and sport practice on cognitive processes, laying the groundwork for understanding how environmental factors shape cognitive outcomes. In the second chapter, the focus turns specifically to VSWM, exploring key theories and assessment methods. We emphasize the need for more realistic and ecologically valid approaches to testing VSWM. A study will be presented in which we developed a novel tool to analyse VSWM in children. Additionally, we will discuss how innovative methodologies, such as virtual reality (VR), can create engaging environments that mirror real-world navigation challenges. This approach not only improves

VSWM assessment but also provides deeper insights into the cognitive processes behind spatial navigation.

In the third chapter, we dive deeper into the intricate dynamics of VSWM within the context of spatial navigation using the Radial Arm Maze (RAM) (Olton et al., 1979), a widely used tool for assessing spatial abilities. We will present the main study of this dissertation, in which a VR version of the traditional RAM task was developed, addressing the limitations of classical RAM paradigms in capturing the complexities of spatial navigation. Additionally, we will introduce new performance evaluation indices and novel analyses to provide a more comprehensive understanding of how this tool can be applied.

Ultimately, this thesis contributes to the growing body of literature emphasizing the importance of ecological validity in cognitive assessments. By bridging the gap between controlled experimental conditions and real-world applicability, we aim to provide insights that can inform interventions for individuals facing challenges in spatial awareness and memory.

1. The Interplay Between Environment and Cognitive Functioning

Cognitive functions are brain's abilities that enable individuals to interact effectively with their environment. These functions include essential mental processes such as perception, concentration, memory, reasoning, learning, and problem-solving (Tikhomirova et al., 2020). Cognitive functions not only help us acquire knowledge but also allow us to make sense of the world around us and respond appropriately to various stimuli. Researchers have developed a taxonomy of cognitive functions. This taxonomy, as described by Metzler & Shea (2011), organizes cognitive functions into three hierarchical levels, with well-defined flows that allow for systematic understanding and analysis. These levels are input, elaboration, and output (Brown, 2018). The input level involves perceiving and processing sensory information, the elaboration level refers to analysing, reasoning, and making decisions, while the output level encompasses the execution of responses and actions based on the processed information. The interaction between cognitive functions and the external environment is a central theme in recent research, challenging traditional views of cognition as purely internal. Rowlands (1999) and Clark & Chalmers (1998) proposed that cognition extends beyond the brain, involving manipulation of environmental objects and active engagement with the world. Kirsh (1999) emphasized the importance of understanding interactivity and distributed cognition in designing work environments. The concept of Immediate Interactive Behaviour (IIB) is introduced by Carlson et al. (1998), highlighting how cognitive systems adapt to and modify their environments to achieve goals. This bidirectional relationship between mind and environment blurs the boundaries between cognition, perception, and action (Carlson et al., 2007).

This interplay between cognition and environment is fundamental to our ability to adapt and function effectively in various contexts. Environments that are rich in stimuli or have specific characteristics can enhance or hinder cognitive performance. For example, well-designed workspaces that minimize distractions can improve focus and productivity, while chaotic or noisy environments may lead to increased cognitive stress and reduced efficiency (Trevarthen, 1977). Understanding how different environments impact cognitive functions can provide valuable insights into how we can optimize our interactions with our surroundings and improve overall well-being.

The interaction between the environment and cognitive functions is bidirectional, meaning that cognitive functions not only enable us to perceive and respond to environmental demands, but also that the environment actively shapes and influences our cognitive functions (Gelfo et al., 2018; Mandolesi et al., 2017; Serra et al., 2022). Repeated exposure to stimulating environmental factors, also known as environmental enrichment, has been shown to significantly enhance cognitive functions across various populations. Environmental enrichment involves providing a stimulating environment that promote physical, cognitive, and social activities, that contribute to well-being and cognitive functions enhancement (Mandolesi et al., 2017, Gelfo et al., 2018).

On the other hand, environmental conditions can have short-term effects on cognitive functions, even online. Research suggests that external feedback and environmental conditions significantly impact cognitive functions during tasks. False cognitive feedback can affect subsequent task performance, although the influence varies depending on the specific executive function assessed (Clark et al., 2024). Providing feedback during tasks can improve cognitive control, behavioural measures, and modulate brain activity related to anticipation, perceptual awareness, and selective attention (Mussini et al., 2022). Environmental stressors such as heat, hypoxia, and cold can alter cognitive function, with effects depending on the task and severity. Complex tasks are particularly vulnerable to extreme heat, while both simple and complex tasks are affected by moderate altitudes and cold stress (Taylor et al., 2016).

Given the evidence regarding the interaction between environment and cognitive functions, it is important to study its implications. Some reasons include:

- Optimizing Learning and Productivity: Understanding how environmental factors influence cognitive performance can help design environments that optimize learning and productivity. For example, creating classrooms that reduce distractions and support memory retention can enhance educational outcomes (Tikhomirova et al., 2020).
- Promoting Mental Health and General Well-being: Cognitive functions are closely linked to mental health. Environments that strain cognitive resources can lead to stress, fatigue, and decreased mental well-being. By identifying and mitigating environmental stressors, we can create spaces that support cognitive health and reduce the risk of cognitive decline (Oei et al., 2006).
- Counteracting Cognitive Decline: Studying how environmental factors influence cognitive functions can help develop strategies to counteract cognitive decline associated with ageing or neurological conditions (Vemuri et al., 2014).
- Adapting to Technological and Environmental Changes: As technology and environments rapidly evolve, understanding how these changes affect cognitive functions is crucial. Testing cognitive reactions to new environments can help individuals and organizations adapt effectively, ensuring that cognitive performance is maintained or enhanced in the face of change (Loh & Kanai, 2014).

Studying cognitive functions from a holistic perspective, considering both the individual and environmental factors, provides valuable insights into optimizing cognitive performance and well-being.

1.1. Environment and Cognitive Processes: The Role of Motor Experience

One of the most influential environmental factors on cognitive functioning is motor experience, with sport representing one of the most comprehensive forms of motor engagement. It combines complex physical and cognitive challenges, shaping neural development and enhancing cognitive performance (Mandolesi et al., 2018). The physical exertion associated with sports—such as running, swimming, and team games—boosts cognitive processes by increasing blood flow to the brain and promoting neurogenesis, particularly in areas linked to memory and learning (Kramer & Erickson, 2007). This physiological impact enhances cognitive functions like working memory, attention, and executive control.

Athletes face complex cognitive challenges, requiring them to make rapid decisions and process large volumes of sensory information while adapting strategies in real-time. For instance, a soccer player continuously assesses the positions of teammates and opponents, making split-second decisions based on dynamic stimuli (Budde et al., 2008; Yao et al., 2020). Such high levels of cognitive engagement not only improve skills like spatial awareness and coordination but also foster cognitive flexibility and problem-solving abilities. Additionally, the social dynamics of team sports promote essential communication skills and teamwork, which are vital for effective cognitive processing and interpersonal interactions (Weinstein et al., 2012). Overall, the interplay of physical activity, cognitive engagement, and social interaction in sports creates a stimulating environment that supports both immediate cognitive improvements and long-term cognitive health and resilience (Erickson et al., 2022).

Research indicates that participation in sports positively influences cognitive functions in children and young adults. For instance, open-skill sports, which require adaptation to changing environments, are particularly beneficial for cognitive development compared to closed-skill sports or inactivity (Becker et al., 2018; Tsai et al., 2017). Engagement in physical activity during childhood and adolescence has been associated with enhancements in attention, language, learning, and memory (Becker et al., 2018). Both short bouts of sports activities and longer training interventions yield cognitive benefits, with effects varying according to the sport modality and cognitive outcomes measured (Mandolesi et al., 2018). While existing evidence supports the cognitive benefits of sports participation, further research is needed to determine which specific cognitive functions are developed through different sporting disciplines (Troisi Lopez et al., 2023).

1.2. Research Highlights: How Motor Experiences Influence Cognition

This section presents a short overview of key research studies conducted during my PhD years, which form part of the main research project but are collateral to the central investigation. These studies explore the impact of physical activity and sport practice on cognitive function across various age groups and illustrate how this influential environmental factor, shape cognitive abilities and emotional well-being throughout the lifespan.

1.2.1. Sport as a Boosting Factor for Cognitive and Emotional Abilities

Our study, titled *"Boosting Effect of Regular Sport Practice in Young Adults: Preliminary Results on Cognitive and Emotional Abilities"* [1], investigates how regular sports participation enhances cognitive and emotional functions in young adults. In this study, we tested a sample of 30 young adults (mean age = 22 ± 2.76) who were divided into two groups: Sportive and Sedentary. The Sportive participants were experienced tennis players with a minimum of eight years of practice. We employed a variety of neuropsychological tests, including the Advanced Progressive Matrices (APM) (Raven, 1962), Verbal Fluency Test (Carlesimo et al., 1996), the

[1] Passarello, N., Varini, L., Liparoti, M., Troisi Lopez, E., Sorrentino, P., Alivernini, F., ... & Mandolesi, L. (2022). Boosting effect of regular sport practice in young adults: Preliminary results on cognitive and emotional abilities. *Frontiers in Psychology*, *13*, 957281

modified Five-Points Test (m-FPT) (Cattelani et al., 2011), and the Toronto Structured Alexithymia Scale (TAS-20) (Bagby et al., 1994) to assess emotional abilities, specifically in recognition (DIF) and verbalization (DDF).

After testing for normality with the Shapiro–Wilk test, data were analysed using a 2x2 ANOVA, with both gender and group (sportive vs. sedentary) as factors.

The results revealed significant differences in APM scores ($F_{1,56} = 5.14$; $p = 0.03$) as well as in the Verbal Fluency test index and word repetition ($F_{1,56} = 14.60$; $p < 0.001$) for the sport factor. Post-hoc comparisons indicated significant differences between sportive and sedentary students in APM scores (mean sportive = 10.80; mean sedentary = 10.16) and word repetition (mean sportive = 5.40; mean sedentary = 2.30). Several notable results emerged from the m-FPT parameters, with the 2x2 ANOVA indicating significant differences in total drawings for the sport factor ($F_{1,56} = 31.22$; $p < 0.001$). Post-hoc comparisons revealed significant differences in total drawing production between sportive and sedentary individuals (mean sportive = 51.43; mean sedentary = 34.77). Moreover, significant differences were noted in total unique drawings for the sport factor ($F_{1,56} = 82.30$; $p < 0.001$), with post-hoc comparisons showing a significant difference between the two groups in unique drawing productions (mean sportive = 47.30; mean sedentary = 29.60). Lastly, significant differences in strategy use were observed for the sport factor ($F_{1,56} = 7.15$; $p = 0.01$), with post-hoc comparisons indicating differences between sportive and sedentary students in strategy use for drawing (mean sportive = 0.14; mean sedentary = 0.10).

As for the TAS-20, the total score exhibited significant differences for the sport factor ($F_{1,56} = 6.01$; $p = 0.02$). Post-hoc comparisons indicated lower emotional unawareness in sportive students compared to their sedentary counterparts (mean sportive = 42.70; mean sedentary = 48.50). The TAS DIF dimension was significantly different for the sport factor ($F_{1,56} = 4.52$; $p = 0.04$), with post-hoc comparisons revealing that sportive students faced fewer difficulties in identifying feelings compared to sedentary students (mean sportive = 11.70; mean sedentary = 13.90). Similarly, the TAS DDF dimension showed significant differences for the sport factor ($F_{1,56}$ = 4.37; p = 0.04), indicating that sportive students had fewer challenges in describing feelings than their sedentary peers (mean sportive = 15.87; mean sedentary = 18.73). Notable results are shown in *Figure 1*.

Our findings reveal that sportive individuals show superior performance in both graphic and verbal fluency tasks and generate more unique items (drawings or words) compared to sedentary students. This supports the selective improvement hypothesis, which posits that aerobic physical exercise enhances brain activities linked to the frontal and prefrontal regions (Weinstein et al., 2012). Our results further indicate that sportive students possess greater emotional awareness, displaying fewer difficulties in identifying and describing emotions. The benefits of sports practice on emotional processing are well-documented, with numerous studies highlighting its positive effects on mood and emotional regulation (Knapen et al., 2009; Mammen & Faulkner, 2013). Participation in sports is associated with fewer challenges in emotional recognition and regulation (Swart et al., 2009).

In conclusion, our preliminary findings suggest that regular exercise and participation in sports positively influence cognitive and emotional functioning. Promoting physical exercise among young and at-risk populations is essential for enhancing psychological well-being (Passarello et al., 2022).

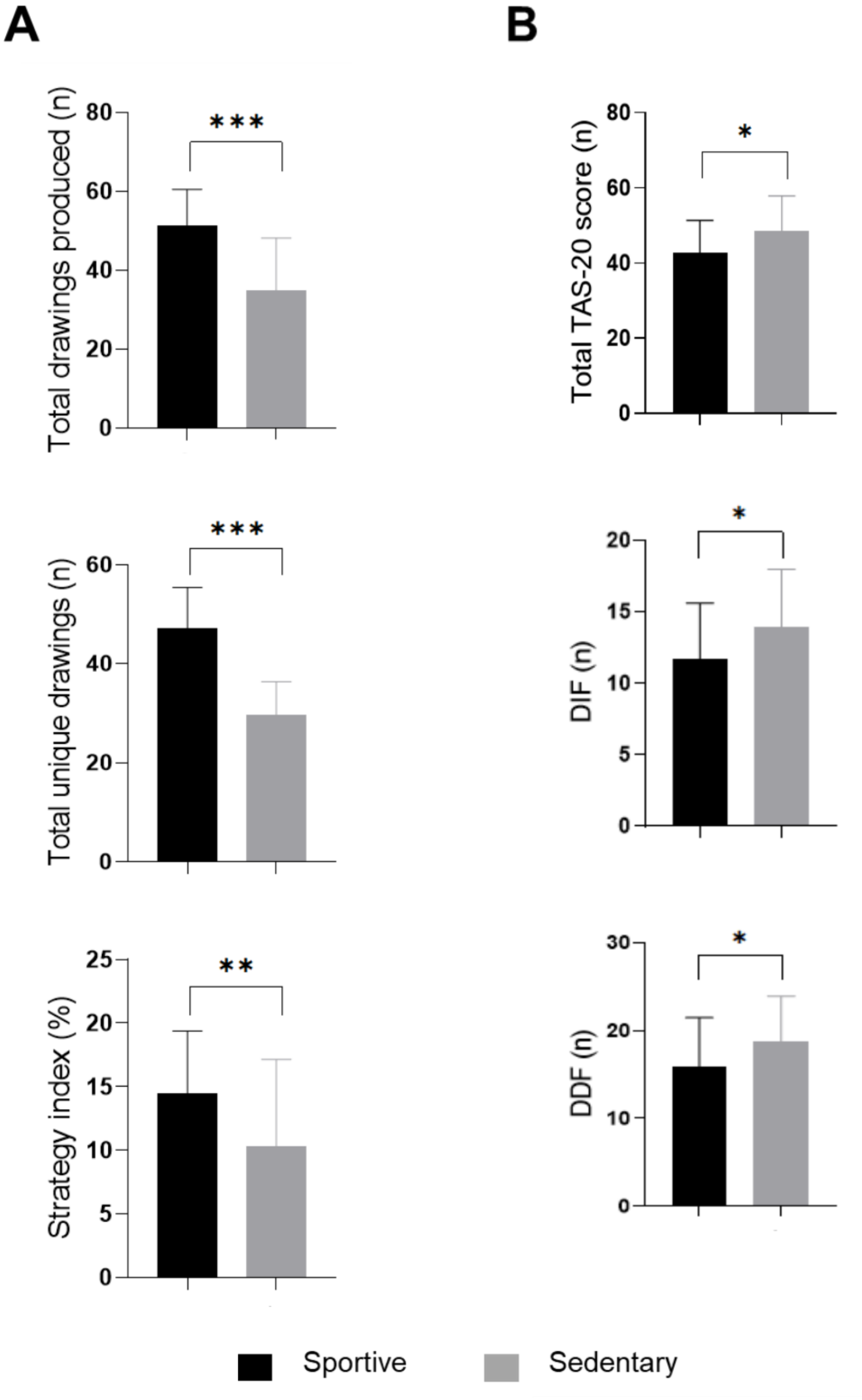

Figure 1. Main results from Passarello et al. (2022). **A.** Differences between Sportive and Sedentary in mFPT parameters (from the top: total drawings produced; total unique drawings; strategy index). **B.** Differences between sportive and Sedentary in TAS-20 (from the top: total score; DIF; DDF). *= p≤ 0.05; **= p≤ 0.01; ***p≤ 0.001.

1.2.2. Cognitive Benefits of Physical Activity in Children

Our study, *"Executive Function and Spatial Abilities in Physically Active Children: An Explorative Study"*[2], aims to investigate potential differences in cognitive performance between active and sedentary children, with a specific focus on inhibitory control, cognitive flexibility and visuospatial working memory.

We tested a sample of 22 children (mean age 9.53 ± 2.20), categorized as active and sedentary, based on their physical activity level (PA). To assess executive abilities, we utilized the NEPSY-II (Davis & Matthews, 2010), while the table version of the Radial Arm Maze (table-RAM) (Foti et al., 2020) - represented in *Figure 2*- was used to evaluate PA effects on visuospatial working memory. Both the NEPSY-II and the table-RAM task can be considered as ecologically valid approach to assess cognitive functions in children. This approach improves the reliability and significance of our findings and enables a thorough analysis of various aspects within these cognitive domains.

To examine differences in executive functions, one-way ANOVAs were performed with group (Active vs. Sedentary) as the factor variable and NEPSY-II parameters (errors, time) as dependent variables across three trials: Denomination, Inhibition, and Switching. One-way ANOVAs were also used to assess visuospatial abilities, with group as the independent variable and relevant table-RAM indices as dependent variables. Z-scores were calculated for NEPSY-II and RAM outputs to handle outliers, and normality was tested with the Shapiro–Wilk test. Non-parametric analyses were used when data deviated from normality, and Levene's test was applied to assess variance homogeneity. Post-hoc comparisons used Games-Howell and Tukey tests, with bootstrapping from 1,000 replicates due to the small sample size.

[2] Passarello, N., Turriziani, P., Lucidi, F., & Mandolesi, L. (2024). Executive function and spatial abilities in physically active children: an explorative study. *BMC psychology, 12(1)*, 325.

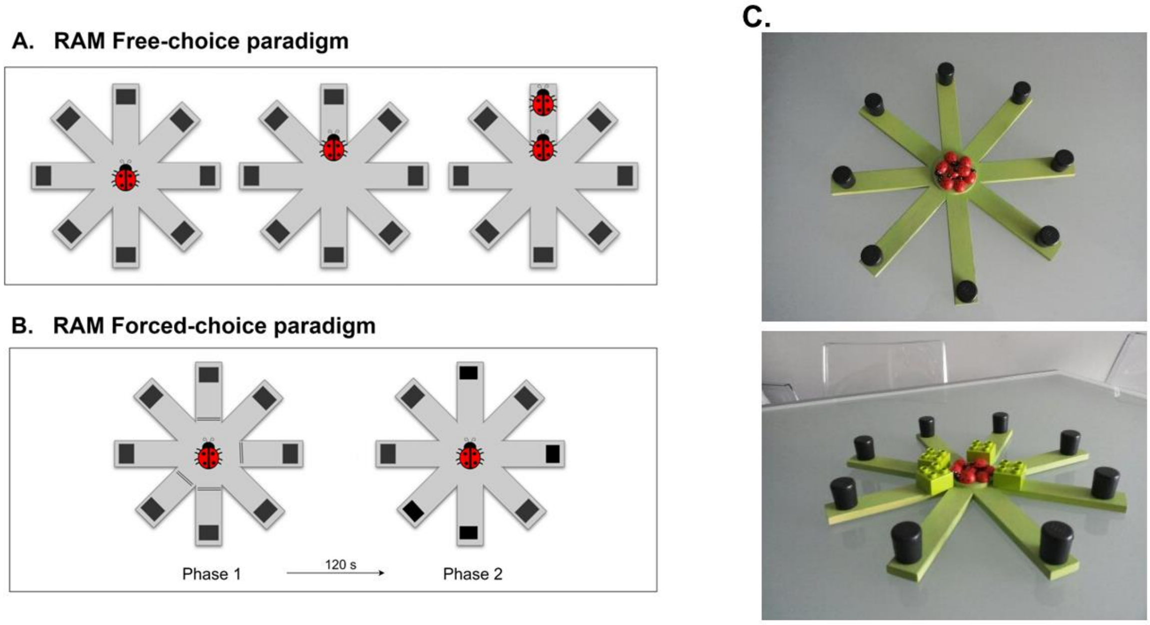

Figure 2. Table version of the Radial Arm Maze (table-RAM) used in Passarello et al. (2024a). **A.** RAM *free choice* paradigm **B.** RAM *forced choice* paradigm. **C.** Picture of the real-life apparatus.

The results of the one-way ANOVAs indicated no significant differences between active and sedentary groups in the Denomination trial for both time ($K_{1,23}$ = 1.74, p = 0.20) and errors (K 1,14 = 4.22, p = 0.06). In the Inhibition trial, while no significant difference was observed for Time ($K_{1,23}$ = .90, p =0 .35), while a significant difference was found for errors ($K_{1,23}$ = 4.99, p = 0.03), with the active group making significantly fewer errors (${}_{BS}$Mean difference = -.82, ${}_{BS}$LCI = -1.71, ${}_{BS}$UCI = -.21, ${}_{BS}$p = 0.03). Similarly, in the Shifting trial, no differences were found for time ($K_{1,23}$ = .63, p =0 .43), but a significant difference was noted for errors ($K_{1,23}$ = 5.77, p = 0.02), with active children again making fewer errors (${}_{BS}$Mean difference = -0.87, ${}_{BS}$LCI = -1.58, ${}_{BS}$UCI = -0.25, ${}_{BS}$p = 0.002).

In terms of visuospatial working memory abilities, a significant difference was found for Spatial Span ($K^{1,12}$ = 5.33, p = 0.04), with active participants showing a greater span (${}_{BS}$Mean difference = .84, ${}_{BS}$LCI = 0.06, ${}_{BS}$UCI = 1.63, ${}_{BS}$p = 0.03). Moreover, significant differences were noted for Total Working Memory Errors ($K_{1,23} = 7.85$, $p = .01$), with active participants making fewer errors overall ($_{BS}$Mean difference = -.96, $_{BS}$LCI = -1.84, $_{BS}$UCI = -.41, $_{BS}p$ = 0.001). Notable results can be found in *Figure 3*.

In conclusion, this preliminary study provides compelling evidence for the beneficial effects of PA on cognitive functions, specifically in the domains of executive functions and visuospatial abilities. Although our results must be considered with caution, given the small sample size, they align with previous research demonstrating the association between physical activity and improved cognitive performance (Serra et al., 2021). An active lifestyle not only promotes physical health and well-being but also contributes to the holistic development of children by fostering social skills, discipline, and perseverance. Future studies should explore these aspects and further explore the potential of digitalization in cognitive assessments (Passarello et al., 2024a).

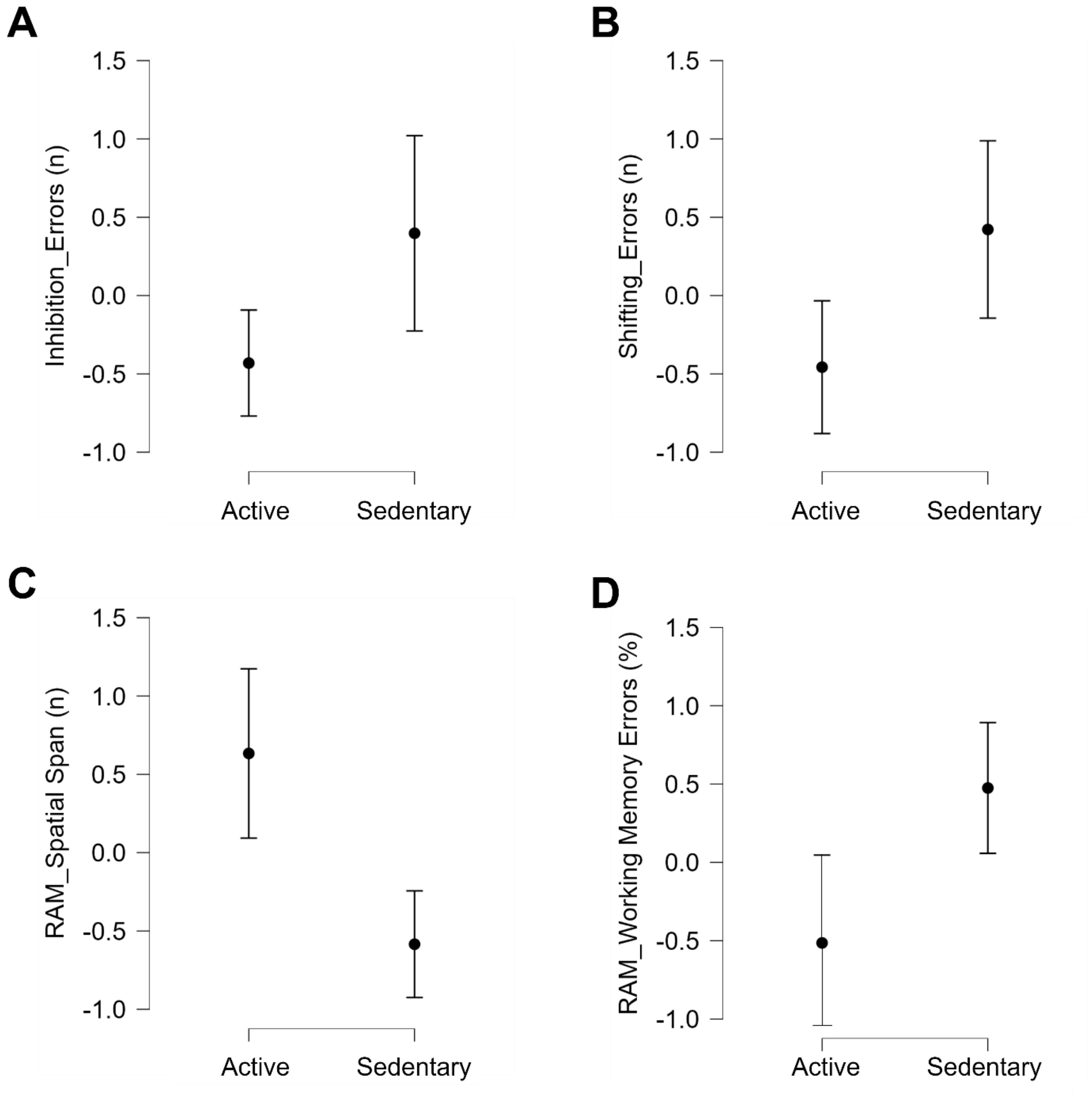

Figure 3. Main results from Passarello et al. (2024a). **A.** NEPSY-II Inhibition Trials Errors. **B.** NEPSY-II Shifting Trials Errors. **C.** table-RAM Spatial Span. **D.** table-RAM Working Memory Errors.

1.2.3. Cognitive Benefits of Physical Activity in Elderly

Our third (unpublished) study, titled *"Examining the cognitive benefits of physical activity in elderly individuals: an evaluation using the modified Five-Point Test"*,[3] investigates the impact of physical activity (PA) on executive functions in elderly individuals, highlighting its protective effects against cognitive decline associated with ageing and dementia (Niemann et al., 2014). We administered a battery of neuropsychological tests—including the Mini Mental State Examination (Folstein et al., 1975), the FAS Fluency Test (Rees et al., 1998), and the modified Five-Points Test (m-FPT) (Cattelani et al., 2011)—to 45 elderly participants without cognitive impairment (mean age = 68.11 ± 3.34 years), classified as active or sedentary based on the International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003).

We employed generalized linear models (GLM) with PA level (active, sedentary) and gender as categorical predictors. The dependent variables included FAS scores (correct number of words) and various parameters from the m-FPT - unique designs (UDs), error index (IE), unique drawings (DSs), and strategy index (ISs)-. GLM outputs were adjusted using the Holm test, with a focus on 95% Confidence Interval Lower (LCI) and Upper (UCI) bounds. Model fit was assessed through Pearson goodness-of-fit tests, and multicollinearity was evaluated using the Variance Inflation Factor (VIF).

The results indicated significant predictions based on PA levels for several m-FPT parameters. Specifically, being sedentary negatively predicted m-FPT UDs ($t = -2.60$; $p_{Holm} = 0.01$), DSs ($t = -3.02$; $p_{Holm} = 0.005$), and ISs ($t = -2.75$; $p_{Holm} = 0.009$). In contrast, neither the m-FPT IE ($t = -0.44$; $p_{Holm} = 0.66$) nor the FAS total score ($t = 1.08$; $p_{Holm} = 0.29$) were significantly predicted by PA levels. While no m-FPT parameters were influenced by sex, males exhibited significantly

[3] Passarello, N., Troisi-Lopez, E., Gigliotta, O., Turriziani, P., Lucidi, F., & Mandolesi, L. (2024). Can an Active Lifestyle Maintain Cognitive Efficiency in the Elderly? Investigating Physical Activity's Influence on Graphic Fluency. *BMC psychology. Submitted under revisions*.

higher FAS total scores ($t = 2.32$; $p_{Holm} = 0.02$). Notable results are shown in *Figure 4*. Overall, this study contributes to the growing body of evidence supporting the cognitive benefits of PA in elderly individuals (Bullo et al., 2015; Choi et al., 2019; Galle et al., 2023). The findings highlight the importance of reducing sedentary behaviour and engaging in regular physical activity to maintain and enhance executive functioning, particularly in females. Future research should further investigate the underlying mechanisms and explore the potential of physical activity interventions to improve cognitive function and promote healthy ageing.

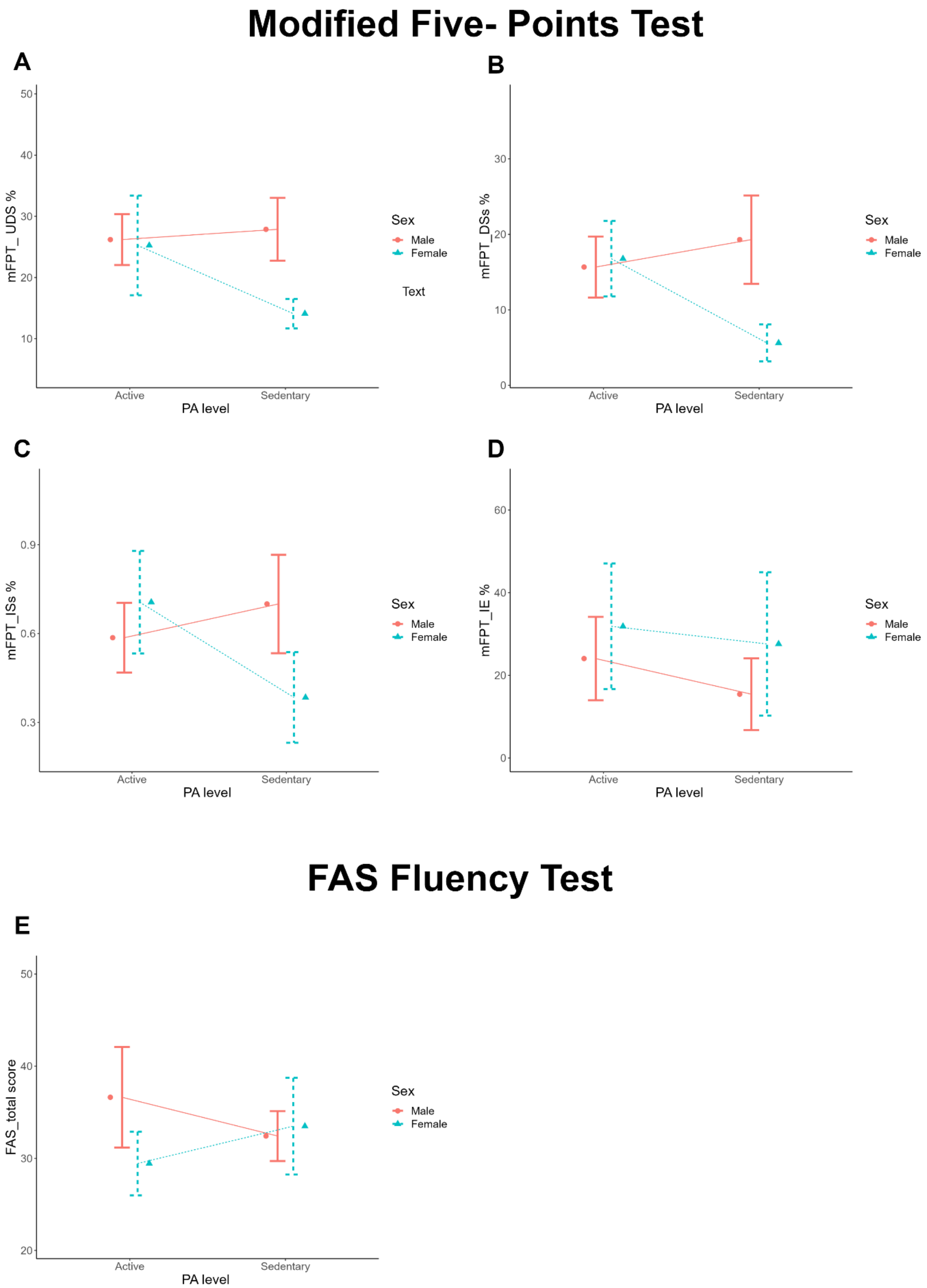

Figure 4. Findings from Passarello et al. (unpublished). **A.** m-FPT UDS (unique drawings). **B.** m-FPT DDS (drawings with strategy). **C.** m-FPT IS (strategy index). **D.** m-FPT IE (error index). **E.** FAS score.

1.2.4. The Effect of Sport on Social Attention

In the study titled *"The Effects of Social Processing and Role Type on Attention Networks: Insights from Team Ball Athletes"*[4], investigates how social processing influences attentional abilities in athletes participating in team ball sports, specifically soccer, handball, and basketball. Attention is defined as a multi-component ability essential for directing and sustaining focus, which plays a critical role in cognitive functioning (Federico et al., 2017). The research focuses on the effects of social and non-social stimuli on the alerting, orienting, and executive-control networks of attention (Fan et al., 2002).

A total of 103 male amateur athletes (mean age = 19.91 ± 3.10), with at least 10 years of experience, were recruited and divided into three groups based on their roles: defenders, midfielders, and strikers. Using a modified version of the Attention Network Test (ANT) (Fan et al., 2002), which included both social (photographs of human faces) and non-social (coloured fish) stimuli (*Figure 5*), the study aimed to assess how these different stimuli influence reaction times (RTs) and accuracy (Acc) across various attention networks.

The study employed a 2 × 3 mixed-model ANOVA with social versus non-social stimuli as a within factor, and role type (defenders, midfielders, strikers) as a between factor. This analysis assessed reaction times (RTs) and accuracy (Acc) across the attention networks: alerting, orienting, and executive control. Post hoc comparisons were performed using the Bonferroni test. Normality of data was assessed through Shapiro-Wilk test. Additionally, a priori power analysis using GPower ensured the sample size was sufficient to detect significant effects, targeting a partial $\eta^2$of 0.04 with 80% power.

[4] Passarello, N., Mellone, M., Sorrentino, P., Chirico, A., Lucidi, F., Mandolesi, L., & Federico, F. (2024). The Effects of Social Processing and Role Type on Attention Networks: Insights from Team Ball Athletes. *Brain Science. 2023, 13(3)*, 476

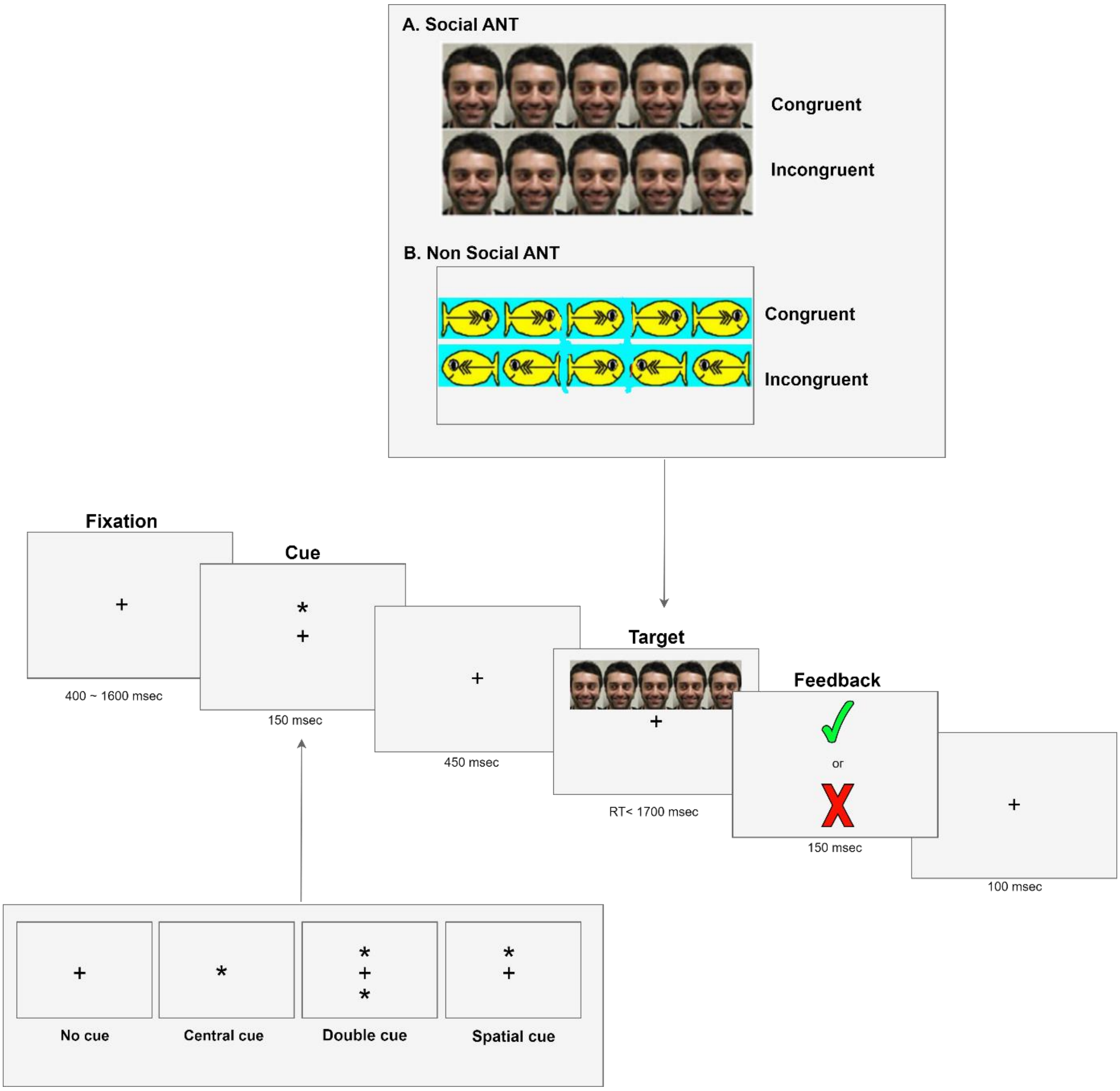

Figure 5. The modified version of the Attention Network Test (ANT) used in Passarello et al. (2023).

Findings on RTs revealed no significant effect for the alerting network in relation to stimulus type ($F_{1,99} = 0.09$, $p = 0.76$) or role ($F_{2,99} = 1.79$, $p = 0.17$). Similarly, the orienting network showed no significant effects for stimulus ($F_{1,99} = 3.64$, $p = 0.06$) or role ($F_{2,99} = 0.88$, $p = 0.41$). However, significant effects were found for the executive-control network, with stimulus type significantly affecting performance ($F_{1,99} = 6.76$, $p = 0.01$). Post hoc Bonferroni testing indicated significant differences between social and non-social stimuli ($t = -2.61$; $p_{bonf} = 0.01$;

mean difference = −27.464). The interaction between stimulus type and role did not yield significant results after correction ($t = 2.63$; $p_{bonf} = 0.09$). In terms of Acc, a significant effect was observed for role in the alerting network ($F_{2,99} = 17.306$; $p < 0.001$), with post hoc testing revealing differences between strikers and midfielders ($t = 3.31$; $p_{bonf} = 0.004$), strikers and defenders ($t = −2.82$; $p_{bonf} = 0.01$), and midfielders and defenders ($t = −5.87$; $p_{bonf} < 0.001$). No significant effects were found for the orienting network (F1,99 = 0.68, p = 0.41) or the executive-control network ($F_{1,99} = 0.07$; $p = 0.68$). Notable results are shown in *Figure 6.* This study highlights the importance of social processing in sports and suggests that athletes' attentional strategies vary by role, emphasizing the need for tailored training to enhance cognitive functions in team ball sports (Scharfen & Memmert, 2019; Vestberg et al., 2012). While the study presents valuable insights, it also acknowledges limitations, such as the variability in performance among strikers and the differences in visual features between social and non-social stimuli. Future research should explore these aspects further, including the specific attentional profiles of athletes within the same sport and potential influences of gender and training experience (Passarello et al., 2023).

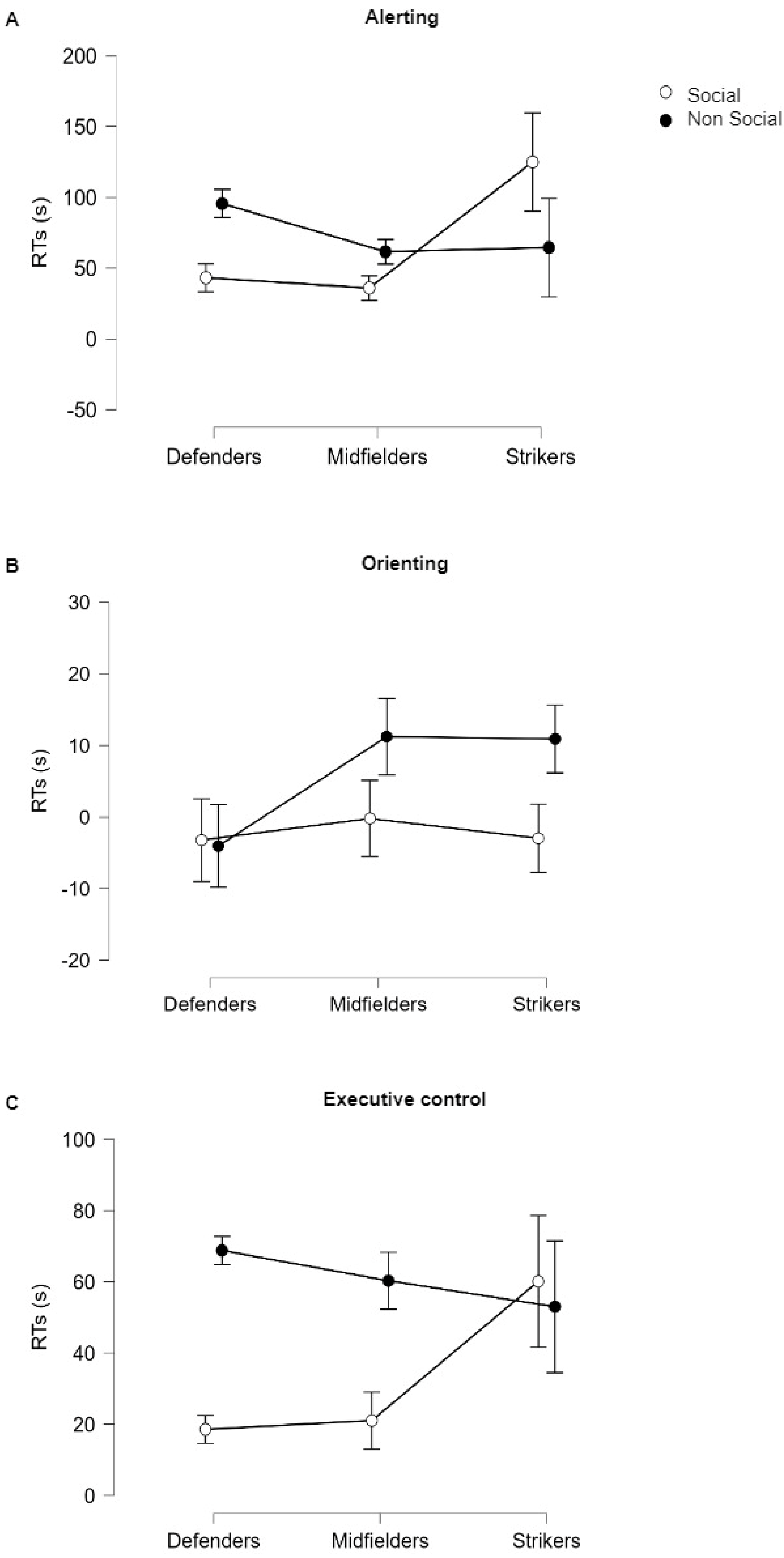

Figure 6. Main results from Passarello et al. (2023). Effect of role and type of stimuli on RTs.

A. Alerting network

B. Orienting network.

C. Executive control

1.2.5. Unimodal and Multimodal Sport Effect on Cognitive Functioning

In the study titled *"Multimodal Physical Exercise Affects Visuospatial Working Memory: Preliminary Evidence from a Descriptive Study on Tai-Chi Practitioners and Runners"*[5] we examined the effects of different types of sports on cognitive abilities, specifically the impact of unimodal versus multimodal exercise on cognitive functions. Unimodal sports refer to traditional motor exercises primarily involving aerobic activities and repetitive movements aimed at improving muscle strength and endurance, without emphasizing cognitive processes such as planning, motor imagery, decision-making, and executive functions; examples include running, swimming, and cycling (Adjetey et al., 2023). In contrast, multimodal physical exercise integrates body and mind, emphasizing conscious movement control and body awareness to enhance physical and psychological well-being, while simultaneously engaging cognitive and motor processes through activities like Tai Chi (Chen et al., 2019).

This study aimed to analyse whether unimodal and multimodal activities influence distinct cognitive domains differently, recruiting a total of 33 participants (mean age = 52.6 ± 7.2), comprising eleven runners, eleven Tai Chi practitioners, and eleven age-matched sedentary individuals who had not engaged in structured or consistent sports activities. We assessed various cognitive functions, including visuospatial working memory (Corsi Block Tapping Test, CBTT) (Corsi, 1972), verbal fluency (Rey Auditory Verbal Learning test, RAVLT) (Schimdt, 1996), and cognitive flexibility and executive functions (Behavioural Assessment of the Dysexecutive Syndrome, BADS) (Norris & Tate, 2000).

After checking for normality of data distribution through Shapiro-Wilk test, scores among the

[5]Troisi-Lopez, E., Liparoti, M., Passarello, N., Lucidi, F., & Mandolesi, L. (2023). Multimodal physical exercise affects Visuo-spatial working memory: preliminary evidence from a descriptive study on Tai-Chi practitioners and runners. *Brain Science. 2023, 13(10),* 1400

three groups were compared using ANOVA analyses, followed by post hoc analysis with two-sample t-tests using the false discovery rate (FDR).
The ANOVA results indicated significant differences in cognitive performance among groups, particularly in the BADS subtest ($F_{2,30} = 6.33$, $p = 0.005$, $p_{FDR} = 0.03$) and the CBTT ($F_{2,30} = 6.44$, $p = 0.005$, $p_{FDR} = 0.03$). Post hoc analysis revealed that runners ($p = 0.02$) and Tai Chi practitioners ($p = 0.007$) achieved significantly higher BADS-RS scores compared to sedentary individuals. For the CBTT, Tai Chi practitioners demonstrated a significantly greater spatial span than sedentary individuals ($p = 0.001$), with a tendency towards a significant difference observed between the runners and Tai Chi groups ($p = 0.047$). Other neuropsychological tests did not yield significant differences among groups, revealing a selective effect of multimodal sport on visuospatial working memory. Notable results are shown in *Figure 7*.
Although preliminary, our findings suggest that Tai Chi, and more in general, multimodal sport activities, can serve as an effective behavioural strategy for enhancing cognitive abilities with important implications for clinical and rehabilitative practices. Specifically, we notice a significant effect on visuospatial working memory (Troisi Lopez et al., 2023). Promoting alternative and adapted modalities of physical exercise could be beneficial in maintaining or strengthening various aspects of memory, especially for individuals with Alzheimer's or other neurodegenerative diseases, and Tai Chi may also serve as a valuable intervention strategy to facilitate active ageing (Passarello et al., 2022).

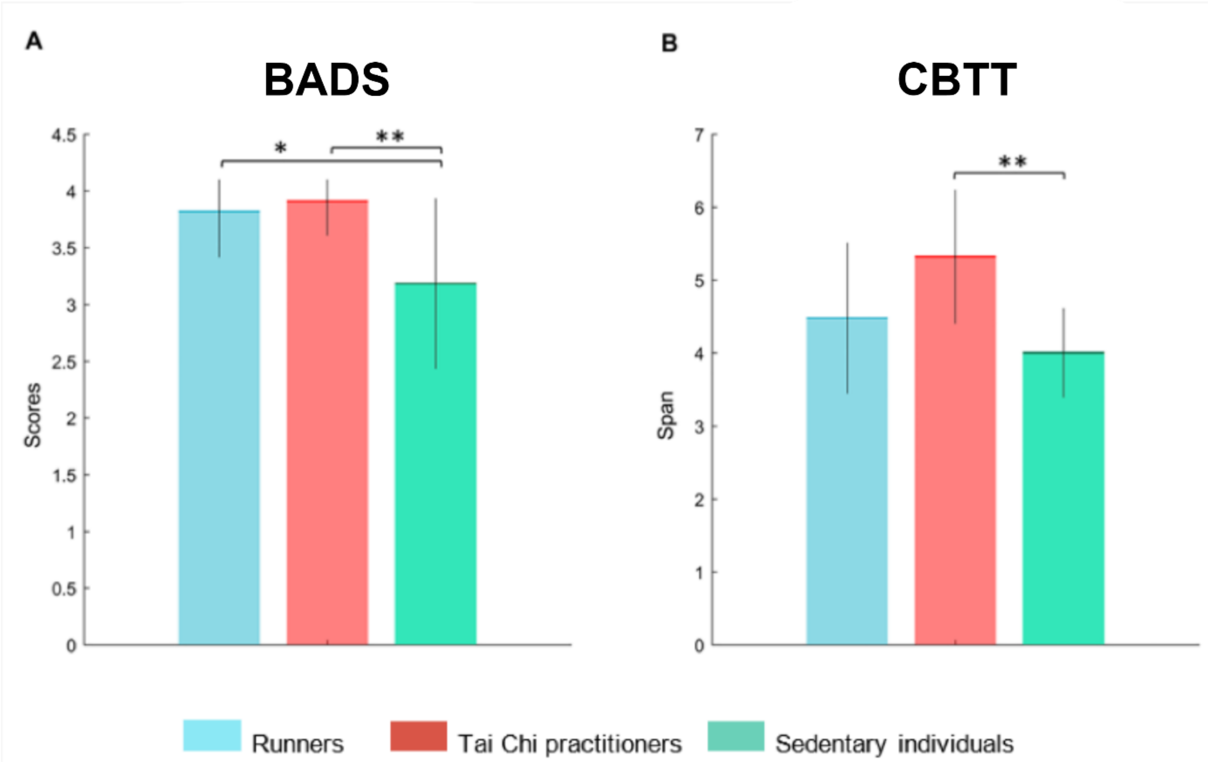

Figure 7. Main results from Troisi-Lopez et al. (2023). **A.** BADS **B.** CBTT. * = p≤ 0.05; * * = p≤ 0.01

1.2.6. Motor Imagery Abilities in Physically Active Adults

The study titled *"Differences in Motor Imagery Abilities in Active and Sedentary Individuals: New Insights from Backward-Walking Imagination"*[6] investigates the influence of physical activity on motor imagery (MI), a process that integrates both motor and cognitive skills. MI refers to the mental execution of a movement without actual physical movement, and requires various cognitive processes for planning and executing motor behaviour (Allali et al., 2014; Allami et al., 2008; Canepa et al., 2020; Passarello et al., 2022). Given that MI shares neural substrates with motor action preparation (Burianová et al., 2020), we hypothesized that physical activity (PA) might enhance motor imagery abilities and tested this hypothesis in a sample of young women. We focused on backward-walking imagery, a complex task

[6] Mandolesi, L., Passarello, N., & Lucidi, F.(2023). Multimodal physical exercise affects Visuo-spatial working memory: preliminary evidence from a descriptive study on Tai-Chi practitioners and runners. *Psychological Research. 2024, 88(2),* 499-508

necessitating significant cognitive effort related to working memory, spatial abilities, and executive control.

We recruited 41 participants (mean age = 21 ± 1.2), divided into active and sedentary. Each participant completed a Mental Chronometric Task (Montuori et al., 2018) where they first imagined and then performed forward and backward walking. We calculated the Isochrony Efficiency (IE) index by measuring the difference between imagination and execution times in both tasks (Battaglia et al., 2014).

To analyse the data, we employed a one-way ANOVA to compare the Motor Imagery Efficiency (MIE) index between the active and sedentary groups for both forward and backward tasks. Normality was tested with the Shapiro–Wilk test, Levene's test assessed variance homogeneity and post-hoc comparisons utilized Tukey tests.

The results revealed no significant effect for the forward MIE index ($F_{1,39} = 0.11$; $p = 0.75$). However, a significant effect was found for the backward MIE index ($F_{1,39} = 4.99$; $p = 0.03$), with post-hoc Tukey tests indicating that the sedentary group exhibited less motor imagery efficiency compared to the active group (mean difference = 2.96; LCI = 0.28; UCI = 5.64; $t_{1,39} = 2.23$; $p_{tukey} = 0.03$).

In addition, we utilized a generalized linear model (GLM) to examine how the ability to vividly imagine actions from different perspectives influenced the MIE index. Our analysis revealed that the external visual imagery (EVI) predicted the MIE index in the forward task ($t_{32,25} = 2.44$; $p = 0.02$; LCI = 0.02; UCI = 0.21). In contrast, both internal visual imagery (IVI) and kinaesthetic imagery (KIN) significantly predicted the MIE index in the backward task (IVI: $t_{32,25} = 2.16$; $p = 0.04$; LCI = 0.03; UCI = 0.61; KIN: $t_{32,25} = -2.34$; $p = 0.03$; LCI = -0.67; UCI = -0.06). We also found a significant effect for the group and KIN interaction ($t_{32,25} = 2.04$; $p = 0.05$; LCI = 0.02; UCI = 0.75).

These findings indicate that PA enhances motor imagery abilities, particularly for complex actions like backward walking (Winter et al., 1989). They underscore the potential for developing imagery training protocols within sports and rehabilitation contexts. Furthermore, the study highlights the importance of the perspective used during motor imagery tasks, suggesting tailored approaches for athletes based on their level of PA (Mandolesi et al., 2023). All notable results are shown in *Figure 8.*

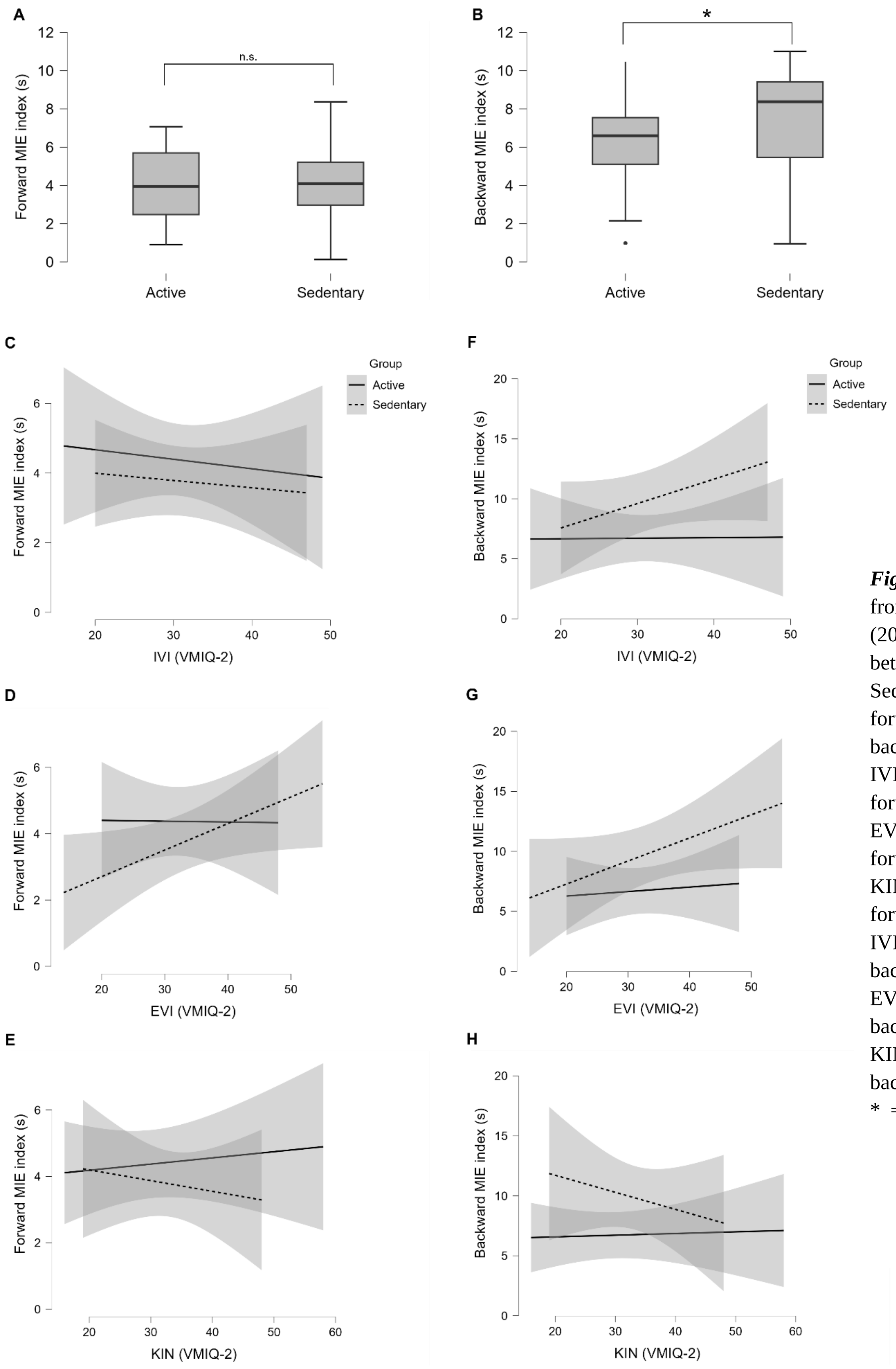

Figure 8. Main results from Mandolesi et al. (2023). Differences between Active and Sedentary on MIE forward **(A)** and backward **(B)**.
IVI prediction on forward MIE **(C).** EVI prediction on forward MIE **(D).** KIN prediction on forward MIE **(E).** IVI prediction on backward MIE **(F).** EVI prediction on backward MIE **(G).** KIN prediction on backward MIE **(H).** * = $p \leq 0.05$

1.2.7 General Discussion

All these research efforts yielded intriguing results that significantly enhance our understanding of the long-term effects of environmental influences on cognitive functioning. As previously noted, environmental factors such as motor experience, education, and language play a crucial role in enriching and boosting cognitive abilities (Howard et al., 2023). Among these, literature has highlighted the importance of motor experiences like sports and physical activity (PA) (Fernandes et al., 2017), likely due to the practicality and accessibility of promoting these factors.

In our research, we first aimed to investigate whether engaging in structured sports practice—characterized by specific times and frequency—could influence cognitive functioning. We chose to focus on executive functions because they are essential for goal-directed behaviour, problem-solving, and adapting to new situations (Bailey, 2007). Executive functions are not only crucial for everyday cognitive tasks, but also highly sensitive to changes in PA (Becker et al., 2018; Passarello et al., 2024), making them a compelling area of study in the context of environmental influences on cognition. We demonstrated that sportive individuals performed better on verbal and graphic fluency task, and had a higher general cognitive level (Becker et al., 2018; Passarello, Varini, et al., 2022; Passarello et al., 2024a).

Research suggests that participation in sports can have a significant positive impact on executive functions and academic performance in children and adolescents (Tikhomirova et al., 2020). Various studies have indicated that both individual and team sports contribute to improved motor coordination and executive functioning when compared to non-practitioners (de Souza Moura et al., 2015). For instance, martial arts practitioners have been shown to exhibit better executive functioning and achieve higher academic marks than their peers engaged in team sports or those who are sedentary (Giordano et al., 2021). Interestingly, different aspects of executive function are influenced by distinct components of sport practice. Specifically, physical health, motor skills, and sport proficiency have been identified as independent predictors of various executive functions, such as inhibition, which is associated with game skills and response orientation ability (Marchetti et al., 2015). Furthermore, open-skills sports, such as soccer, appear to offer greater benefits for enhancing executive functions compared to closed sports like athletics (Tsai et al., 2017).

We then hypothesized that the same “benefit” effect could be found in different age groups and also by only testing the level of physical activity (PA), which actually refers to any motor behaviour such as daily and leisure activities, and it is considered a determinant lifestyle for general health status (Burkhalter and Hillman, 2011). We then studied visuospatial working memory, as it plays a crucial role in how individuals interact with their environment (Van der Stigchel & Hollingworth, 2018). Visuospatial working memory allows for the temporary storage and manipulation of visual and spatial information, which is essential for navigating and making sense of the world around us (Baddeley, 2021). To assess this cognitive function, we employed a table version of the Radial Arm Maze (table-RAM) (Foti et al., 2020; Olton et al., 1979) a widely recognized tool that has been adapted for our purposes to better simulate real-world spatial navigation. This adaptation aimed to provide a more ecologically valid assessment of performance, allowing us to observe how participants engage with spatial tasks in a setting that more closely resembles their everyday experiences. Ecological validity is defined as the extent to which research findings can be generalized to real-world settings (Schmuckler, 2001). It ensures that the experimental conditions reflect the complexities and nuances of daily life, thereby enhancing the relevance of the findings.

While our intention was to create a more naturalistic testing environment using the table-RAM, we recognize that this approach was not without its limitations. Several factors may have compromised the ecological validity of our study, including the constraints of the laboratory setting, participant familiarity with the task, and potential differences in motivation and engagement levels compared to real-world situations. As we delve deeper into our findings, we will discuss these limitations and their implications for our understanding of visuospatial working memory in ecological contexts. However, we did confirm, once again, that PA boosted cognitive functioning, even in children (Passarello et al., 2024a).

We successfully replicated these results .in an elderly population, revealing that individuals who are more physically active demonstrate significantly better performance in graphic fluency tasks (Passarello et al. *unpublished*). This finding is particularly significant, as it suggests that engaging in physical activity not only helps prevent cognitive decline but also holds potential for mitigating the effects of neurodegenerative pathologies (Rizzo et al., 2021). Regular physical exercise may act as a protective factor against age-related cognitive deterioration, fostering brain health and resilience (Ainslie et al., 2008).

Research on ageing and cognitive fluency reveals a complex relationship between cognitive processes and performance. While ageing negatively impacts certain cognitive domains, its effects are not uniform across all areas (Rosano et al., 2012). For instance, processing speed plays a crucial role in both category and letter fluency, with younger individuals outperforming older adults in category fluency and processing speed (Elgamal et al., 2011). However, when controlling for the decline in processing speed, older adults may perform better on letter fluency tasks (Elgamal et al., 2011). In the domain of graphic fluency, individuals with Alzheimer's disease exhibit higher perseveration rates compared to healthy older adults, indicating that certain cognitive impairments manifest differently across fluency tasks (Sunderaraman et al., 2015). While much of the existing literature has primarily focused on verbal fluency, our findings align with these studies by demonstrating the relationship between physical activity and cognitive performance.

One of the key mechanisms through which PA enhances cognitive function is neuroplasticity.

This dynamic process involves structural and functional changes at the cellular and molecular levels, including the formation of new synaptic connections, modifications in neurotransmitter release, and alterations in receptor and signalling mechanisms (Chakraborty et al., 2007; Mandolesi et al., 2017; Virginia et al., 2021). Neuroplasticity mechanisms occur throughout life, from early development to ageing, and plays a crucial role in learning, memory, and recovery (Kong et al., 2016; Ware et al., 2021). Notably, environmental factors, specifically enriched environments—those providing enhanced cognitive, sensory, social, and motor stimulation—have been shown to promote neuroplasticity and improve cognitive function (Mishra & Gazzaley, 2014; Sale et al., 2014). These enriched environments impact various aspects of brain plasticity, including neurogenesis, neuron-glia interactions, and synaptic transmission (Mandolesi et al., 2017). Moreover, environmental enrichment can induce both structural and functional changes in the brain, influencing neurotransmitter dynamics in regions such as the hippocampus and prefrontal cortex, which are critical for memory and executive functions (Mora et al., 2007). While ageing occurs at different rates across brain regions, environmental factors can modulate this process, offering potential avenues for interventions that enhance neuroplasticity in both young and older individuals (Passarello et al., 2022). Activities that enrich cognitive functioning, like PA, are key to enhancing neuroplasticity and preventing cognitive decline (Rizzo et al., 2021; Serra et al., 2022; Troisi Lopez et al., 2023). Both PA and sport practice play a central role in skill acquisition and cognitive function, especially in high-performance sports (Mang et al., 2019). Through practice and repetition, the brain undergoes functional and structural adaptations, leading to improvements in motor skills and cognitive processes (Nielsen & Cohen, 2008), Given that the brain adapts based on repeated life experiences and that sport practice serves as a powerful external factor in promoting cognitive enrichment through neuroplasticity, we sought to investigate whether playing different roles in a team might lead players to acquire specific cognitive and motor skills.

Our research on social processing in sports reveals that social stimuli can positively influence athletes' ability to focus and ignore conflicting environmental cues, particularly in team ball sports (Passarello et al., 2023). Furthermore, different roles within a specific sport, such as striker, midfielder, or defender in soccer, are associated with distinct attentional profiles and performance outcomes (Montuori et al., 2019; Passarello et al., 2023). These roles are not only important for the technical aspects of performance but also contribute to identity formation, with varying levels of role commitment shaping an athlete's sense of self (Snyder, 1983). The adoption of specific roles in sports reinforces identity and enables social recognition, as sports are highly visible in cultural contexts (Weiss et al., 2003).

According to dual-process theories, both automatic (Type 1) and controlled (Type 2) processing guide athletes' behaviour, with Type 2 processing, which requires greater working memory capacity, playing a key role in decision-making and strategic thinking during gameplay (Furley et al., 2015). Therefore, the intersection of neuroplasticity, role adoption, and cognitive processes in sports offers rich opportunities to understand how athletes develop specific cognitive and motor skills through their engagement in PA and team dynamics.

The type of sport played can exert differential effects on cognitive functions, particularly when distinguishing between unimodal and multimodal activities. Unimodal sports, such as running or cycling, are characterized by repetitive, cyclic physical movements that involve relatively lower cognitive demands. These activities predominantly stimulate aerobic capacity and cardiovascular health, contributing to cognitive improvements in areas such as sustained attention and mood regulation, primarily through enhanced oxygenation and neurotrophic factor release (Troisi Lopez et al., 2023). Unimodal activities typically involve fewer cognitive complexities, such as strategic planning or multitasking, thus offering limited stimulation of higher-order cognitive processes (Troisi Lopez et al., 2023).

In contrast, multimodal sports, such as soccer, basketball, or martial arts, require the integration of both physical and cognitive components. These sports involve simultaneous engagement in decision-making, problem-solving, spatial awareness, and social interaction, which places higher cognitive demands on the individual (Voss et al., 2010). The continuous need for rapid processing of sensory information, coordination with teammates, and adaptation to dynamic environments engages executive functions, working memory, and attention networks more intensively than unimodal activities (Vestberg et al., 2012). This complex interplay of motor and cognitive tasks stimulates brain regions like the prefrontal cortex and hippocampus, promoting neuroplasticity through mechanisms such as synaptic pruning, long-term potentiation, and neurogenesis (Cotman et al., 2007).

In line with this, in our research we demonstrated that multimodal sports have stronger impact on cognitive functioning, specifically visuospatial working memory (Troisi Lopez et al., 2023). These findings suggest that multimodal activities may provide more robust cognitive benefits by engaging diverse neural networks involved in both motor coordination and higher cognitive functions (Best, 2010). Therefore, while both unimodal and multimodal sports contribute to cognitive health, multimodal sports may offer superior enhancements in cognitive function by creating a more enriched, cognitively demanding environment conducive to neuroplasticity. In light of this understanding, we investigated motor imagery, a capacity that require significant mental effort, focusing on the ability to imagine walking backward (Mandolesi et al., 2023). We aimed to explore whether physically active individuals rely more on motor imagery than sedentary ones. Our results showed that motor imagery is more prominent in physically active individuals, particularly regarding complex motor actions like backward walking. The interplay between motor imagery and physical action is underpinned by shared neural networks that activate during both processes (Jeannerod, 2006). This convergence of pathways highlights the importance of integrating motor imagery training within athletic development programs, as it can further enhance performance and cognitive functioning. Additionally, the application of motor imagery is not limited to athletes; it can also benefit non-athletes in various contexts, including rehabilitation, skill acquisition, and everyday activities (Passarello et al., 2022). For instance, individuals recovering from injuries can use motor imagery to facilitate movement re-learning and enhance their rehabilitation outcomes (Fusco et al., 2019).

In conclusion, our researches highlight the significant impact of PA, particularly through multimodal sports, on cognitive functioning. Engaging in these motor activities not only enhances physical performance but also boosts executive functions, such as verbal and graphic fluency, and visuospatial working memory. Our findings on motor imagery further indicate that physically active individuals involved in complex motor tasks, like backward walking, exhibit stronger mental rehearsal abilities. Importantly, the cognitive benefits of PA extend to non-athletes as well, reinforcing the importance of integrating PA into daily life for improved cognitive health and overall well-being.

2. Visuospatial Working Memory and Environmental Influence

After demonstrating how long-term motor experience can shape cognitive functioning, we turned our attention to whether similar influences could occur instantly during task performance. Specifically, we explored how the dynamic nature of environmental demands—such as continuously updating spatial information and adapting to new obstacles—might affect cognitive functioning in real time. To investigate this, we focused on visuospatial working memory, which plays a crucial role in navigating and responding to these changing environmental challenges.

Among cognitive functions, working memory stands out as particularly crucial. Building on the idea that cognitive functioning is shaped by environmental factors, working memory is one of the most sensitive to these influences. It is the cognitive system responsible for temporarily holding and processing information, making it essential for tasks like problem-solving, decision-making, and adapting to dynamic environments (Baddeley, 2021). Given the evidence that enriched environments promote neuroplasticity and cognitive enhancement, it makes sense to focus on working memory. This function not only reflects the brain's adaptability to external stimuli but also plays a key role in how we interact with our surroundings (Barker et al., 2010). Working memory is a cognitive system that provides temporary storage and manipulation of information necessary for complex tasks such as comprehension, learning, and reasoning (Baddeley, 1992; Baddeley, 2001). It consists of multiple components, including the central executive, visuospatial sketchpad, and phonological loop. The concept has evolved from a unitary short-term memory system to a more complex model involving simultaneous storage and processing of information (Baddeley, 2000).

Working memory has been widely applied across various fields, including cognitive psychology, neuroscience, education, and psychiatry (Brown, 2018). Some researchers also propose that working memory may comprise multiple specialized systems for different types of stimuli and information processing (Becker & Morris, 1999). Within this framework, visuospatial working memory (VSWM) emerges as a crucial component, particularly in activities that require cognitive flexibility, spatial awareness, and problem-solving abilities (Cowan, 2008).

Understanding the relationship between VSWM and the environment is crucial for developing accurate assessments of cognitive processes. Traditional methods for measuring VSWM have predominantly relied on static and controlled settings, which may not fully represent the complexities of real-world memory functioning.

This thesis section explains how VSWM is used and shaped by spatial navigation, and dynamic environments. By integrating insights from various theoretical frameworks and addressing the limitations of traditional measurements, the emphasis is on developing more ecologically valid methods. In particular, the use of virtual reality (VR) is highlighted as an innovative approach, offering a more realistic and immersive way to assess memory performance in dynamic, real-world-like environments.

2.1. Theories of Memory

Memory theories offer a multifaceted view of how information is encoded, stored, and retrieved, each contributing to a nuanced understanding of cognitive processes. The Atkinson-Shiffrin model (1968) is a seminal framework that divides memory into sensory memory, short-term memory (STM), and long-term memory (LTM). This model suggests that information enters the sensory register, moves to STM through selective attention, and is then encoded into LTM (Shura et al., 2016). While the model provides a simple approach to understanding memory, it has been criticized for oversimplifying the process and making incorrect assumptions about information transfer between stages. Some researchers argue that the model lacks theoretical coherence and fails to explain relationships in experimental data (Tarnow, 2010). Despite its limitations, the Atkinson-Shiffrin model has been influential in memory research and continues to serve as a starting point for new interpretations and models of information processing in humans.

A refined version of this framework is represented by Baddeley's (2000) working memory model, which introduced a more sophisticated and detailed structure. Baddeley & Hitch's multicomponent working memory model (1974) revolutionized memory research (Harasimczuk, 2024). The model proposes a system for temporary maintenance and manipulation of information, crucial for complex cognitive tasks. It consists of an attentional central executive and two slave systems: the articulatory loop and visuospatial sketchpad (Parkin, 1988).

Over time, the model has been refined, with extensive investigation into the phonological and visuospatial subsystems and the addition of a fourth component, the episodic buffer (2001). The embedded processes model (Cowan, 1999) further refines our understanding by suggesting that working memory is not a separate entity but a subset of activated long-term memory. Cowan's working memory model (1999) proposes a limited-capacity focus of attention within activated long-term memory. This contrasts with traditional fixed-item capacity models, suggesting instead a flexible resource allocation approach where memory quality, not quantity, determines performance (Ma et al., 2014). Cowan's model emphasizes the role of attention in working memory, controlled by both voluntary and involuntary processes (Cowan, 2008). The impact of this theory extends beyond cognitive psychology, influencing research in biological systems and visual modality (Gruszka & Orzechowski, 2016). Cowan's work has been influential in challenging the notion of a fixed working memory capacity, proposing instead that capacity limits arise from various mechanisms including interference and time decay. This evolving conceptualization of working memory has important implications for understanding cognitive processes and their limitations in daily life (Cowan, 2016).

Tulving's model of long-term memory (1972) complements these views by differentiating between episodic memory (personal experiences), semantic memory (general knowledge), and procedural memory (skills and habits). This differentiation underscores that different types of information are processed and retrieved through distinct mechanisms, offering a more detailed picture of memory organization. Tulving emphasized the interdependence of these memory systems and their crucial role in normal declarative memory functioning (Tulving, 1972). While Tulving focused on long-term memory, other researchers have explored working memory. Logie (2021) proposed a time-based theory of working memory, suggesting that processing and storage compete for attention, leading to a trade-off between these activities. This theory emphasizes the role of temporal decay and attentional refreshing in maintaining information in working memory, providing insights into the development of working memory capacity. In contrast, Craik and Lockhart's Levels of Processing theory (1972) shifts the focus from storage systems to the depth of processing, proposing that the strength and durability of memories are influenced by the level of cognitive engagement during encoding. This theory suggests that deeper, more meaningful processing leads to more robust and long-lasting memories.

Johnson & Hirst (1995) introduced the distinction between source memory, which involves recalling the context of learned information, and familiarity, which pertains to recognizing information without specific contextual recall. This model highlights the complexity of memory retrieval and the need to differentiate between various types of memory processes. The ecological approach (Nigro & Neisser, 1983) criticizes traditional laboratory-based memory research for lacking ecological validity and advocates for studying memory in naturalistic settings to better understand its real-world applications. Nigro & Neisser contributions to autobiographical memory accuracy research emphasized memory as a reconstructive process influenced by social context and personal goals. The ecological approach to memory, while broadening research scope, faced challenges in delivering theoretical advancements (Conway et al., 2001). However, these studies have been instrumental in shaping contemporary memory research by emphasizing the importance of studying memory in naturalistic settings.

The Adaptive Control of Thought (ACT-R) theory (Anderson, 2007) integrates cognitive processes into a modular system that includes both declarative and procedural knowledge. The ACT-R is a comprehensive cognitive framework that encompasses both memory and other cognitive processes. While it is not solely a theory of memory, it integrates key aspects of declarative and procedural memory within its modular system. In ACT-R, declarative memory refers to the storage and retrieval of explicit knowledge, such as facts and events, represented as "chunks." The retrieval of these chunks is influenced by factors like frequency of use and the context in which they were learned, resembling traditional long-term memory (Anderson et al., 1999). On the other hand, procedural memory within ACT-R consists of learned skills and habits that guide actions automatically, without conscious recall, managed by "if-then" rules called productions (Anderson & Lebiere, 1998). This allows ACT-R to model how different types of memory interact with other cognitive functions like perception, attention, and motor control, providing an integrated understanding of cognition. This theory illustrates how memory and other cognitive functions adapt based on experience and task demands.

Connectionist models of memory simulate cognitive processes through networks of interconnected nodes that function like simplified neurons (McClelland et al., 1995). These models emphasize parallel processing and distributed representations, suggesting that memory is not localized but rather spread across an entire network. In this framework, memories are formed through patterns of activation that emerge from the connections among nodes. When a specific stimulus is encountered, it activates a particular pattern within the network, effectively retrieving the associated memory. This approach highlights that learning involves the strengthening of connections based on experience, akin to synaptic plasticity in biological systems. By representing memory as a dynamic interplay of activation patterns across a network, connectionist models provide insights into the complexities of memory processes and their relevance to cognitive functioning.

In conclusion, while all the cited theories of memory, possess distinct strengths and limitations, not all have been fully confirmed through empirical experiments. Nonetheless, they play a crucial role in enhancing our understanding of the complex nature of memory and its significance in cognitive functioning. Among the various types of memory, we will focus specifically on visuospatial working memory due to its essential role in navigating and interacting with our environment.

2.2. Visuospatial Working Memory and Spatial Navigation

Visuospatial working memory (VSWM) emerges as a crucial component, particularly in activities that require cognitive flexibility, spatial awareness, and problem-solving abilities (Cowan, 2011). Its importance extends to spatial navigation, where VSWM plays a vital role in encoding, maintaining, and manipulating spatial information to help individuals orient themselves in complex environments (Baddeley, 2021).

Consider the example of navigating a city. When an individual is walking or driving to a new destination, VSWM is actively engaged. As they follow a route, they must remember previously encountered landmarks, interpret visual cues such as traffic lights and signs, and adjust their path in response to changing conditions, such as detours or unexpected roadblocks. This real-time integration of visual and spatial information is essential for making quick and informed decisions that keep them on track. Another compelling example of working memory in navigation can be seen when someone is trying to find their way in a crowded space, such as an airport. Upon arriving, they may need to recall the layout of the terminal, remember the gate number for their flight, and process announcements regarding gate changes. As they navigate through the throngs of people, they must also be aware of their surroundings, adjusting their route based on the location of shops, restrooms, and other facilities. Here, VSWM is crucial not only for retaining this information, but also for manipulating it to determine the most efficient path while avoiding obstacles.

Effective spatial navigation relies on the ability to remember landmarks, routes, and spatial relationships, making VSWM essential for moving through both familiar and unfamiliar spaces (Smith & Jonides, 1997). This cognitive function is not only vital in everyday tasks such as driving or finding one's way through a city, but also in more specialized domains like sports, where athletes must quickly process and react to dynamic spatial configurations (Miyake & Shah, 1999). Studies have shown that individuals with superior VSWM perform better in navigation tasks, including route learning and integration (Blacker et al., 2017; Garden et al., 2002). The processing of spatial information during navigation engages different components of working memory, with the visuospatial component being crucial for both route and survey perspectives (Deyzac et al., 2006). However, this may vary depending on the type of information being processed and the individual's spatial ability (Deyzac et al., 2006; Garden et al., 2002). These findings highlight the complex relationship between VSWM and spatial navigation, emphasizing the importance of considering individual differences in working memory capacity when assessing spatial abilities and navigation performance.

Now, we previously said that cognitive functions are not static; they are influenced by and adapt to the environment in which they operate. The environment provides a continuous stream of sensory input that cognitive processes must interpret and respond to. This dynamic interaction applies to VSWM as well. For instance, the cognitive demands of navigating a busy urban area differ significantly from those of walking through a quiet park. In the urban setting, cognitive resources are taxed by the need to process numerous stimuli simultaneously, while in a natural setting, the cognitive load is often reduced, allowing for easier concentration (Bronfenbrenner, 1979).

One of the foundational concepts in understanding this environment- VSWM relationship is context-dependent memory (Chocholáčková et al., 2023), which asserts that memory retrieval is significantly enhanced when the context during recall matches the context during encoding. This phenomenon was first demonstrated by Godden & Baddeley (1975) in their seminal underwater study. Divers who learned words underwater were able to recall them more effectively when tested in the same underwater environment compared to when they were tested on land. This context-dependent effect is not limited to such extreme settings but extends to more common environments. For instance, Smith (1979) found that students performed better on exams when tested in the same room where they had studied, reinforcing the idea that matching encoding and retrieval contexts enhances memory performance. Hockley (1992) extended these findings to virtual environments, demonstrating that even in digital contexts, such as virtual reality (VR), the principle of context-dependent memory holds true, thereby highlighting the adaptability and robustness of this effect across diverse contexts. This evidence collectively illustrates that memory is profoundly influenced by the environment, whether in physical or virtual settings, the alignment of encoding and retrieval contexts significantly enhances memory performance. Given the close connection between VSWM and spatial navigation, it becomes evident that environmental demands related to spatial navigation can directly impact the efficiency and functioning of VSWM. This highlights the intricate relationship between memory systems and the environments in which they operate. The mechanism through which VSWM could be involved in spatial navigation is explained by Tolman's Cognitive Map Theory (1935), which posits that individuals create mental representations of their environments to aid in navigation (Epstein et al., 2017). This theory has been supported by research utilizing virtual mazes, where participants used spatial landmarks to navigate effectively. This ability to build and use cognitive maps is not merely theoretical but has practical implications. For instance, research by Maguire et al. (1999) demonstrated that London taxi drivers, who possess extensive spatial knowledge of the city, have larger hippocampi compared to non-taxi drivers. This anatomical difference highlights a strong relationship between extensive spatial navigation experience and cognitive functions, illustrating how the structure of the hippocampus is influenced by the demands of spatial memory. Moreover, neuroimaging studies reveal that spatial and object working memory are governed by distinct neural systems. For example, spatial tasks primarily activate right-hemisphere regions, including the occipital, parietal, and prefrontal areas, while object tasks engage left-hemisphere regions such as the inferotemporal and parietal areas (Smith & Jonides, 1997). A specific region for spatial working memory has been located in the superior frontal sulcus (Courtney et al., 1998). Further research by De Beni et al. (2005) highlights the role of VSWM in processing spatial information in texts, while van der Stigchel et al. (2007) demonstrated that external visual events can influence spatial working memory, with memorized locations shifting towards irrelevant nearby stimuli. These findings not only confirm the distinct neural mechanisms behind spatial working memory but also emphasize its interaction with external spatial cues.

Dynamic environments introduce additional complexity to our understanding of VSWM processes. Dynamic systems' theory, proposed by Thelen & Smith (2007), suggests that memory is continuously shaped by interactions with changing environments. This perspective is supported by Wang & Spelke (2002), who demonstrated that working memory adapts to real-time spatial changes, indicating that individuals modify their memory strategies based on evolving contexts. Similarly, Olton et al (1979), proved how spatial cues could be used to navigate and remember reward locations. Studies using these models reveal that individuals’ ability to navigate and remember locations is influenced by the environmental features and the task demands, underscoring the importance of environmental context in memory processes.

2.3. Methods to Test Visuospatial Working Memory

To effectively evaluate VSWM, researchers have developed a range of assessment methods. Classical assessment methods have been foundational in understanding VSWM, utilizing tasks that measure an individual's ability to manipulate and retain visuospatial information. These traditional approaches, while providing valuable insights, have their limitations in capturing the complexity of VSWM (*Table 1)*.

The *Corsi Block-Tapping Task (CBTT)* (Corsi, 1972) is one of the most widely used tools for assessing visuospatial working memory, and its effectiveness has been well-documented across various populations, including patients with brain damage (Brunetti et al., 2014; Kessels et al., 2000). In the task, participants are required to replicate sequences of block taps demonstrated by the experimenter. The length of the sequences, or "path length," increases gradually, and performance tends to decline as these sequences become longer and more complex (Busch et al., 2005). This task has been standardized, showing robust reliability in testing visuospatial short-term memory, particularly in neurological cases where damage to specific brain regions impairs performance. Studies have found that patients with right hemisphere brain damage perform worse than those with left hemisphere damage, further highlighting CBTT's sensitivity to specific cognitive deficits (Kessels et al., 2000).

The CBTT has evolved over time to include digital versions, such as eCorsi, which provide enhanced accuracy and automation in measuring task performance (Brunetti et al., 2014). These digital tools offer several advantages, including precise timing, fewer human errors, and the ability to standardize administration across different contexts. Additionally, digital versions allow for more extensive data collection and analysis, making them particularly useful in research settings where accuracy is paramount. The automation of measurements reduces the chances of biases and errors in recording responses, offering a more objective assessment. Interestingly, the backward condition of the task, where participants must reproduce the block sequence in reverse order, does not appear to be more difficult than the forward condition. This finding contrasts with the Digit Span Task, where the backward condition is consistently more challenging. It has been suggested that the backward CBTT relies more on the slave systems of working memory—specifically, the visuospatial sketchpad—rather than the central executive component (Iersel et al., 2008). This suggests a different cognitive load and processing mechanism for visuospatial tasks, which may explain the observed differences between the two tasks.

Another key finding is that the path configuration—the spatial layout of the blocks—can significantly affect performance, particularly at higher difficulty levels (Busch et al., 2005). Complex or irregular configurations can lead to performance decline due to increased difficulty in maintaining and manipulating spatial representations in working memory. Clinicians and researchers should be aware of this when designing studies or using the Corsi task in clinical settings, as it could lead to misinterpretations of a patient's visuospatial abilities if not accounted for. Thus, attention to path complexity is critical when interpreting results, especially in populations with neurological impairments.

The *Visual Patterns Test (VPT)* (Della Sala et al., 1999) is a well-established tool for assessing visual working memory by measuring an individual's ability to recall and reproduce visual patterns. This task involves presenting participants with a grid containing a pattern of filled and unfilled cells, which they must reproduce from memory. Research has demonstrated that verbal coding can influence VPT performance, as individuals may verbally encode some aspects of the visual patterns, thereby using verbal strategies to aid recall. To minimize this influence and provide a purer measure of visual working memory, a modified version of the VPT was developed, which limits the opportunity for verbal coding (Brown, 2018). By controlling for this confounding factor, the revised version allows for a more accurate assessment of visual working memory, specifically its visual rather than verbal components.

Further studies have examined how the mode of presentation in visuospatial memory tasks can affect performance outcomes. In particular, simultaneous presentation of stimuli, where all elements are shown at once, tends to result in better performance compared to sequential presentation, where elements are shown one after the other (Lecerf & Roulin, 2009). The advantage of simultaneous presentation likely stems from the ability to process and hold more visual information in working memory at one time, providing a more coherent and stable visual representation. This finding is particularly relevant when designing tasks for different populations, as the mode of presentation can significantly impact the results, especially in children and older adults, who may have varying capacities for sequential memory.

In developmental research, a dissociation between visual and spatial working memory has been identified in children. Studies indicate that visual pattern memory improves more with age than spatial memory, highlighting distinct developmental trajectories for these two aspects of working memory (Logie & Cowan, 2015). This suggests that while both forms of working memory are critical, visual memory may develop at a different rate, potentially reflecting differences in the underlying neural mechanisms and cognitive processes that support these skills. As children grow, their ability to remember and manipulate visual patterns becomes more refined, which has important implications for educational interventions aimed at improving visuospatial skills.

To address the limitations in existing visual working memory assessments, such as the VPT, the *Computerized Object and Abstract Designs Test* (COAD) (Price, 2009) was developed. This test incorporates Baddeley's episodic buffer concept, which integrates information from various sources, including visual and verbal information, to create a multidimensional memory representation. The COAD test was specifically designed to detect visual working memory deficits with greater sensitivity compared to traditional standardized tests (Price, 2009). It has shown promise not only in research settings but also in clinical applications, such as the early detection of neurological disorders and use in rehabilitation. The increased sensitivity of the COAD test makes it a valuable tool for identifying subtle deficits in visual working memory, which could be crucial for early intervention in conditions like Alzheimer’s disease, traumatic brain injury, and other cognitive impairments. In summary, both the VPT and the COAD test provide critical insights into the functioning of visual working memory, with the latter offering innovative advancements by incorporating more complex cognitive processes through the episodic buffer.

The *N-back task i*s a highly influential measure of working memory, originally introduced by Kirchner (Kane et al., 2007). In this task, participants must indicate when a presented stimulus matches the one shown n trials earlier, with n representing a varying level of difficulty depending on the task design. This task has become a cornerstone in cognitive neuroscience, particularly for assessing executive functions and working memory processes. One reason for its popularity is its adaptability to different cognitive tasks, including both verbal and visuospatial stimuli. Moreover, Owen et al. (2005), through meta-analyses, revealed consistent activation of the frontoparietal cortex during N-back tasks, highlighting its engagement of key brain regions associated with working memory.

However, despite its widespread use, the N-back task's construct validity has come under scrutiny. Kane et al. (2007) questioned its effectiveness in distinguishing between different working memory processes, arguing that it may not accurately represent the multifaceted nature of working memory capacity. Furthermore, the task's reliability as a measure of individual differences in working memory capacity has been criticized, with some studies finding limited correlations between N-back performance and other working memory measures. Notably, Jaeggi et al. (2010) found that while the N-back task can predict certain cognitive abilities, such as fluid intelligence, its utility as a definitive measure of working memory capacity remains questionable.

In addition to these concerns, researchers have noted the importance of reporting both reaction times and accuracy when interpreting N-back performance. Meule (2017) emphasized that these two metrics can have distinct correlates and interpretations, offering a more nuanced understanding of task performance. While the task may not fully capture the complexity of working memory, it continues to hold significant value in experimental paradigms and predicting performance in broader cognitive functions.

The *Memory-Tracking Task* (2006) is designed to evaluate how well individuals can keep track of the locations of items that appear and disappear within a spatial layout. This task is significant for understanding the cognitive mechanisms underlying dynamic spatial awareness. Research indicates that working memory plays a vital role in this process, as central executive functions are responsible for managing the ongoing tracking of multiple objects (Allen et al., 2006). Electrophysiological (EEG) studies have revealed distinct neural signatures associated with tracking spatial positions, highlighting the brain's specialized pathways for processing and maintaining items in working memory (Allen et al., 2006). These neural signatures suggest that various cognitive processes are engaged when individuals attempt to update their mental representations of object locations. For instance, experts in tracking—such as military trainees—demonstrate enhanced capabilities for updating visuospatial information in real time. However, this expertise does not necessarily translate to improved long-term memory for the locations of objects, indicating that different cognitive skills may be at play (Barker et al., 2010).

Further research has shown that the consistency of the local spatial layout can influence how individuals terminate their searches during visual tasks. While stable layouts may aid in memory retrieval, they do not significantly enhance memory during the visual search process itself (Becker & Morris, 1999). Overall, findings from studies on the Memory-Tracking Task illustrate that effective memory tracking relies on a complex interplay of pre-attentive indexing, conscious strategic planning, and executive functions. Moreover, expertise in tracking can improve certain dimensions of performance, underscoring the importance of both innate cognitive abilities and practice in mastering dynamic spatial tasks.

The *Dot Matrix Task* is a widely utilized measure of VSWM, that assesses participants' ability to remember and replicate the locations of dots on a grid after a brief delay (Burggraaf et al., 2018). This task has demonstrated moderate test-retest reliability, making it valuable for repeated-measures designs (Burggraaf et al., 2018). Research has shown that performance on the Dot Matrix Task significantly improves throughout adolescence, highlighting its sensitivity to developmental changes in working memory capacity. Moreover, the task has revealed specific VSWM deficits in individuals with Down syndrome, particularly in spatial-simultaneous tasks that require processing multiple items concurrently (Lanfranchi et al., 2009). Individual differences in VSWM capacity, as measured by the Dot Matrix Task, are also linked to distractor inhibition abilities, with low-span individuals exhibiting more intrusion and spatial errors compared to their high-span counterparts (Lecerf & Roulin, 2009). These findings underscore the utility of the Dot Matrix Task as a diagnostic tool for assessing working memory functions across various populations.

Dual-Task Paradigms are designed to assess VSWM by requiring participants to engage in two cognitive tasks simultaneously (Olive, 2004). This approach is particularly effective in evaluating the load placed on working memory, as it simulates real-world situations where individuals must multitask and manage competing cognitive demands. By combining a primary task—such as remembering spatial locations or sequences—with a secondary task, researchers can observe how the cognitive load affects performance in both tasks (Jaroslawska et al., 2018).

These paradigms provide insights into the capacity and limitations of working memory, highlighting the interplay between various cognitive processes involved in multitasking. For instance, studies using dual-task paradigms have shown that increased cognitive load can lead to declines in performance on the primary VSWM task, revealing the finite nature of working memory resources (Lecerf & Roulin, 2009). Additionally, dual-task paradigms can help distinguish between automatic and controlled processes, shedding light on how individuals allocate cognitive resources when faced with competing tasks (Murray et al., 1997). Furthermore, dual-task paradigms have important implications for understanding cognitive performance across different populations, including older adults and individuals with cognitive impairments, where the ability to manage dual tasks may be compromised. Research has demonstrated that older adults often exhibit greater difficulty in dual-task conditions, which can be attributed to declines in working memory capacity and executive function (Olive, 2004). All these methods for VSWM assessment offer precise measurements, primarily due to their implementation in controlled laboratory settings. While some tasks may not be fully standardized, they still provide valuable insights into cognitive functioning. However, these traditional methods often lack ecological validity, meaning they do not effectively simulate real-world scenarios where VSWM is typically utilized. To address these concerns, researchers are increasingly exploring alternative instruments that incorporate more realistic contexts and tasks, thereby enhancing our understanding of VSWM in practical settings.
The *Route Learning Task* (Ishikawa & Montello, 2006) serves as a valuable measure of spatial working memory, emphasizing ecological validity by simulating real-world navigation scenarios. Unlike traditional memory tasks conducted in controlled settings, this assessment engages participants in broader spatial environments, allowing them to learn and recall specific routes while considering various environmental cues. This task often involves navigating through a virtual or physical space, where participants must remember the sequence of turns,

landmarks, and distances to reach a destination (Ishikawa & Montello, 2006).

By requiring individuals to navigate through complex layouts, the task captures the intricacies of spatial memory as it occurs in daily life, enhancing the relevance of findings to real-world situations. The Route Learning Task effectively evaluates cognitive processes involved in spatial learning and memory, highlighting how individuals utilize landmarks and spatial relationships to navigate their surroundings (Hegarty & Waller, 2005). For instance, research indicates that effective route learning often relies on the integration of both visual and spatial information, underscoring the multifaceted nature of spatial cognition (Meneghetti et al., 2011). Moreover, this approach is particularly relevant for assessing spatial memory across diverse populations, including those with cognitive impairments such as Alzheimer's disease and developmental disorders, where navigational skills may be compromised (Moffat et al., 1998). The Route Learning Task's emphasis on practical applicability makes it a robust tool for studying spatial memory and contributes to a deeper understanding of the mechanisms underlying spatial navigation, thereby advancing both theoretical frameworks and clinical applications in cognitive research.

Following a similar approach, the *Ecological Momentary Assessment (EMA*) (Moran et al., 2017)has emerged as a valuable method for studying WSWM in real-world contexts, providing researchers with a dynamic and immediate perspective on cognitive processes as they unfold in daily life. Unlike traditional laboratory-based assessments, EMA allows for the collection of data in naturalistic settings, thus offering insights into how working memory operates outside controlled environments. Research has demonstrated the feasibility and validity of administering VSWM tasks via EMA, affirming its utility in capturing real-time cognitive performance (Schuster et al., 2015).

EMA-based VSWM assessments have consistently shown strong associations with laboratory measures of VSWM, indicating that findings from EMA can be reflective of traditional cognitive assessments. Additionally, EMA is particularly sensitive to contextual factors that influence cognitive performance, such as substance use. For instance, acute marijuana and alcohol consumption have been found to negatively impact VSWM performance, highlighting the impairing effects of these substances on cognitive functions (Schuster et al., 2016). In contrast, tobacco use was associated with improved VSWM performance, suggesting that the relationship between substance use and VSWM may be complex and context-dependent. Further, within-person variations in VSWM capacity, as measured through EMA, have been linked to negative affect reactivity to stressors. These variations suggest that individuals' cognitive resources may be dynamically influenced by their emotional states and environmental demands, thus impacting their VSWM performance in real-time (Benson et al., 2023). While methods that operate in less constrictive environments, provide valuable insights into working memory and cognitive processes in real-world contexts, they often lack the rigour and control associated with traditional laboratory-based assessments. The ability to capture cognitive functioning in naturalistic settings offers a more holistic understanding of how VSWM operates in daily life, particularly in response to varying contextual factors. However, the trade-off for this ecological validity is a reduction in the precision and control over extraneous variables, which can compromise the reliability and generalizability of findings.

With the advancement of technologies in research, there are now more diverse methods available, such as neuroimaging and eye tracking, that can enhance our understanding of cognitive processes. These techniques allow researchers to explore the underlying neural mechanisms of working memory while maintaining some level of ecological validity. *Eye tracking* is a valuable tool for studying VSWM. Research has demonstrated a strong interconnection between VSWM, attention, and eye movements. Eye movements, particularly eye movement control, can selectively disrupt spatial working memory but not visual memory for shapes (Postle, 2006). VSWM is integral to the eye movement system, supporting target selection, feature maintenance across saccades, and gaze correction (Van der Stigchel & Hollingworth, 2018). Maintaining spatial information in working memory may involve attention-based rehearsal in higher brain areas while inhibiting specific motor programs in lower areas (Van Der Stigchel et al., 2007). Studies have shown that eye movements produce significantly greater interference with spatial span compared to limb movements or covert attention shifts, highlighting the crucial role of oculomotor control processes in rehearsing location-specific representations in working memory (Pearson & Sahraie, 2003). These findings underscore the intricate relationship between VSWM and oculomotor processes in visual cognition, making eye tracking an essential method for investigating how we encode, maintain, and manipulate spatial information in working memory.

Neuroimaging studies are instrumental in advancing our understanding of VSWM by elucidating the distinct neural networks associated with different types of working memory tasks. For instance, while verbal working memory primarily engages left-hemisphere regions, such as the posterior parietal cortex for storage and frontal areas for rehearsal (Smith & Jonides, 1997), spatial working memory predominantly activates right-hemisphere regions, including the posterior parietal, occipital, and frontal cortices (Carlson, 1998; Smith & Jonides, 1997). This hemispheric specialization highlights the unique cognitive processes involved in VSWM compared to verbal tasks.

Furthermore, neuroimaging research has identified separable components within both verbal and spatial working memory systems, distinguishing between passive storage, which predominantly relies on posterior brain regions, and active maintenance, which engages more anterior areas (Smith & Jonides, 1997). For spatial working memory, executive processes, such as inhibition, are often associated with activity in the prefrontal cortex, underscoring the complexity of managing spatial information in a dynamic context (Smith & Jonides, 1998). Additionally, activation in key regions—such as the medial frontal gyrus, superior frontal sulcus, and intraparietal sulcus—has been shown to increase with memory load, indicating that these areas are crucial for handling greater demands on working memory (Carlson et al., 1998). Meta-analyses have further confirmed the dorsal-ventral dissociation for spatial versus non-spatial working memory storage in the posterior cortex, and have shown that executive demands generally produce more dorsal frontal activation than tasks focused solely on storage (Smith, 2010).

By integrating neuroimaging techniques with other methodologies, researchers can gain a more nuanced understanding of how VSWM operates within the broader cognitive framework. This multi-faceted approach not only enhances our grasp of the neural mechanisms underpinning working memory but also allows for a more comprehensive exploration of its role in spatial orientation and navigation within dynamic environments. Ultimately, combining neuroimaging with other instruments like eye tracking and ecological assessments strengthens the overall rigour and relevance of cognitive research, providing insights that are both theoretically grounded and practically applicable in understanding VSWM in real-world contexts.

VSWM Task	Description	Setting	Target	Strengths	Limitations
Corsi Block-Tapping Task (CBTT)	Sequential block tapping task to assess VSWM. Sequence length increases gradually.	Lab-based or digital version	Children, adults	Widely used, sensitive to brain damage (especially right hemisphere). Digital versions enhance precision.	Sequence configuration can affect performance, potentially leading to misinterpretation. May not capture complexity of VSWM.
Visual Patterns Test (VPT)	Participants need to reproduce visual patterns from memory (grid-based).	Lab-based or digital version	Children, adults	Effective in measuring visual working memory. Modified version limits verbal encoding strategies.	Verbal strategies may still influence results, limiting purity as a visual memory test.
N-back Task	Participants indicate when a stimulus matches the one shown n trials earlier.	Lab-based or mobile device	Children, adults	Versatile across different stimuli (verbal, visuospatial). Widely used to measure working memory and predict cognitive abilities.	May not fully capture the complexity of working memory processes; construct validity has been questioned.
Memory-Tracking Task	Assesses tracking of items within a spatial layout.	Lab-based	Children, adults	Captures dynamic spatial awareness. Reveals specific neural signatures linked to visuospatial tasks.	Expertise in tracking does not necessarily translate to improved long-term memory of spatial locations.
Dot Matrix Task	Participants remember and replicate the locations of dots on a grid after a delay.	Lab-based	Children	Moderate reliability, sensitive to developmental changes. Identifies specific VSWM deficits, e.g., in Down syndrome.	Limited sensitivity in adults; primarily focused on simultaneous rather than sequential spatial processing.

Dual-Task Paradigms	Simultaneous engagement in two cognitive tasks, often involving spatial memory.	Lab-based	Children, adults, elderly	Simulates real-world multitasking. Highlights cognitive load and resource allocation.	Dual tasks may be too complex for certain populations, such as older adults or those with cognitive impairments.
Route Learning Task	Participants navigate virtual/physical environments and recall routes based on environmental cues.	Virtual or real-world	Children, adults	High ecological validity, relevant for real-world spatial navigation studies.	May not be suitable for all populations due to navigation impairments.
Computerized Object and Abstract Designs (COAD)	Combines visual and verbal information in a multidimensional memory representation (episodic buffer).	Lab-based or digital version	Adults, elderly,	Highly sensitive, especially for early detection of visual working memory deficits.	Limited in availability; relatively new compared to traditional VSWM tasks.
Ecological Momentary Assessment (EMA)	Collects real-time data in naturalistic settings (mobile VSWM assessments).	Real-world (mobile)	Adult, elderly	Offers dynamic and immediate insights into cognitive processes in real-world scenarios.	Context-sensitive, may be influenced by environmental factors, making interpretation more complex.

Table 1. The most commonly used VSWM tasks in research.

2.3.1. Research Highlights: Assessing Visuospatial Working Memory with the Brick Game Task

Our study titled *"Visuospatial Working Memory Abilities in Children Analysed by the Bricks Game Task (BGT)"*[7] , aimed to develop a novel, ecologically valid assessment measure for evaluating visuospatial working memory (VSWM) in children. VSWM is essential for children's cognitive development, as it supports key skills such as letter recognition, reading,

[7] D'Aurizio, G., Di Pompeo, I., Passarello, N., Troisi-Lopez, E., Sorrentino, P., Curcio, G., & Mandolesi, L. (2023). Visuospatial working memory abilities in children analysed by the bricks game task (BGT). *Psychological Research, 87(7), 2111-2119.*

writing, and mathematics (Tikhomirova et al., 2020). Moreover, it predicts academic achievement in areas such as geometry and general performance in early school years (Kyttälä & Lehto, 2008). Traditional VSWM tasks, while reliable, lack ecological validity, highlighting the need for more naturalistic tools in developmental research (Foti et al., 2020). The Bricks Game Task offers a small-scale, ecologically valid alternative, inspired by real-world navigation and behavioural tasks. The BGT is an ecological adaptation of the Corsi Block-Tapping Test (CBTT) (Corsi, 1972), designed to assess VSWM by integrating the dynamics of peri-personal space. The task involves a square blue platform (25 cm × 25 cm) with nine white bricks (1 cm wide × 1 cm long × 2 cm high) arranged in three different configurations: Matrix (M-BGT), Cluster (CL-BGT), and Cross (CR-BGT) (*Figure 9*).

During the task, the experimenter taps a sequence of blocks at a rate of one block per 2 seconds, lifting their hand straight up for 2 seconds before moving to the next block. The child is then required to reproduce the same sequence of blocks in the exact order. The task becomes progressively more difficult as the length of the block sequences increases, starting from two blocks up to a maximum of nine. For each sequence length, three sequences are presented, and the test continues as long as the participant correctly reproduces the sequences. Once the child fails to correctly reproduce the three sequences, the task is stopped, and the longest sequence accurately recalled is recorded as the BGT span measure.

The study involved 228 Italian children (121 females, mean age: 7.22 ± 1.18 years) divided into three groups based on school class. Neuropsychological assessment included the forward and backward version of the Digit Span task (DSF, DSB) (Wechsler, 1945) and the Corsi Block-Tapping test (CBT) (Corsi, 1972), alongside the novel Bricks Game Task (BGT) in three configurations (Matrix, Cluster, Cross)*)*, with span measures recorded for each. Pearson correlations examined associations between BGT, Digit Span, and CBT scores, while multiple linear regression explored whether CBTT, Digit Span, and age predicted BGT performance. Group differences in performance were analysed using MANOVA with Gender and Group as factors, followed by post-hoc tests with Bonferroni. A mixed-model ANOVA was used to assess BGT span scores across configurations, with Bonferroni post-hoc tests applied when necessary.

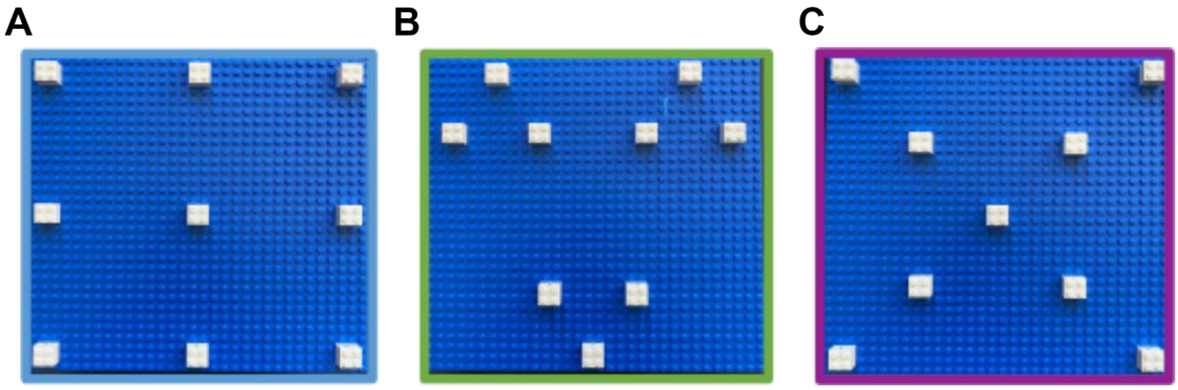

Figure 9. The Bricks Game Task. **A.** Matrix configuration **B.** Cluster configuration **C.** Cross configuration

The results of this study showed a strong positive correlation between M-BGT scores and both CBT ($r = 0.48$, $p < 0.001$) and DS-B ($r = 0.36$, $p < 0.001$), with similar correlations found across the Cluster and Cross configurations. Multiple linear regression indicated that predictors like CBT performance and age significantly explained variance in M-BGT ($R^2 = 0.28$), CL-BGT ($R^2 = 0.23$), and CR-BGT ($R^2 = 0.35$) scores. MANOVA revealed significant group differences in executive performance across age groups ($F_{12,434} = 15.06$, $p < 0.0001$), with older children performing better. Mixed-model ANOVA showed superior performance in the Matrix configuration compared to Cluster and Cross. Notable results are shown in *Figure 10*. The BGT was validated as a reliable, ecologically valid tool to measure children's visuospatial abilities, with performance improving with age and educational level. These findings align with previous research indicating the development of visuospatial skills with age and their relationship to academic success. The use of different spatial configurations highlighted the cognitive demands of each layout, reinforcing the importance of ecological tasks in neuropsychological assessments.

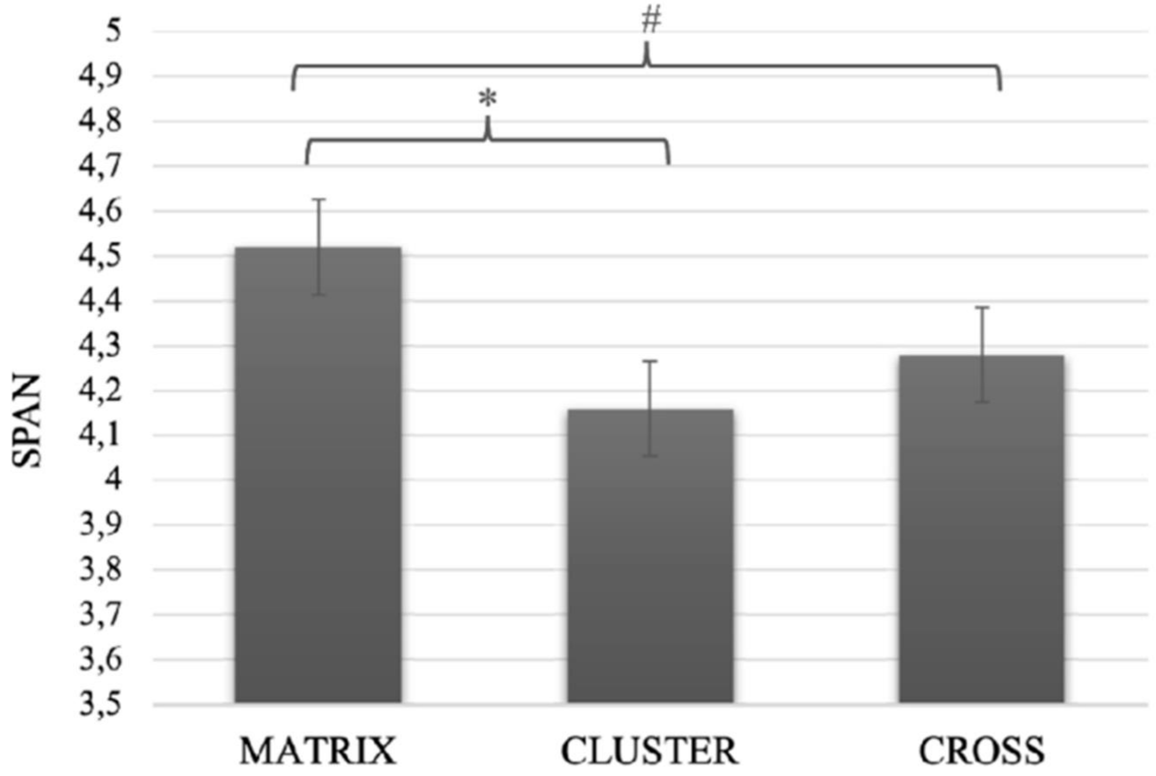

Figure 10. Differences between spatial configurations in BGT (D'Aurizio et al., 2023). */# = $p \leq 0.05$

2.4. How to Test Visuospatial Working Memory Dynamically

In the previous sections, we delved into the significant role that the environment plays in shaping cognitive processes, with a particular focus on visuospatial working memory (VSWM). We emphasized the importance of investigating how environmental demands interact with VSWM, especially in tasks requiring spatial orientation, as these are crucial for real-world navigation and daily functioning (Blacker et al., 2017). Traditional methods of assessing VSWM, primarily through behavioural neuropsychological tasks, have proven effective in controlled experimental settings. However, despite their utility, these tasks often fall short in terms of ecological validity—they do not fully capture the complexities of real-world environments (Passarello et al., 2024a). Conversely, instruments that strive for greater ecological validity, aiming to simulate more realistic scenarios, frequently lack the necessary control over confounding variables, potentially undermining the precision of the assessments (Holleman et al., 2020).

Recognizing this gap, we sought to create an assessment tool that strikes a balance between ecological validity and scientific rigour. This tool -the Bricks Game Task-, presented as a game to engage children, was designed to simulate different spatial configurations and more accurately reflect the dynamic nature of real-world spatial tasks (D'Aurizio et al., 2023). While this is a significant step forward, challenges remain, particularly in how to assess spatial orientation and VSWM in environments that change continuously and dynamically—contexts that more closely resemble real-life situations where individuals must constantly adapt to their surroundings. Imagine driving in an unfamiliar city, where you must constantly adapt to new traffic signs, intersections, and buildings while navigating towards your destination. As you make turns and encounter unexpected detours, your mental map of the environment must be continuously updated. In this scenario, spatial orientation and VSWM are essential to avoid wrong turns and recalibrate your route. Traditional assessments of VSWM, which often use static or simplistic tasks, fall short of capturing the complexity of this real-world scenario where environments are in constant flux.

These open questions form the foundation for the third part of this thesis, where we introduce a novel assessment instrument aimed at addressing these concerns. However, before introducing this tool, it is crucial to explore two key concepts that underpin this effort: the use of virtual reality (VR) as a medium for assessing cognitive functions, including VSWM, and the broader concept of ecological validity, which seeks to bridge the gap between experimental control and real-world applicability.

2.4.1 Visuospatial Working Memory Assessment in Virtual Reality

Virtual reality (VR) has gained significant popularity over recent years, emerging as a valuable tool not only for entertainment but also for research and clinical applications. Its immersive and interactive nature offers researchers a unique opportunity to simulate real-world environments with high precision, allowing for controlled experimentation that would be difficult to achieve in traditional settings (Palombi et al., 2022). One of the key advantages of VR is its ability to create dynamic, complex, and customizable scenarios that can closely mimic everyday experiences. This flexibility makes VR an appealing option for assessing cognitive functions, as it allows researchers to control for confounding variables while maintaining ecological validity. Moreover, VR enables researchers to track detailed data on users' movements, behaviours, and responses in real time, providing a rich source of information for cognitive studies (Slater 2009).

The success of VR technology is primarily driven by three critical factors: immersion, sense of presence, and interaction.

1. Immersion: VR systems are designed to replicate real-world stimuli through a combination of visual, auditory, and sensory feedback (Slater et al., 1996; Slater & Wilbur, 1997). The integration of hardware and software elements enables the creation of detailed and responsive virtual environments that enhance the user's feeling of being physically present in the virtual world (Al-Jundi & Tanbour, 2023). Immersive experiences are achieved through different types of VR systems, ranging from non-immersive 2D environments to highly immersive head-mounted displays (Cipresso et al., 2018).
2. Sense of Presence: presence refers to the users' psychological and emotional experience of being in a virtual environment, where they interact and respond to stimuli as if they

were in the real world (Cipresso et al., 2018; Heeter, 1992). This phenomenon involves spatial awareness, depth perception, and the overall sensation of physical involvement in the virtual space (Coelho et al., 2006). Researchers argue that presence is a subjective outcome of immersion, influenced by the technical features of VR systems (Slater & Wilbur, 1997). The heightened sense of presence improves the realism and effectiveness of VR experiences, fostering deeper user engagement (Palombi et al., 2022).

3. Interaction: Interaction with the virtual environment is a fundamental aspect of VR technology. Users can engage in a range of activities, from simple observations to complex manipulations, using input devices like controllers or more immersive tools such as gloves or motion-tracking systems (Li et al., 2019). This ability to interact realistically with the virtual world enhances both immersion and presence, making VR a powerful tool for applications across gaming, education, therapy, and more (F.-Q. Chen et al., 2020).

By integrating these three elements—immersion, presence, and interaction—VR systems offer a highly effective and engaging platform for simulation, learning, and experience enhancement. Thanks to the development of VR, significant progress in scientific literature led to the creation of clinical systems for surgery, telemedicine, and human spatial navigation (Iggena et al., 2023; K. W. Kim et al., 2023; Mantovani et al., 2020). As VR technology advanced, research increasingly focused on clinical applications, particularly in rehabilitation and neurosurgery, supported by innovations in hardware like Head-Mounted Displays (HMDs) and software development (Rizzo & Koenig, 2017). This shift resulted in bespoke VR programs tailored to meet specific needs in various domains, including healthcare, education, and industrial sectors (Cipresso et al., 2018). VR's immersive capabilities have since revolutionized fields such as psychology and neuroscience, enabling researchers to study complex cognitive processes, including memory, motor control, and spatial navigation (Bohil et al., 2011; Georgiev et al., 2021). Additionally, VR's controlled and adaptable environments have proven invaluable in therapeutic interventions, particularly for anxiety, phobias, and stress-related disorders, by simulating safe, anxiety-inducing situations for treatment (Botella et al., 2017). Moreover, VR interventions have shown promising results in enhancing cognitive functions across various populations. For instance, studies have demonstrated that VR exergaming can improve cognitive skills in young adults, particularly in areas such as selective attention, inhibitory processes, and observational skills (Palombi et al., 2022). The immersive nature of VR seems to stimulate these cognitive functions more effectively than traditional tasks, possibly because it requires participants to engage more deeply with their environment. Similarly, VR has proven beneficial for older adults with mild cognitive impairment. Research has shown that VR-based rehabilitation programs lead to significant improvements in orientation, visuospatial perception, visuomotor organization, thinking operations, and attention/concentration when compared to conventional cognitive rehabilitation methods (Torpil et al., 2021). The interactive and dynamic features of VR may help stimulate these cognitive processes more intensely, offering a novel way to engage older adults in cognitive training.

In children with hemiplegic cerebral palsy, VR interventions have been linked to greater improvements in spatial perception, praxis, visuomotor construction, and thinking operations (Kim et al., 2023). VR's ability to simulate real-life tasks and challenges in a controlled environment allows children with motor and cognitive impairments to practice these skills in a more engaging and adaptive way. The repeated exposure to spatial challenges within a virtual world seems to contribute to their cognitive development, offering a safe space to practice and improve.

Neuroscientists have also harnessed VR technology to gain deeper insights into brain function.

VR’s ability to create complex, controlled environments is essential for studying neural responses to various stimuli and tasks (Georgiev et al., 2021). Memory research particularly benefits from VR by enabling the simulation of real-world scenarios in controlled settings, crucial for understanding memory processes (Sauzéon et al., 2012). Additionally, VR aids in studying motor control, where virtual tasks requiring precise movements help researchers analyse brain-body coordination, which is invaluable for developing treatments for motor impairments (Levac et al., 2019; Tieri et al., 2018). VR is also used to study cognitive processes like attention, perception, and decision-making, where immersive and engaging environments may lead to more accurate data (Bohil et al., 2011).

One of the major strengths of VR-based experiments is their potential to replicate everyday situations with high fidelity, thus enhancing the ecological validity of cognitive assessments and rehabilitation (Negut, 2014). Traditional neuropsychological assessments often lack this real-world relevance, limiting their applicability to daily functioning. VR fills this gap by providing immersive environments that closely mirror the complexity and unpredictability of real-life scenarios. For this reason, VR technologies have been used extensively to assess spatial navigation abilities (Moffat et al., 1998; Palombi et al., 2022). In the domain of spatial navigation, VR enables the design of virtual mazes, shedding light on neural pathways involved in spatial awareness and memory formation. A significant contribution to the field is the research conducted by Cipresso et al. (2018), which emphasized the extensive application of VR in navigation studies. Several studies have shown that VR-based tasks can effectively assess large-scale navigation abilities and reveal age-related and dementia-related differences in spatial memory and route learning (Zakzanis et al., 2009). VR also allows for the manipulation of sensory information, such as using auditory cues for navigation in the absence of visual input (Fialho et al., 2023). This versatility makes VR an invaluable tool for examining the neural underpinnings of spatial navigation and developing potential rehabilitation strategies for individuals with navigation difficulties(Jeung et al., 2023).

Further, evidence indicates that VR-based learning activities can significantly improve spatial visualization skills compared to traditional methods (Molina-Carmona et al., 2018). VR offers unique advantages for assessing, training, and rehabilitating spatial abilities by providing dynamic 3D environments and precise measurement of user interactions (Kaufmann et al., 2005). Studies have demonstrated that interactive VR can be especially beneficial for developing spatial abilities in low-ability learners, although it may also favour high-ability learners in some cases (Gittinger & Wiesche, 2023). Researchers have developed VR-supported spatial ability tests that measure the ability to visualize and mentally manipulate 3D objects directly in virtual space, potentially offering higher ecological validity than traditional tests (Kaufmann et al., 2005). These advancements suggest that VR technology holds significant potential for improving spatial abilities across various applications and user groups. As for VSWM, studies have shown that working memory capacity significantly influences spatial memory performance in VR tasks (Castillo Escamilla et al., 2020). Both verbal and spatial working memory components are involved in route learning within virtual environments, with their engagement depending on task perspective and individual visuospatial abilities (Gras et al., 2013). VR has been utilized to develop novel assessments for visuospatial memory, such as the Hidden Objects Test, which may be particularly relevant for detecting impairments in Alzheimer's disease (Kim et al., 2023). Additionally, VR paradigms have been employed to induce negative memories, which can then be targeted for degradation using dual-task approaches. One study found that a visuospatial task performed while recalling VR-induced memories reduced their emotional intensity, suggesting potential applications in clinical settings (Cuperus et al., 2016).

In conclusion, VR shows great promise as a tool for testing VSWM in realistic spatial orientation scenarios. By creating immersive environments, VR can simulate complex situations that reflect real-world navigation challenges, enhancing ecological validity and providing valuable insights into cognitive processes. This innovative approach has the potential to deepen our understanding of VSWM and inform interventions for individuals with spatial awareness difficulties.

2.4.2. The Issue with Ecological Validity

In the previous paragraphs, we extensively discussed ecological validity and its importance in testing VSWM. However, to fully appreciate the implications of ecological validity in psychological research, it is essential to delve deeper into this construct. Ecological validity has emerged as a critical concept that bridges the gap between laboratory findings and real-world applications, yet it remains a topic of considerable debate and critique among researchers (Holleman et al., 2020).

Scholars like Brunswik (1943) and Barker (1968) have argued that laboratory experiments often isolate narrow aspects of psychological phenomena that do not reflect broader life patterns, while others, such as Neisser (1991) and Bronfenbrenner (1979), have noted that the artificial conditions of such experiments can yield results that are difficult to generalize. This has led to what is known as the 'real-world or the lab'-dilemma, posing a crucial methodological question about whether psychological research should prioritize generalizability to real-world scenarios or maintain traditional lab paradigms (Hammond & Stewart, 2001).

Over the past few decades, researchers have increasingly emphasized ecological validity as a way to address these limitations, advocating for research designs that more accurately reflect the complexities of everyday life (Dunlosky et al., 2009). However, the concept of ecological validity has become muddied with varying interpretations, making it challenging to establish clear definitions and criteria (Hammond & Stewart, 2001). Traditionally, ecological validity refers to the extent to which research findings can be generalized from controlled laboratory settings to more naturalistic environments (Schmuckler, 2001). While this notion underscores the importance of studying psychological phenomena in contexts that closely resemble real-life situations, its application often lacks clear criteria. Some definitions of ecological validity emphasize the need for research to resemble real-world situations to ensure generalizability (Schuster et al., 2015), while others suggest that ecological validity should be determined by the appropriateness of the research context based on theoretical considerations (Bronfenbrenner, 1979).

In fields like neuropsychology, ecological validity has been linked to external validity, focusing on whether cognitive assessments predict functional impairments in daily life (Gibson, 2014a). Consequently, there have been efforts to enhance the ecological validity of psychological research by developing measures that relate closely to real-world tasks, integrating behavioural observations, and utilizing technologies such as VR to create more authentic assessment environments (Parsons, 2015; Parsons et al., 2017).

In a review by Holleman et al. (2020), it is emphasized how researchers must specify and describe the particular contexts of behaviour they investigate, instead of solely attempting to understand cognitive and behavioural functioning in 'real-world' contexts (Hammond & Stewart, 2001). The real challenge lies in developing a theory that connects specific environmental contexts to various forms of cognitive and behavioural functioning. Tolman and Brunswik (1935) emphasized that the nature of the environment, as perceived by the organism, is inherently uncertain. The organism interprets its environment through an array of proximal 'cues' and 'signs' (i.e., sources of information) that serve as 'local representatives' of various distal objects and events. To function efficiently, the organism must accumulate, combine, and substitute, the information gleaned from these cues and signs, enabling it to adjust its means to achieve behavioural goals, such as finding food or shelter. However, given the probabilistic and partially unpredictable nature of the environment, the organism must continually update its assumptions based on available information (Tolman & Brunswik, 1935).

Barker (1968) further elaborated on this idea with his concept of ‘behaviour settings’, which describes how the environment shapes the frequency and occurrence of human cognition and behaviour. Behaviour settings arise from the collective actions of groups of individuals and can be defined by their geographical locations (e.g., supermarkets, cinemas) and specific temporal and physical boundaries (e.g., opening hours, entrances). These settings are independent of an individual’s subjective experience, yet the activities within them exhibit a high degree of interdependency and similarity among individuals (e.g., most people in a supermarket are shopping, while those in a cinema are watching movies).

Gibson (2014b) proposed a strong mutuality and reciprocity between the organism and its environment, introducing the concept of ‘affordances’ to describe how individuals can directly perceive the inherent ‘meaning’ of objects (i.e., their functional significance). For instance, a firm, smooth surface may afford walking, running, or dancing, whereas a rough, cluttered surface does not (Heft, 2016). Affordances, thus, are properties of the organism-environment system; they represent perceiver-relative functional qualities that depend on specific environmental features and the capabilities of the individual (Holleman et al., 2020).

The study presented in the next chapter aims to directly address the principles discussed earlier. We seek to provide a more realistic evaluation of visuospatial working memory (VSWM) by creating not only an immersive and realistic environment but also by testing this cognitive process within an action-oriented context—specifically, navigating a maze. This approach allows us to examine how individuals utilize their VSWM in real-time, engaging with their surroundings as they actively seek their way through the maze. By doing so, we aim to deepen our understanding of VSWM and its practical applications, highlighting the crucial interplay between cognitive processes and environmental contexts.

3. Testing Visuospatial Working Memory in a Dynamic Environment: the Radial Arm Maze Task

3.1. Background

As emphasized earlier, there is a clear need in the literature for studies and methods that focus on testing cognitive processes in contexts that naturally elicit them. Visuospatial working memory (VSWM) is known to be crucial for spatial navigation, but the key challenge lies in how to effectively test it. While numerous spatial navigation tasks exist in the literature, many of these tasks are performed in controlled laboratory settings that predominantly focus on the peri-personal space—the immediate area surrounding the individual (Foti et al., 2020; Mandolesi et al., 2009). However, this approach is insufficient for capturing the full complexity of VSWM, particularly in relation to real-world navigation tasks (Sauzéon et al., 2012). Laboratory tasks often limit participants to static or small-scale environments, and fail to reflect the dynamic, constantly changing nature of real-world navigation. These tasks lack the element of movement through space and rarely involve interaction with distant environmental cues or alterations in the environment itself, such as changes in landmarks or the layout of the surroundings (Kelly et al., 2008). Additionally, because they focus on peri-personal space, laboratory tasks typically neglect the broader spatial elements necessary for navigation over larger distances, which are critical for testing how VSWM supports navigation beyond the immediate vicinity (Blacker et al., 2017).

Moreover, without the ability to introduce dynamic changes to the environment—such as moving objects, shifting pathways, or varying spatial configurations—these tasks fail to capture the adaptability of VSWM. In real-world navigation, an individual constantly updates their mental representation of space as they move and encounter changes in the environment, which is a core function of VSWM that cannot be adequately examined in static, limited settings. Therefore, current lab-based spatial navigation tasks do not fully engage the complexities of this cognitive process, nor do they offer insight into how individuals use VSWM in more ecologically valid, real-world situations (Parsons et al., 2017).

Some limitations in traditional laboratory tasks, can be addressed through the use of virtual reality (VR). VR allows researchers to create immersive, dynamic environments where individuals can interact with large-scale spaces and experience realistic environmental changes, all while maintaining control over experimental variables. This makes VR an ideal tool for studying visuospatial VSWM and spatial navigation in more ecologically valid contexts. Several spatial tasks have already been implemented in virtual environments. For example, Iggena et al. (2023) used a VR version of the Morris Water Maze task to compare the navigation patterns; Castegnaro et al. (2022) used Object Location Memory Tasks to test the ability to remember the location of objects within a virtual space; Ruddle et al. (2013) evaluated how well individuals can orient themselves in a virtual space through the Spatial Orientation Tasks; Lochhead et al. (2022) used the Immersive Mental Rotation Task assessed how VR-based visualizations impact mental rotation performance.

In line with all this evidence—and given the potential of VR to address key limitations in traditional methods—we chose to implement the Radial Arm Maze (RAM) (Olton et al., 1979) in our study.

3.1.1. A Non-conventional VSWM Task: The Radial Arm Maze

The Radial Arm Maze Task (RAM) (Olton et al., 1979) was originally developed to investigate spatial memory in rodents, using a central platform from which eight identical arms radiate outward. The difficulty of the task is influenced by the number of arms. Over time, the task has been adapted for humans in a variety of settings (Leplow et al., 2003). In these adaptations, the participants—often children—are rewarded with small tokens like toys or coins hidden at the end of each arm. RAM paradigms are designed to assess different types of spatial memory processes by manipulating environmental cues and task parameters.

The two primary paradigms in RAM tasks are the *free-choice* and *forced-choice* versions (*Figure 11*). In the *free-choice* version, the subject's aim is to collect all the rewards from the maze while avoiding revisiting previously explored arms. This version relies on memory and spatial mapping, requiring efficient exploratory strategies (Foti et al., 2020; Leplow et al., 2003; Palombi et al., 2022; Passarello et al., 2024b). Historically, the *free-choice* RAM has been a popular tool for assessing working memory. However, the performance in this task can also reflect the procedural strategies used by individuals to explore the maze, such as repeating specific sequences or relying on spatial cues in the environment (Foti et al., 2020; Mandolesi, Addona, et al., 2009; Mandolesi et al., 2003; Mandolesi, Petrosini, et al., 2009). These strategies allow researchers to evaluate the cognitive mapping abilities of individuals, which are crucial for understanding spatial navigation and memory processes.

The *forced-choice* version of the RAM, on the other hand, focuses specifically on VSWM by splitting the task into two phases. In the first phase, the subject collects rewards from only a subset of the arms, while others remain inaccessible. In the second phase, they must collect the remaining rewards, relying on their memory of which arms they visited earlier. The forced-choice paradigm removes reliance on exploratory strategies, isolating the working memory component (Iaria et al., 2003; Overman et al., 1996).

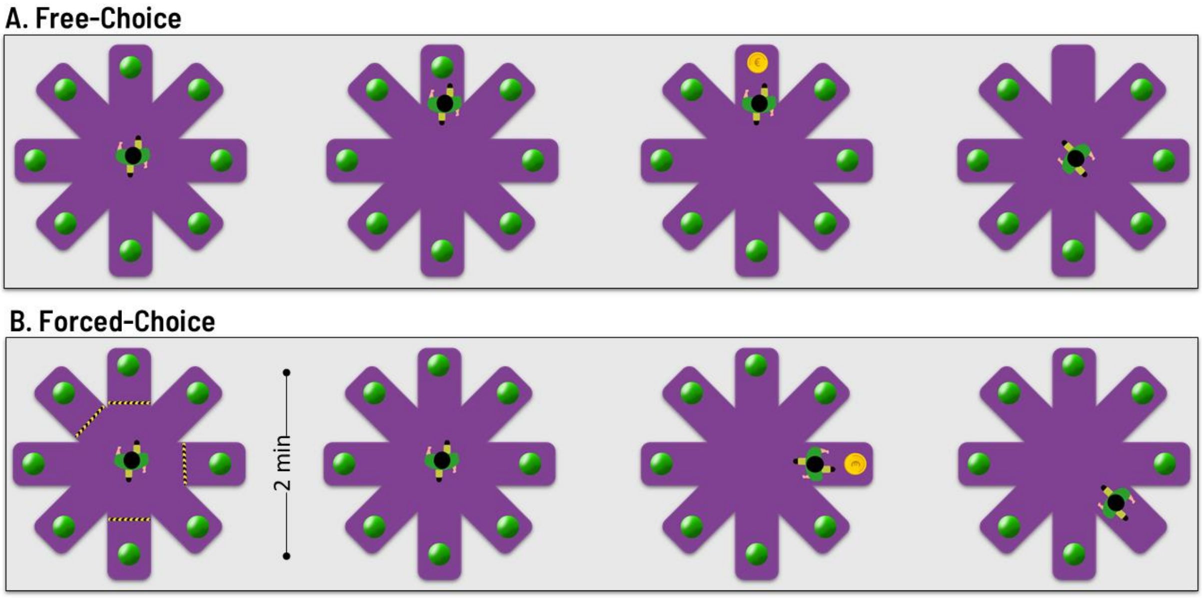

Figure 11. Conceptualization of RAM *free-choice* **(A)** and *forced- choice* **(B)** paradigms**.**

Both RAM paradigms can be further divided into cued and un-cued versions. In the cued version, each arm contains visual stimuli that guide subjects toward rewards, favouring a strategy that relies on external visual cues. In contrast, the un-cued version requires subjects to use distal environmental cues to navigate, promoting the development of a cognitive map, a strategy known as allocentric navigation (Leplow et al., 2003).

The adaptability of RAM paradigms has made them suitable for a wide variety of research contexts, from exploring developmental differences in children to investigating clinical populations with spatial memory deficits. The RAM task can also be used to study the interplay between declarative and procedural memory processes through an analysis of the subject's exploratory strategies, such as whether they rely on environmental cues, follow a consistent path, or create a flexible cognitive map of the environment.

Recent developments include a tabletop version of the RAM task designed to examine visuospatial peri-personal abilities, which involve the interaction between the body and objects within arm's reach. For instance, the "Ladybug game" requires children to navigate a maze by moving a central figure to find hidden "sisters" (Foti et al., 2020; Passarello et al., 2024b) (*Figure 2)*. This tabletop version simplifies the task, making it ideal for younger children or populations with cognitive impairments. The task is small-scale, emphasizing interactions within peri-personal space, which elicits complex integration of motor, perceptual, and cognitive processes, and has applications in assessing and improving spatial skills. Research has demonstrated that peri-personal space stimuli activate multiple cognitive and motor processes, further supporting the RAM's utility in studies of motor perception and spatial navigation (Serino, 2019).

Moreover, RAM's applications extend beyond the physical world, with virtual reality (VR) adaptations offering new possibilities for exploring spatial cognition in immersive environments. Virtual RAM (vRAM) paradigms allow researchers to replicate the task in controlled virtual spaces, which has shown promise in the rehabilitation of spatial memory deficits and the assessment of spatial learning in more realistic, ecologically valid settings. With VR, participants can experience a fully interactive, customizable environment, offering greater flexibility and personalization in neuropsychological assessments and training protocols (Bohbot et al., 2017)). In this context, RAM tasks can bridge the gap between laboratory settings and real-world environments, making them a valuable tool for both research and clinical applications in spatial memory and navigation.

In line with the above, several studies have developed different VR versions of RAM. However, the choice of method in developing software to reproduce the virtual environment would depend on the specific requirements of the spatial navigation study. A study conducted by Iaria et al. (2003) used the Unreal Tournament 3D game engine to implement a custom-made level containing the maze. Their approach is minimal, as the operator must manually track the participant’s movements and actions, which can lead to errors and reduce accuracy. Certain data, such as the participant's time in each maze arm, is difficult to measure accurately by hand. Additionally, the software offers no interface for maze configuration; modifications must be done manually in the configuration files. Actions are recorded using external video capture software, which may hinder computer performance. While the app allows participants to familiarize themselves with the controls, the process is not as polished compared to other implementations, such as the one in which software guides the participant through each aspect of the task (Iaria et al., 2003).

Marsh et al. (2010) implemented a virtual environment using C++ and OpenGL, a low-level 3D graphics library. The application includes a training section that allows participants to become familiar with the maze, but it is unclear whether instructions were provided internally by the software or externally via voice or paper. In this version, participants are teleported back to the maze's centre once they reach the end of an arm, and their orientation is randomly altered. The game can automatically scramble the background image, and the position of participants is recorded every 50 milliseconds. However, it remains unclear if other data is logged and in what format (Marsh et al., 2010).

Another study by Taheri Gorji et al. (2021) developed a virtual RAM using the open-source software Maze Suite to create a 3D maze environment. The game logs the participant's position and orientation into a text file, requiring a post-experience model to analyse behaviour. The maze has a fixed structure with six arms, and no alternative configurations are possible. This version does not provide replays of the participant's actions, nor does it support any distraction activities. Although a tutorial section allows participants to familiarize themselves with the movement keys, the game logic deviates from the classic RAM task and is divided into multiple stages, which include an object recognition task in addition to orientation (Taheri Gorji et al., 2021).

While the aforementioned versions do not support VR headsets, Kim et al. (2018) designed a virtual RAM system that does, allowing traditional keyboard and mouse input as well. This version not only logs the player's position and orientation but also tracks errors, travel distance, and timing. The training session takes place in the maze and lasts five minutes, after which the actual experiment begins. However, the maze is not customizable to accommodate different experimental conditions, and the software lacks an integrated replay mode. Surveys related to the participant’s experience are completed outside the game, limiting real-time feedback (Kim et al., 2018).

While existing VR approaches for spatial navigation studies, including virtual RAM, have contributed significantly to the field, there is still a need for refinement in terms of user interaction, data collection accuracy, flexibility, and immersion. Many virtual RAM implementations lack intuitive user interfaces, leading to a less engaging experience for participants, which could affect the reliability of the collected data. Another critical issue is the accuracy of behavioural data collection. Many systems do not capture detailed movement patterns, gaze direction, or decision-making processes, which are vital for understanding spatial navigation and memory. Furthermore, the fixed maze structures in many virtual environments limit the scope for customization, restricting their use in varying experimental conditions. Lastly, most RAM studies employ non-immersive VR approaches, and the shift toward fully immersive VR offers an opportunity for future improvements in the ecological validity and participant engagement of these tasks.

Another issue with previous research on RAM lies in the evaluation methods used to assess performance, which are often limited in capturing the full range of cognitive processes involved in spatial navigation. For the *free-choice* version of the task, classical parameters typically include:

- Total time (in seconds): Time spent completing the task;
- Latency of the first arm visit (in seconds): Time it takes to visit the first arm;
- Number of entries: Total number of arms entered;
- Number/ proportion of errors: Incorrect entries into previously visited arms;
- Spatial span: The longest sequence of correctly visited arms.

Whereas, in the *forced-choice* version, performance is evaluated through:

- Total time (in seconds): Time spent completing Phase 2 of the task;
- Latency of the first arm visit (in seconds): Time it takes to visit the first arm Phase 2;
- Time it takes to visit the first arm in Phase 2;
- Number of entries in Phase 2: Total number of arm entries in Phase 2;
- Spatial span of Phase 2: Longest sequence of correctly visited arms in Phase 2;
- Number of / proportion of Errors: Re-entries into arms that were already visited in Phase 2.

These parameters, while useful, are somewhat problematic because they primarily focus on certain aspects of VSWM, such as spatial span, but they fail to capture the exploratory aspect of RAM. For instance, Foti et al. (2020) attempted to address this limitation by analysing exploratory strategy through the proportion of 45-degree angle entries, which involves a participant moving sequentially from one adjacent arm to another (Foti et al., 2020; Mandolesi et al., 2009; Mandolesi et al., 2009). This strategy is thought to rely less on memory processes and more on procedural actions. However, this and other studies missed a key feature of the RAM: its ability to dynamically assess how participants represent and update their spatial environment during exploration.

The true value of RAM lies in its capacity to engage participants in a continuous process of exploration and VSWM updating. As individuals explore the maze, they are constantly storing new information about the space around them and updating their spatial representation with each new entry into an arm. Importantly, these updates are based on whether the entry is correct (reward) or incorrect (no reward). This is in line with the concept of VSWM being dynamic, constantly integrating new spatial information as participants explore the environment (Garden et al., 2002).

For example, making an incorrect entry early in the task, when the spatial representation is still forming, is fundamentally different from making an error later in the task, when the participant has a clearer understanding of the space. The nature of the error also changes when participants have already completed the task - visiting all arms, and collecting all rewards-, and continue exploring. Take, for instance, three participants, they all make one error during the exploration: participant A makes an error at their second entry; participant B at their sixth entry; and participant C after having already collected all the rewards, continuing to explore and make repeated mistakes. In this scenario, there is a clear difference in the nature of the errors made by each participant, reflecting how their recall of spatial information in visuospatial working memory (VSWM) differs:

- Participant A likely lacks a well-formed spatial representation of the maze, as they are still in the early stages of exploration. Their VSWM is not fully engaged, resulting in a mistake that could be attributed to limited knowledge about the environment. This initial error could stem from uncertainty or a failure to encode relevant spatial information adequately.
- Participant B has had more opportunities to explore the maze and should have formed a more robust mental representation of the space. However, they still made a mistake,

indicating potential lapses in memory-based recall or difficulties in updating their spatial understanding.

- Participant C likely relies on a procedural strategy rather than VSWM. Their decision to navigate by entering adjacent arms may reflect a more automatic, chance-driven approach rather than a conscious recall of spatial information. In this case, they are not actively engaging their memory, but instead following a repetitive pattern that does not incorporate previous experiences, similar to one explained by Foti et al. (2020). Thus, while they continue to explore, their actions are not informed by a dynamic updating of spatial representations, highlighting a distinct absence of memory-based recall in their navigation strategy.

Using classical RAM evaluation parameters, these differences in navigational strategies would not be effectively highlighted. Traditional measures focus primarily on quantifiable outputs, without capturing the underlying cognitive processes involved in spatial navigation. All three participants might receive similar scores if evaluated solely on the number of errors or time taken to complete the task, leading to a misleading interpretation of their spatial memory performance.

To truly understand the complexities of spatial navigation and the dynamic nature of VSWM, there is a need for assessments that differentiate between these exploratory strategies. Evaluating not just the outcome but also the process—how participants navigate, the strategies they employ, and how they update their spatial representations—will provide a richer understanding of their spatial memory capabilities.

3.1.2. Study Aim

This study was carried out thanks to the joint forcest of the Experimental Psychology Lab (Federico II, University of Naples) and the Health and Sport Psychology Lab (Sapienza, University of Rome). The primary aim of this study is to assess visuospatial working memory (VSWM) in a more comprehensive manner through the implementation of a navigational task: the Radial Arm Maze (RAM. By utilizing virtual reality (VR), we aim to enhance immersivity and facilitate the exploration process, thereby allowing participants to develop a more accurate representation of their spatial environment within their VSWM.

To achieve this, we seek to identify new parameters for evaluating performance that reflect the nuanced cognitive processes involved in spatial navigation and memory recall. Specifically, we tested 60 participants (mean age 24.72 ± 2.57) in two versions of the vRAM: the *free choice* version (vRAM-Free), which promotes exploratory behaviour (Experiment 1), and the *forced choice* version (vRAM-Forced), which aligns more closely with traditional VSWM paradigms (Experiment 2). This dual approach enables us to investigate the relationship between VSWM and spatial navigation.

In Experiment 1, we tested participant in the vRAM-Free across two trials. We also introduced a novel index that incorporates the weights of each entry and error (Weighted Performance Index, WPI), merging navigational elements with VSWM capacity assessment. Alongside this, we employed Cowan’s K (K_c) (Cowan, 2001) to measure VSWM capacity and examined the use of procedural exploration strategies to evaluate their relationship with our new index. Additionally, we analysed learning effects between Trial 1 and Trial 2 and administered the Corsi Block Tapping Test (CBTT) (Corsi, 1972) and a modified Five-Point Test (m-FPT) (Cattelani et al., 2011) to explore potential connections with the WPI, while also utilizing the Raven's Advanced Progressive Matrices (APM) (Raven, 1962) to establish a baseline of participants’ general cognitive abilities. Furthermore, we implemented a battery of self-report questionnaires to assess participants' experiences within the VR environment. In Experiment 2, we assessed the same participants using the vRAM-Forced across two trials, evaluating classic VSWM capacity through the K_c. We compared these results with traditional assessments (CBTT; m-FPT) to study the associations between RAM performance and these classic measures. Additionally, we continued to examine learning effects between Trial 1 and Trial 2 and explored the relationships between the *free* and *forced* choice paradigms, aiming to deepen our understanding of the interplay between VSWM and spatial navigation processes.

3.2. Method

3.2.1. Software development

The developed virtual version of RAM allows running the test on any consumer-level desktop computer equipped with a VR headset, even in a tiny physical space. Additionally, it does not require any particular skill to supervise the test, as the software measures every aspect of the experiment, allowing playback of the individual’s actions and storing data into multiple files for further analysis. The app can be connected to an external smartwatch (i.e., Microsoft Band) to monitor the individuals’ heartbeat and skin conductance during the simulation. Finally, our vRAM version can be easily configured by, for example, changing the arms' size in terms of the height and length of the arms for running the test on children or clinical individuals. Further, an immersive VR version of the RAM has the following advantages: to reduce the space in which the experiment can be conducted, as participants can use controllers to move around in the maze; to provide a consistent environment across participants, thus removing the influence of external landmarks on the experiment; to add different types of cues and landmarks both inside and outside the maze; to be easy to be run by the operator, as menus and views can facilitate the RAM setup; to be cost-effective as the game can run on cheap hardware, VR headsets are becoming increasingly cheaper every year, and the rendering requirements are low enough that even a mid-range GPU one or two generations old can run the game without stutters.

3.2.2. Sampling

The study sample comprised 60 individuals (mean age 24.72 ± 2.57), all students at Sapienza University of Rome. Participants were selected based on the following criteria: fluency in Italian, absence of major medical or neurological conditions such as dementia, traumatic brain injury, or schizophrenia, and no current psychiatric disorders, including major depression. Additionally, participants with severe sensory or motor impairments that could interfere with their ability to interact with VR devices were excluded. These inclusion and exclusion criteria were assessed through a self-reported questionnaire administered during recruitment, followed by a brief interview conducted after obtaining informed consent.

Ethical approval for the study was granted by the Ethical Committee of the Department of Psychology of Developmental and Socialization Processes at the University of Rome, in accordance with the guidelines of the Declaration of Helsinki. All participants provided written informed consent, which outlined the potential risks associated with virtual reality usage. Participants were also asked whether they had experienced symptoms of motion sickness during previous VR exposures or when using other visual devices (e.g., televisions, video games).

3.2.3. Measures

3.2.3.1. Neuropsychological Assessment

Raven's Advanced Progressive Matrices (APM). We administered the APM set 1, which includes the first 12 matrices, to assess the typical development of all participants. APM requires the subject to replace the missing part of a model, based on increasing difficulty. The model figures consist of graphic patterns that change from left to right and top to bottom. To achieve the solution, the subject must understand the underlying logic and apply it. The total score of APM allowed us to evaluate abstract reasoning and global cognitive functioning in the participants (Raven, 1962).

Corsi Block-Tapping Test (CBT). The CBTT is a widely used neuropsychological tool designed to assess visuospatial working memory. The test involves a series of spatial sequences, where a sequence of blocks is tapped by the examiner, and the participant is then required to reproduce the sequence by tapping the same blocks in the correct order. The difficulty increases as the length of the sequences progresses. This task evaluates an individual's ability to temporarily store and manipulate visuospatial information in their working memory, providing valuable insights into their visuospatial processing and organizational skills (Corsi, 1972).

Modified Five-Point Test (m-FPT). The m-FPT is a reliable non-verbal measure that assesses executive functioning by evaluating participants' graphic-figural fluency (Fernandez et al., 2009). This test measures an individual's ability to produce unique geometric drawings within a specified time interval of 3 minutes (Cattelani et al., 2011). The m-FPT involves an A4 sheet with 40 square matrices, each containing five dots positioned at the vertices and one in the centre. Participants are instructed to connect two or more dots within each square using straight lines, while adhering to specific rules such as avoiding repeated shapes and lines that do not connect the dots. The m-FPT provides insights into three subdomains of executive functions: flexibility, rule-breaking, and strategic performance. Several parameters were evaluated, including the number of unique drawings (UDs), produced without breaking the rules or repeating shapes; the error index (IE) calculated as the number of drawings with errors divided by the total number of drawings multiplied by 100; the number of drawing performed with a cognitive strategy (DSs) (i.e., rotate the same pattern; add or subtract elements to the pattern);

and the strategy index (ISs) calculated as the number of drawings with strategy divided by the number of unique drawings.

3.2.3.2. Radial Arm Maze in VR (vRAM)

The vRAM apparatus consisted of a round central platform with eight arms (each arm is 6 meters long; arm walls can vary between 0.5 and 2 meters, with a step of half a meter). At the end of each arm, there was a green plastic bucket (18 cm wide, 9.28 cm high) containing the reward (a coin). The RAM was located in a large virtual garden, participants saw a cloudy sky above their head and heard birds chirping (*Figure 12*).

The VR RAM application run smoothly at XX FPS on an Intel i7 3.7GHz Gaming Desktop, with 16 GB RAM and an NVIDIA GeForce GTX1070 8 GB graphic card. The Oculus Quest 2 head-mounted display allows users for a fully immersive virtual experience. The headset has a single fast-switch LCD panel with a per-eye resolution of 1832×1920 and a refresh rate of up to 120 Hz. The VR software was developed with Unity3D, a game development platform that provides native VR support on the Windows platform. Windows was the only possible choice, as all the other platforms lacked the support for VR headsets.

Users interact with the vRAM through the Oculus Quest 2 controllers. They use them to move forward and backward, while the left and right rotation is performed by physically rotating on the swivelling office chair they are sitting on. By constraining the left-right rotation to the physical movement, we expect to decrease movement sickness.

The application provides two views, one for the operator and another for the participant. The operator has a birds-eye view of the maze to monitor the patient's actions and some additional automatically computed data, such as the elapsed time, the number of errors (i.e., the number of times the user explores the same arm), the number of remaining rewards to be collected, and so on.

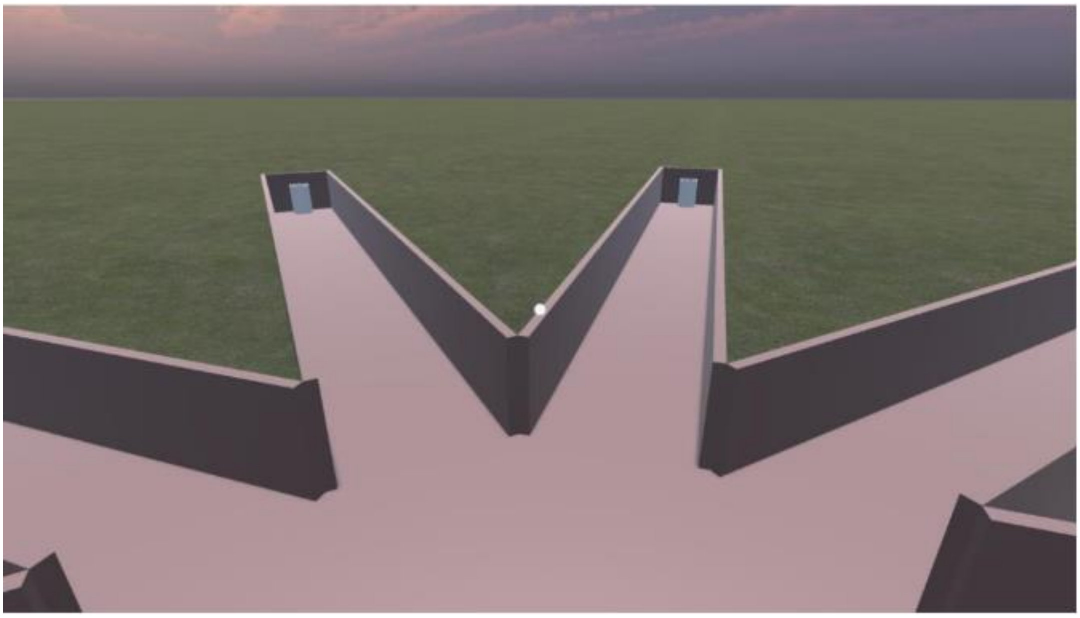

Figure 12. vRAM player interface.

Free-choice paradigm

In Experiment 1, participants were allowed to freely explore the eight arms to retrieve their rewards. A trial ended when: A) the participant stopped after all eight rewards had been collected; B) twenty entries had been made; C) A total time of 15 minutes had elapsed from the start of the task. Since the buckets were never rewarded twice, the optimal performance consisted of visiting each bucket only once. An error was made when the participant re-entered an arm already visited during the same trial. The participants practised collecting coins and moving around the virtual environment before beginning the trial. The training was allowed only before the *free-choice* trial. Participants were given the option of repeating it immediately or moving on to the trial. After the training, they saw (and heard) RAM instructions on the screen. Instructions stated: “This game is called vRAM. To win the game, you have to collect all the coins located at the end of each arm, inside the little baskets. After collecting the coin, you will have to return to the maze centre before visiting the next arm. Press the trigger button when you’re ready. Enjoy!”. The vRAM application automatically scored participant behaviour in the maze, recording entries (number of attempts); errors (re-enters in a previously visited arm); successes (rewards collected); movement patterns (if participant visited the adjacent arm); memory loads (the weight of each entry on the complete representation of the maze).

Parameters used to evaluate performance are the following:

- *VSWM capacity*: to test participants' VSWM capacity we used Cowan's K (K_c) (Cowan, 2001). K_c is a widely used formula to estimate working memory capacity, particularly in tasks that involve short-term retention of information. It is calculated as:

  $$K_c = N \times (H - FA)$$

  where N is the number of items presented (in vRAM it is 8 arms), H is the hit rate (proportion of correct responses; in vRAM it is the proportion of correctly visited arms), and FA is the false alarm rate (proportion of incorrect responses; in vRAM it is the proportion of re-enters/errors). K_c provides an index of how many items, on average, a person can store in their working memory. K_c accounts for both accuracy and potential guessing, making it a robust tool for evaluating the efficiency of working memory systems.
- *Procedural Strategy*: Procedural strategy was calculated as suggested by Foti et al. (2020), by measuring the proportion of 45-degree angle entries made during the participant's exploration movements. This metric indicates how often a participant moved to adjacent arms in the radial arm maze, consistently visiting neighbouring arms in sequence. Such a strategy is believed to reflect a reliance on procedural navigation rather than an integrated VSWM representation of the environment. In essence, when participants use this pattern, they may not fully engage VSWM to create a

comprehensive map of the maze but instead follow a simpler, automatic exploration process.

- *Checking Behaviour:* After participants finished the exploration phase and collected all available rewards, some continued to search for more rewards instead of stopping, displaying what we termed checking behaviour. In an exploratory approach, we decided to record this tendency using three variables: a binary variable indicating whether the participant engaged in checking (yes/no) (Checking Tendency), a continuous variable capturing the total number of checks made (Number of Checks), and a second binary variable indicating whether the participant revisited the first arm they had explored during their search (First Entry Check). Revisiting the first arm may reflect a strategic or cautious approach, possibly driven by expectations of the game (such as anticipating a game-over sign), while not returning to the first arm could suggest the participant lacks an integrated spatial representation of the environment.
- *Weighted Performance Index:* We created the Weighted Performance Index (WPI) as a measure for assessing performance in the vRAM. It represents the proportion of correct entries out of the total entries, but with an added complexity: each correct entry and each entry (whether correct or incorrect) are multiplied by their respective memory load. This memory load is a weight that reflects the significance of each entry in contributing to the participant's creation of a complete spatial representation of the maze. WPI can be expressed as:

$$WPI = \frac{\sum_{i=1}^{n} C_i \times W_i}{\sum_{1=1}^{n} E_i \times W_i}$$

where C_i is a correct entry at position *i; E_i* is a entry at position *i* (whether correct or incorrect); W_i is the memory load or weight associated with entry *i*, representing the contribution of that entry to the formation of the spatial representation.

The WPI, therefore, not only accounts for the accuracy of the entries but also emphasizes how crucial each entry is in forming a dynamic VSWM representation of the environment.

Forced-choice paradigm

In Experiment 2, each trial consisted of two phases. In Phase 1, only four of the eight arms (e.g. arms 1, 3, 4, 7) were reachable, and the remaining arms were closed by a wall. The spatial configuration of arms open and closed was randomly selected by the software. Participants were allowed to explore the four open arms. No training phase was planned for this trial. Instructions stated: "Let's play a different version of vRAM. To win the game, you have to collect all the coins located at the end of each arm, inside the little baskets. After collecting the coin, you will have to return to the maze centre before visiting the next arm. Be careful, some arms are closed by a wall. Press the trigger button when you're ready. Enjoy!". After completing Phase 1, they were guided out of the maze, in a neutral space, where they played a memory game for 120 seconds. At the beginning of Phase 2, participants saw instructions on the screen stating: "Something has changed. Now you can access all the arms. Go and find the missing coins. Press the trigger button when you're ready. Enjoy!". Only participants' behavioural parameters in Phase 2 were taken into account when evaluating their performance. In Phase 2, participants had to remember the spatial configuration explored in Phase 1 and collect the missing coins (located in the arms previously closed), while minimizing errors. The vRAM application automatically scored participant behaviour in the maze, recording entries (number of attempts); errors (re-enters in a previously visited arm); successes (rewards collected). In this iteration, the spatial pattern was fixed: participants explored a configuration consisting of four arms, followed by a retention phase during which they were outside the maze and could memorize the pattern. Upon returning, they were required to repeat the sequence in reverse order, navigating to the arms they had previously blocked since the remaining rewards were located there.

Given that the forced-choice version of the task resembles a more traditional VSWM task, we utilized only Cowan's K (Forced-K_c) to evaluate performance. The formula for calculating K_c remained the same as previously described, with the sole exception that the value of N was adjusted to 4, as there were four non-blocked arms to remember from Phase 1.

3.2.3.3. VR Self-report Questionnaires

Immersive Tendencies Questionnaire (ITQ). The ITQ is designed to measure how likely individuals become immersed in virtual environments. It evaluates aspects like focus, involvement in activities, and emotional engagement during immersive experiences. Higher scores on the ITQ indicate a greater capacity for immersion, which can influence how participants interact with and respond to VR tasks. The ITQ is often used in VR research to predict individual differences in user experiences within virtual environments. (Witmer & Singer, 1998).

Presence Questionnaire (PQ). The study participants completed the Italian version of the Presence Questionnaire to assess their sense of presence in virtual reality. The questionnaire consisted of 24 items that measured various aspects of VR experience, including realism, interface quality, ability to act, ability to examine, performance self-evaluation, and sound, using a 7-point Likert scale (Witmer & Singer, 1998).

Cybersickness Symptoms (CS). The Italian version of the VR Cybersickness Symptoms was used to assess the prevalence and severity of side effects caused by VR exposure. The symptoms evaluated included general discomfort, fatigue, boredom, drowsiness, headache, dizziness, concentration difficulties, and nausea. Participants reported the presence of these symptoms on a 6-point Likert scale, with higher scores indicating more severe symptoms (Solimini et al., 2011).

System Usability Scale (SUS). The SUS is a 10-item questionnaire that asks participants to rate their level of agreement/disagreement with positive and negative statements about the RAM test in VR, using a five-point scale ranging from strongly disagree to strongly agree. The SUS scores are then transformed into a single score ranging from 0 to 100, with higher scores indicating better usability. This scale is a reliable measure of system usability, even with a small sample size. In this study, the Italian version of the SUS was utilized (Borsci et al., 2009).

Attitudes toward RAM in VR (AT-VRAM). After the vRAM experiments, the participants evaluated their response to the VR test environment on five dimensions using a five-point scale. The dimensions were useless/useful, not pleasant/pleasant, boring/funny, tiring/resting, and stressing/relaxing. The scores obtained for each dimension were combined to form a composite score ranging from 0 to 5, where higher scores indicated more favourable attitudes toward the test condition. The composite scale was developed by the study authors using the methodology described by Ajzen & Fishbein (2005).

3.2.4. Procedure

Upon arrival, participants completed a survey collecting demographic information including gender, age, years of education, information about their sportive activities (experience, frequency, level) weight, height, income, occupation, and residency, aimed at ensuring a balanced sample. Following this, participants completed the ITQ to assess their immersive tendencies prior to the VR experience. The participants were also asked if they had ever experienced any symptoms of motion sickness in past VR experiences or other visual devices (e. g. television, video games).

Next, participants were tested using the Advanced Progressive Matrices (APM) to evaluate their general cognitive level.

Subsequently, participants were positioned in a swivelling office chair that facilitated a full rotation of 360 degrees. Before the vRAM, the participants wore the Oculus Quest 2 Head-Mounted Display (HMD) and completed a training session with the VR system. Within the virtual environment, participants were asked to navigate and retrieve objects from the ground using the VR controllers. To move forward and backward in the virtual environment, participants were guided to utilize the analogue stick on the VR controller. Thanks to the office chair, participants can rotate both left and right. To interact with a virtual object, the user is instructed to press the trigger button of the VR controller once the object is highlighted/selected. To end the interaction, the user is instructed to release the trigger. Training included one mini-task regarding the research and the manipulation of virtual objects within the virtual environment. The mini-tasks were not related to the tasks performed during the trial. Once participants were familiar with the virtual environment, the participants received the instructions to perform two trials of the vRAM-Free.

After a brief break, participants completed the Corsi Block Tapping Test (CBTT) and the modified Five-Point Test (m-FPT).

Following another break, participants underwent the two trial of the vRAM-Forced.

At the conclusion of the sessions, participants filled out a follow-up survey related to their VR experience, which included the Presence Questionnaire (PQ), System Usability Scale (SUS), Cyber Symptoms (CS), and the Attitude toward vRAM (AT-vRAM).

Data collection was conducted at the Health and Sport Psychology Lab (Sapienza, University of Rome). The total duration of the examination was approximately 1.5 to 2 hours.

3.2.5. Data Analysis

For each participant, we calculated three key measures: Weighted Performance Index (WPI), Cowan's K (K_c), and Procedural Strategy, as described in the previous sections. We also examined parameters related to Checking Behaviour in a purely exploratory manner. To further analyse WPI, we performed different analysis models using Bayesian General Linear Models (GLM). For all models, we tested both Log-normal GLM, Gamma GLM, and Gaussian GLM (only for dependent variables with negative values) and we ran models with and without interactions between predictors. Model comparisons were conducted using Bayes Factors (BF) to determine the best-fitting models.

We also used cluster analysis to explore the nature of WPI a bit further. We chose k-means clustering approach.

To assess changes between Trial 1 and 2 of both vRAM-Free and vRAM-Forced, we used Bayesian paired t-test for continuous dependent variables, and Bayesian models with Bernoulli or categorial distributions for categorickal dependent variables.

In Experiment 1:

- *Model 1A* aimed to test whether WPI could be predicted by K_c or Procedural Strategy. A Bayesian GLM was employed with WPI as the outcome variable and both K_c and Procedural Strategy as predictors, examining both additive and interaction effects. A clustering analysis using k-means algorithm was also conducted to determine whether clusters formed by WPI were reflected in K_c and Procedural Strategy.
- *Model 2A* explored the effect of Checking Behaviour on WPI. We used a Bayesian GLM where WPI was predicted by the categorical variable Checking Tendency (yes= 1 /no= 0), the continuous variable Number of Checks, and the First Entry Check variable (0 = Checking Any Arm; 1= Checking The First Arm; 2= No Checking).

- *Model 3A* explored the association between WPI and the classic neuropsychological tests like Corsi Block-Tapping Test (CBTT) and Modified Five-Point Test (m-FPT). A Bayesian GLM was used, where WPI was predicted by CBTT and m-FPT scores.
- *Model 4A* examined the influence of demographic variables on WPI. We used a Bayesian GLM with Gender (categorical), Age, Education (continuous), and Physical Activity Level (PA) (ordinal: 0 = low PA, 1 = middle PA, 2 = high PA) as predictors. We determined PA with a k-means clustering method using three information given by the participant during the pre-assessment survey: sport experience (how long and whether they practised any sport), sport frequency (how many times per week do they train), sport level (if they are non-sportive, amateur or agonist).
- *Model 5A* focused on the learning effect between trials. A Bayesian paired-sample t-test was used to compare WPI, K_c, Procedural Strategy and Number of Checks across Trial 1 and Trial 2. We used Bayesian comparison with Bernoulli and categorial families for Checking Behaviour categorial variables (Checking Tendency; First Entry Check).

In Experiment 2:

- *Model 1B* used Bayesian GLM to assess whether WPI in the vRAM-Free could predict Forced-K_c in the vRAM-Forced. We then divided the sample based on the WPI clusters and examined the mean and standard deviation for Forced-K_c within those clusters to determine if the clustering based on WPI was also reflected in the Forced-K_c data distribution.
- *Model 2B* focused on the learning effect between trials in the vRAM-Forced. We conducted Bayesian paired t-tests to compare Forced-K_c across trials.
- *Model 3B* used Bayesian GLM to assess whether CBTT and m-FPT could predict Forced-K_c.

- *Model 4B* examined the influence of demographic variables on Forced-K_c. We used a Bayesian GLM with Gender (categorical), Age, Education (continuous), and Physical Activity Level (ordinal: 0 = low PA, 1 = middle PA, 2 = high PA) as predictors.

All Bayesian models were conducted in R version 4.3.0 using the brms package.

3.3. Experiment 1: Results

3.3.1. Sample description

The dataset comprises a balanced sample with an average participant age of 24.72 years (SD = 2.57), spanning from 20 to 32 years. The median age is 24, reflecting a young adult population. On average, participants have completed 17.93 years of education (SD = 2.34), with an educational range between 12 and 24 years, and a median of 18 years, suggesting a well-educated cohort *(Table 2*). All participants had values within the norm on the Raven Advanced, indicating typical cognitive functioning *(Table 2*). The sample demonstrates varied sports experience, with participants reporting an average of 3.21 years (SD = 4.90), ranging from no experience to 21 years, and a median of 1 year. Gender distribution is relatively balanced, consisting of 35 females (60.34%) and 23 males (39.66%).

	Median	**Mean**	**SD**	**Minimum**	**Maximum**
Age	24	24.72	2.56	20	32
Education	18	17.93	2.33	12	24
APM	10.5	10.27	1.34	9	12

Table 2. Descriptive statistics for three main demographic variables (age, education, APM score).

To categorize physical activity levels (PA) for the subsequent analyses, k-means clustering was applied to the sample. This approach identified three distinct clusters, that provide a well-rounded classification of participants PA. The cluster distribution reveals that the majority of participants fall into PA category 1 (48.28%), representing those with a high level of sports experience and general physical activity level. This is followed by PA category 2 (39.66%), indicating participants with sufficient physical activity and moderate sport experience, while PA category 3 (12.07%) consists of those with minimal or poor sports experience and low physical activity. This distribution provides a diverse representation of varying levels of physical activity engagement across the sample (*Table 3*).

Cluster	**Count**	**Proportion**	**Agonist**	**Amateur**	**Sport Experience**	**Sport Frequency**
0	23	39.66%	0	0	0	0
1	28	48.28%	2	26	3.01 ± 2.37	3.5± 1.2
2	7	12.07%	1	6	14.57 ± 3.51	6± 1

Table 3. PA clusters composition. Cluster 0 = low PA; Cluster 1 = middle PA; Cluster 2 = high PA.

3.3.2. Model 1A

Model 1A aimed to investigate the relationship between Cowan's K (K_c) , Procedural Strategy, and their interaction in predicting the WPI using a Bayesian log-normal GLM model. The results revealed that K_c was a significant positive predictor of WPI, with an estimate of 0.14 (95% CI [0.10, 0.18]) (*Figure 13A*). Conversely, the effect of Procedural Strategy was non-significant, with an estimate of -0.01 (95% CI [-0.26, 0.25]) (*Figure 13B*). The interaction between variables was also non-significant, with an estimate of -0.02 (95% CI [-0.07, 0.03]). The model's sigma parameter was estimated at 0.09 (95% CI [0.08, 0.11]), indicating low residual variability. A comparison using Bayes Factors favoured the log-normal model with interactions over a gamma model (BF = 6.39), but the simpler model without interactions was strongly favoured (BF = 156.81), suggesting that the interaction between K_c and Procedural Strategy does not meaningfully contribute to predicting WPI.

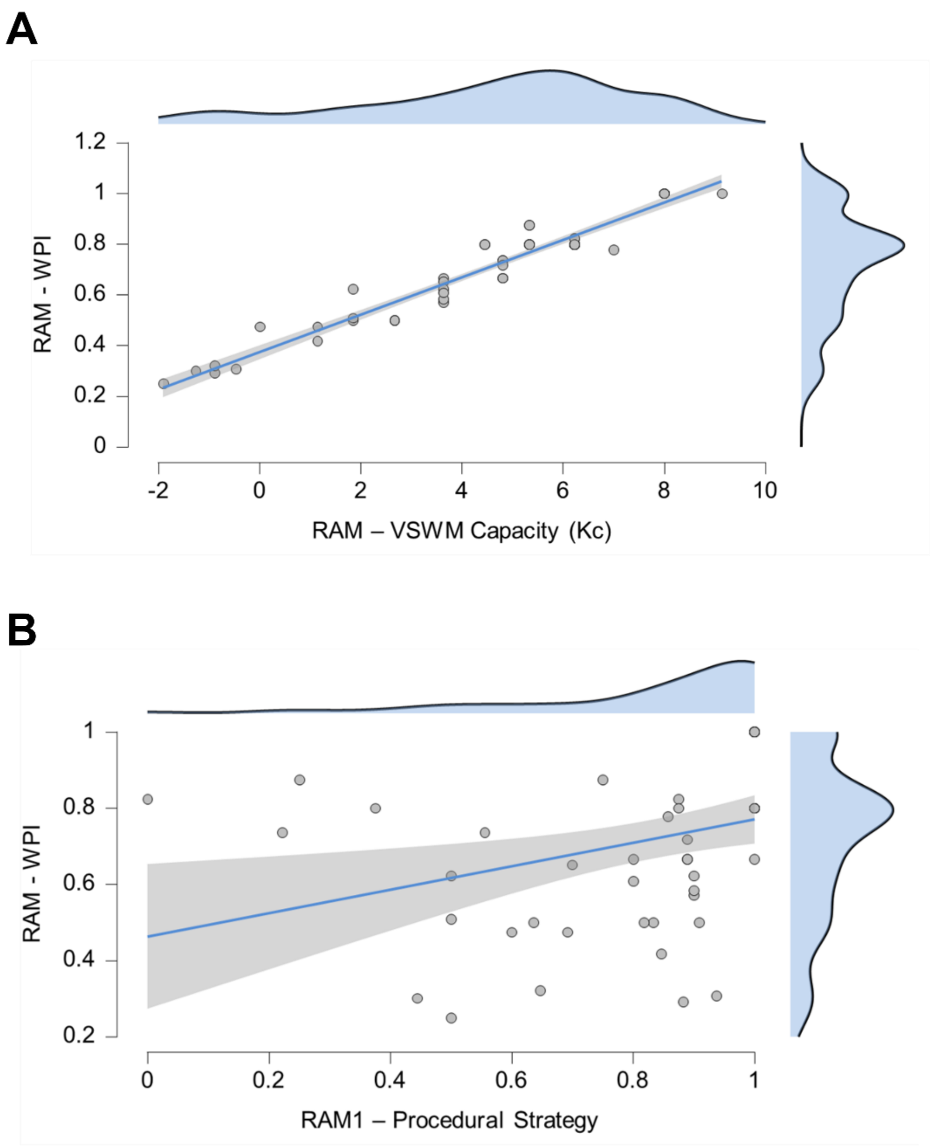

Figure 13. Scatter plots showing the relationship between WPI and other RAM parameters: **(A)** K_c and WPI; **(B)** Procedural Strategy and WPI.

Additionally, a clustering analysis was conducted using the k-means algorithm to categorize participants based on their WPI scores. This analysis revealed three distinct clusters of performance. For Cluster 1 (mean WPI = 1.00; SD = 0.00; Min = 1.00, Max = 1.00), representing the highest performance level, the mean K_c was 8.11 (SD = 0.36; Min = 8.00, Max = 9.14), while the mean Procedural Strategy was 1.00 (SD = 0.00; Min = 1.00, Max = 1.00). In Cluster 2 (mean WPI = 0.76; SD = 0.07; Min = 0.61, Max = 0.88), which indicates sufficient performance, the mean K_c was 5.27 (SD = 1.12; Min = 1.85, Max = 7.00), with a mean Procedural Strategy of 0.82 (SD = 0.27; Min = 0.00, Max = 1.00) Lastly, Cluster 3 (WPI mean = 0.43; SD = 0.11; Min = 0.25, Max = 0.58), representing the lowest performance level, showed a mean K_c of 1.06 (SD = 1.84; Min = -1.90, Max = 3.64), a mean Procedural Strategy of 0.74 (SD = 0.17; Min = 0.44, Max = 0.94). These findings suggest that the categorization based on WPI performance is consistently reflected across the other parameters (*Figure 14*). However, some participants categorized as top performers in WPI did not necessarily exhibit higher K_c scores or lower Procedural Strategy scores. This variation highlights the complexity of the relationships among the parameters and proposes that performance in WPI may be influenced by factors beyond K_c and Procedural Strategy, necessitating further investigation into the underlying mechanisms driving these outcomes.

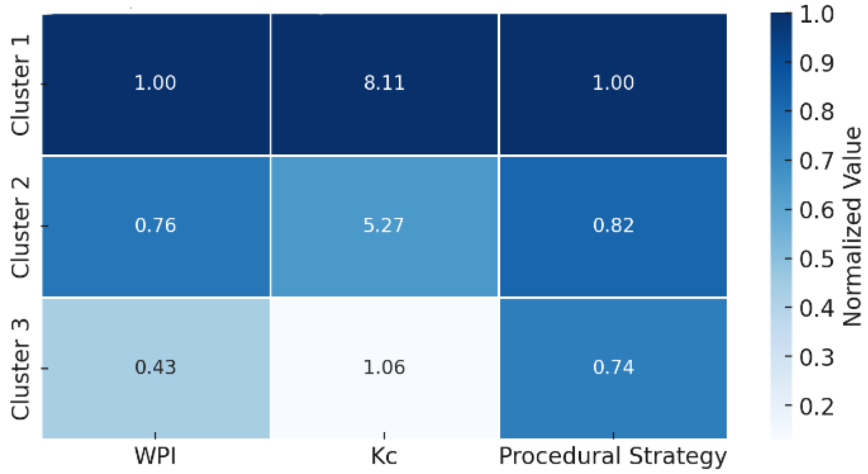

Figure 14. Clustered heatmap representing the normalized average values of WPI, K_c, and Procedural Strategy across three distinct clusters identified using a k-means clustering algorithm. Darker colours

indicate higher values. The values for K_c are normalized (maximum value = 8) to allow for comparison with WPI and Procedural Strategy, which both have a maximum of 1.

3.3.3. Model 2A

Model 2A examined the influence of Checking Behaviour (Number of Checks, Checking Tendency, First Entry Check) on the WPI using a Bayesian log-normal GLM model, incorporating interactions among several predictors. The results indicated that Number of Checks showed significant negative effects, with an estimate of -0.13 (95% CI [-0.15, -0.12]) (*Figure 15A*). In contrast, First Entry Check was a positive predictor of WPI with an estimate of 0.13 (95% CI [0.03, 0.23]) (*Figure 15C*). The reference level for First Entry Check was Level 1 (Checking The First Arm), which indicates middle performance. In contrast, Level 0 (Checking Any Arm) reflects poorer performance, while Level 2 (No Checking) suggests higher performance. Checking Tendency showed a non-significant effect on WPI, with an estimate of 0.11 (95% CI [-0.05, 0.26]) (*Figure 15B*), as well as the interaction terms. The model's sigma parameter was estimated at 0.14 (95% CI [0.11, 0.16]), indicating relatively low variability in residuals. The analysis favoured the simpler model without interactions over the interaction model, based on Bayes Factors, which indicated an advantage for the log-normal model over the gamma model (BF = 0.79) and the log-normal interaction model (BF = 1.42).

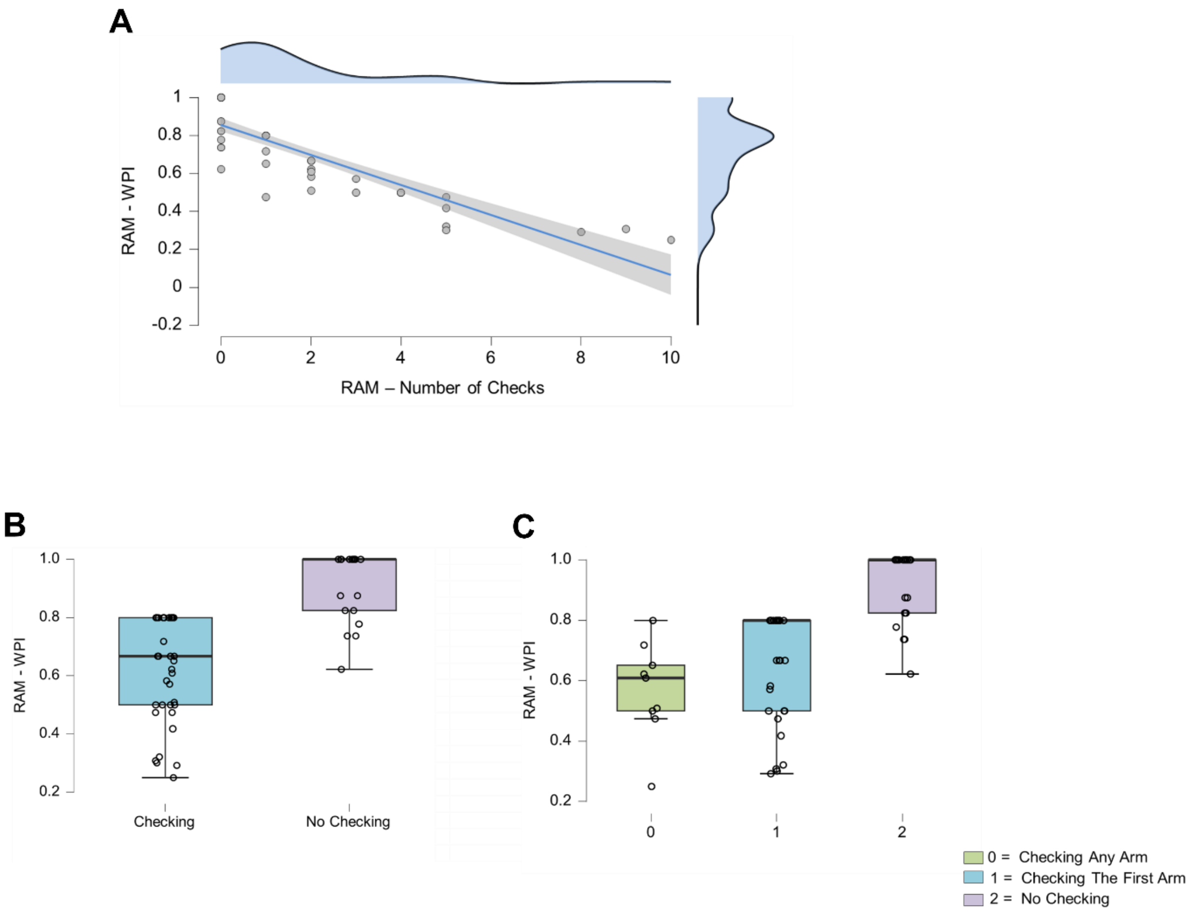

Figure 15. **A.** Scatter plot showing the relationship between WPI and Number of Checks (continuous variable); **B.** Boxplot illustrating the relationship between WPI and Checking Tendency (categorical variable); **C.** Boxplot displaying the relationship between WPI and First Entry Check (categorical variable).

3.3.4. Model 3A

Model 3A aimed to investigate the relationship between neuropsychological measures (CBTT, m-FPT) and the WPI. The results from the Bayesian log-normal GLM model suggested that the CBTT- in both its forward and backward versions-, was not a significant positive predictor of WPI, with an estimate of 0.39 (95% CI [-0.12, 0.93]) (*Figure 16A*) for the CBTT forward, and an estimate of 0.58 (95% CI [-0.05, 1.24]) (*Figure 16B*) for the CBTT backward. Similarly, no significant effect was found for m-FPT parameters UDs (estimate of 0.02; 95% CI [-0.03, 0.07]) (*Figure 16C*), and DSs (estimate of -0.02; 95% CI [-0.08, 0.04]) (*Figure 16D*). However, m-FPT parameter CSs showed a significant positive effect on WPI, with an estimate of 0.55 (95% CI [0.18, 2.23]) (*Figure 16E*). The model's sigma was estimated at 0.36 (95% CI [0.30, 0.43]), reflecting a moderate level of residual variability. The analysis showed a substantial preference for the simpler log-normal model over the interaction model based on Bayes Factors, indicating a strong advantage for the log-normal model over the gamma model (BF = 0.31) and the interaction model (BF = 7059406.66).

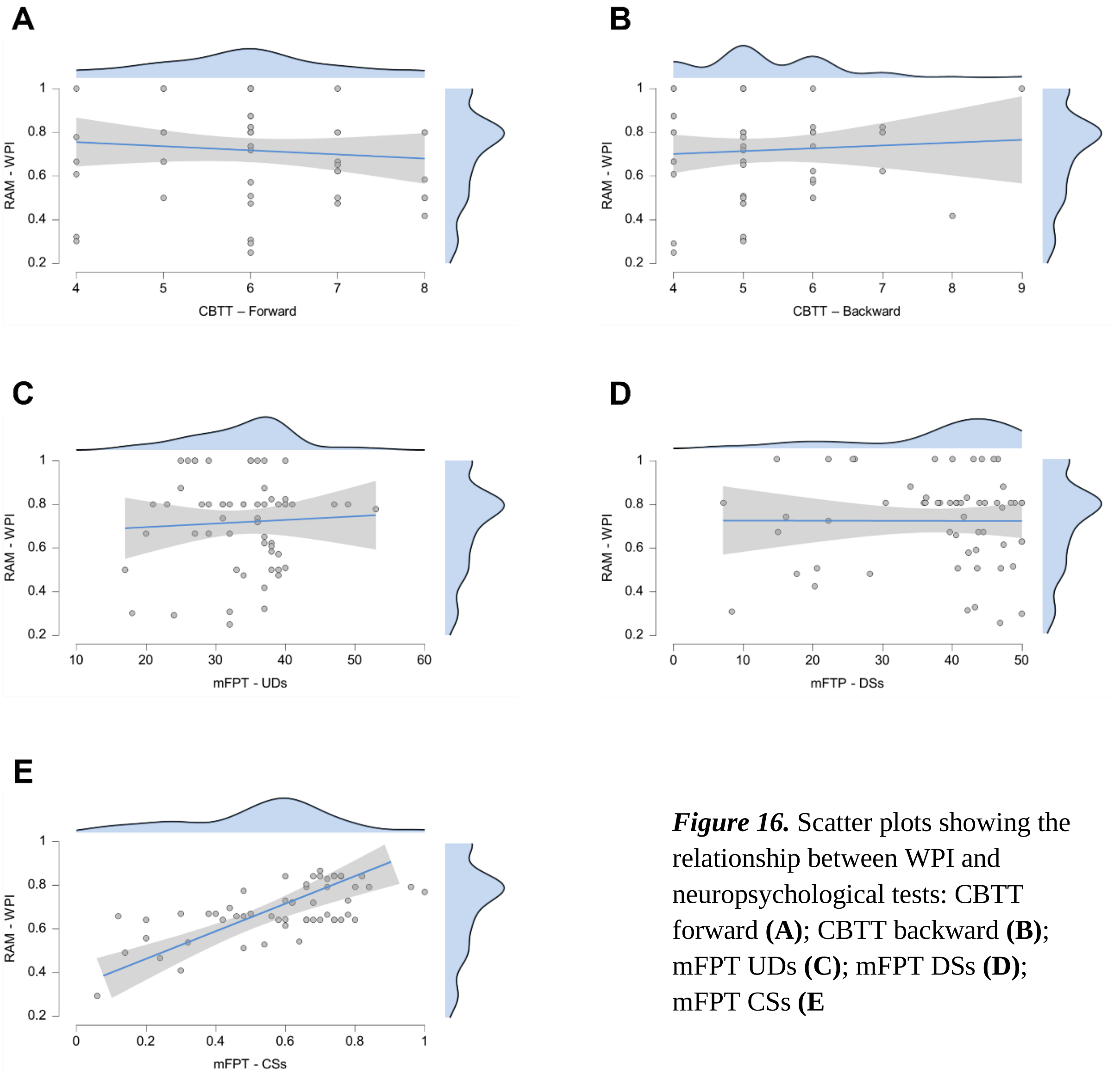

Figure 16. Scatter plots showing the relationship between WPI and neuropsychological tests: CBTT forward **(A)**; CBTT backward **(B)**; mFPT UDs **(C)**; mFPT DSs **(D)**; mFPT CSs **(E**

3.3.5. Model 4A

Model 4A explored the influence of demographic variables (Age, Education, Gender, PA cluster) on WPI, employing a Bayesian log-normal GLM model that included interactions among several predictors. The model revealed a non-significant main effect for both Age, with an estimate of -0.14 (95% CI [-0.42, 0.12]) (*Figure 17A*), and for Education (-0.31, 95% CI [-0.72, 0.10]) (*Figure 17B*). A non-significant main effect of Gender, with an estimate of -0.07 (95% CI [-0.27, 0.34]) (*Figure 17C*) was found. Similarly, the PA cluster variable also showed a non-significant effect on WPI, with an estimate of 1.74 (95% CI [-0.17, 3.70]) (*Figure 17D*). The model's sigma was estimated at 0.35 (95% CI [0.29, 0.44]), indicating moderate variability in the residuals. The analysis favoured the simpler model without interactions over the interaction model based on Bayes Factors, indicating a preference for the log-normal model over the gamma model (BF = 0.29) and the log-normal interaction model (BF = 0.97).

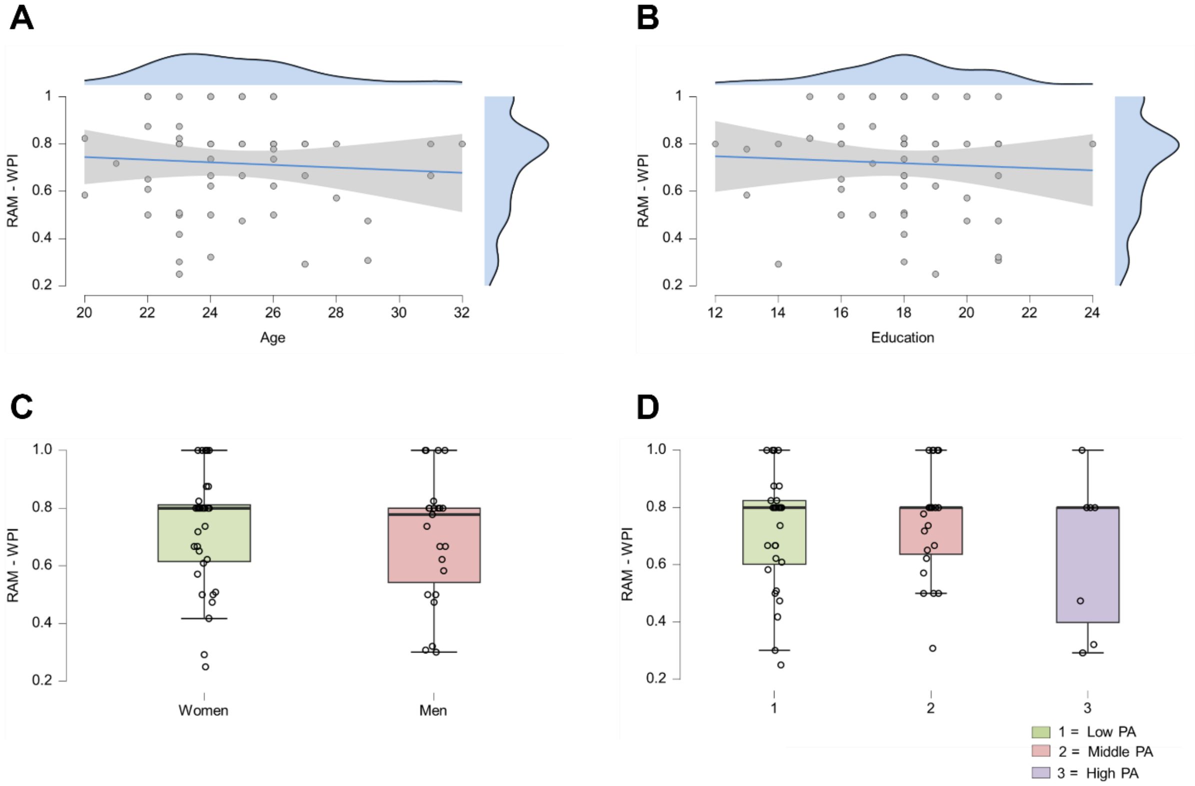

Figure 17. Scatter plots showing the relationship between WPI and demographic variables (continuous variables): Age**(A)**; Education **(B).** Boxplots illustrating the relationship between WPI and demographic variables (categorial variables): Gender **(C)**; PA cluster **(D)**.

3.3.6. Model 5A

In Model 5A, we employed Bayesian paired t-tests to analyse the changes in the WPI, K_c, Procedural Strategy, and Checking Behaviour between Trial1 and Trial2. For continuous dependent variables, we utilized a log-normal distribution. WPI paired t-test revealed an intercept estimate of 0.12 (95% CI [0.05, 0.18]) (*Figure 18A*), indicating a slight- and significant- positive change in WPI over time. For Procedural Strategy, the paired t-test yielded an intercept estimate of 0.11 (95% CI [0.05, 0.17]), suggesting a small but significant increase in procedural strategy use (*Figure 18B*). Paired t-test on K_c indicated a significant improvement with an intercept of 1.61 (95% CI [0.78, 2.45]) (*Figure 18C*), highlighting greater memory capacity in Trial2. In contrast, Number of Checks revealed a significant decrease, with an intercept estimate of -0.96 (95% CI [-1.51, -0.40]) (*Figure 18D*), indicating that participants tended to perform fewer checks in Trial 2.

Additionally, we used Bayesian models for Checking Tendency and First Entry Check, applying a Bernoulli distribution for the former and a categorical distribution for the latter. The Check Tendency model showed an intercept estimate of 0.00 (95% CI [-0.98, 0.94]) (*Figure 18E*), indicating no significant change in Checking Tendency between the two trials. Meanwhile, the First Entry Check model revealed that the average response for each category (2= no check; 1= check first entry; 0 = check, but not first entry) remained consistent, with estimates suggesting no significant changes in participants' tendencies to check at the first entry (estimate of -0.83; 95% CI [-2.93, 1.09]) (*Figure 18F*).

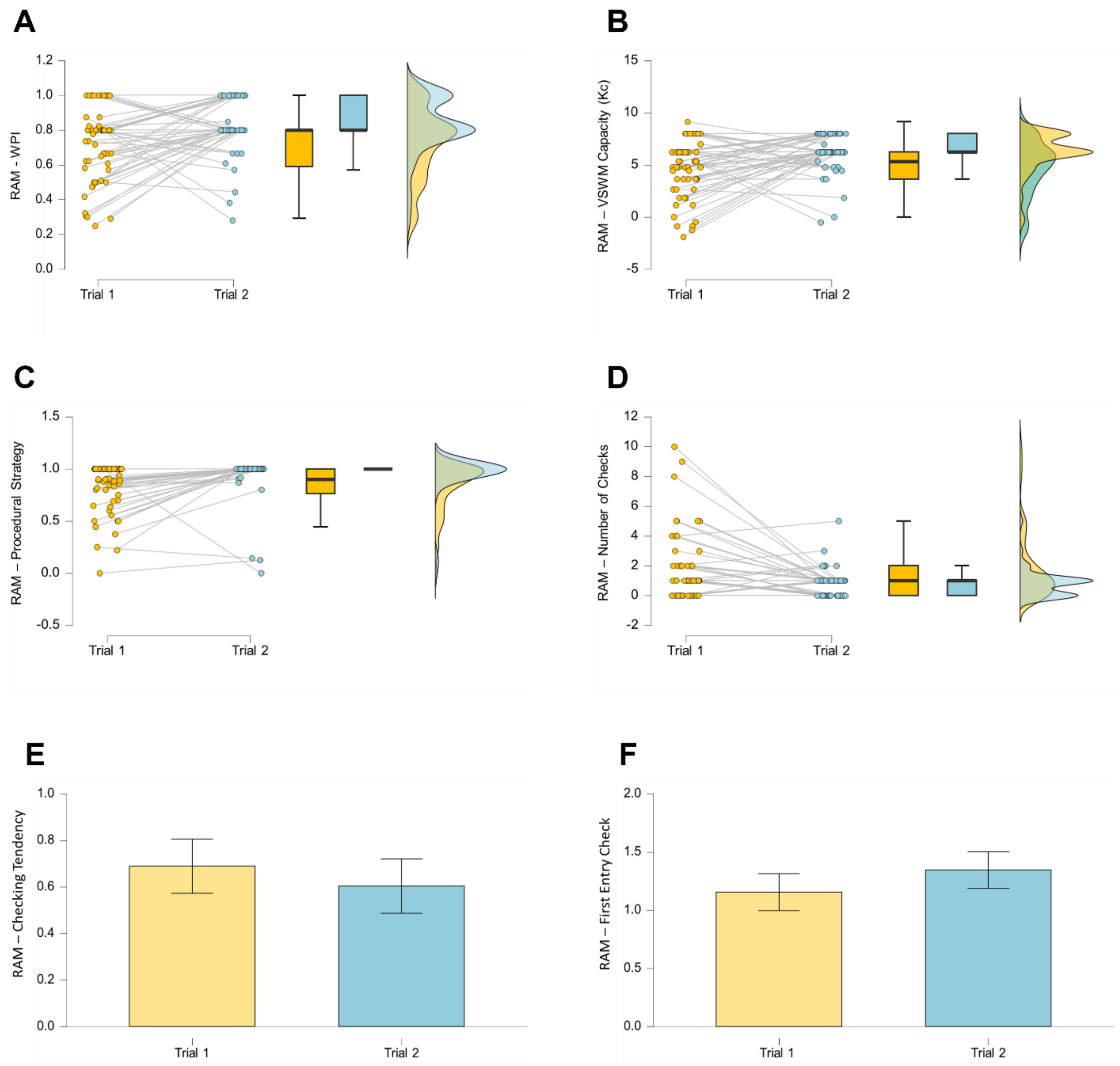

Figure 18. Changes in performance metrics across trials, illustrated using raincloud plots for WPI **(A)**, Procedural Strategy **(B)**, K_c **(C)**, and Number of Checks **(D)**, and bar plots for Checking Tendency (**E**; Yes = 1 / No = 0) and First Entry Check (**F**; 0 = Checking Any Arm, 1 = Checking the First Arm, 2 = No Checking).

3.4 Experiment 2: Results

3.4.1. Model 1B

Model 1B aimed to investigate the influence of vRAM- Free indexes (WPI, K_c, Procedural Strategy) on vRAM-Forced performance, expressed by Cowan's K (Forced-K_c). To assess this, we used Bayesian Gaussian GLM models with interactions. The results revealed that Forced-K_c was not significantly predicted by any vRAM-Free parameters: WPI estimate was 0.84, with 95% CI [-7.85, 6.19] (*Figure 19A*); K_c estimate was 0.72, with 95% CI [-0.01, 1.45] (*Figure 19B*); Procedural strategy estimate was 0.14, with 95% CI [-3.81, 5.53] (*Figure 19C*). No interactions terms were significant. The model's sigma parameter was estimated at 1.32 (95% CI [1.09, 1.66]), indicating moderate residual variability. A comparison using Bayes Factors favoured simpler model without interactions was strongly favoured (BF = 156.81). Additionally, the cluster obtained in the k-means clustering analysis described in Model 1B, were used to confirm that there was no association between the performance in the two tasks (free and forced). For Cluster 1 representing the highest WPI level, the mean Forced-K_c c was 0.53 (SD = 1.48; Min = -2.00, Max = 2.4). In Cluster 2, which indicates sufficient WPI level, the mean Forced- Kc was 0.79 (SD = 1.45; Min = -1.54, Max = 4.00). Lastly, Cluster 3, representing the lowest WPI level, showed a mean Forced -K_c of 0.38 (SD = 0.91 Min = -1.74, Max = 2.4) (*Figure 18D*).

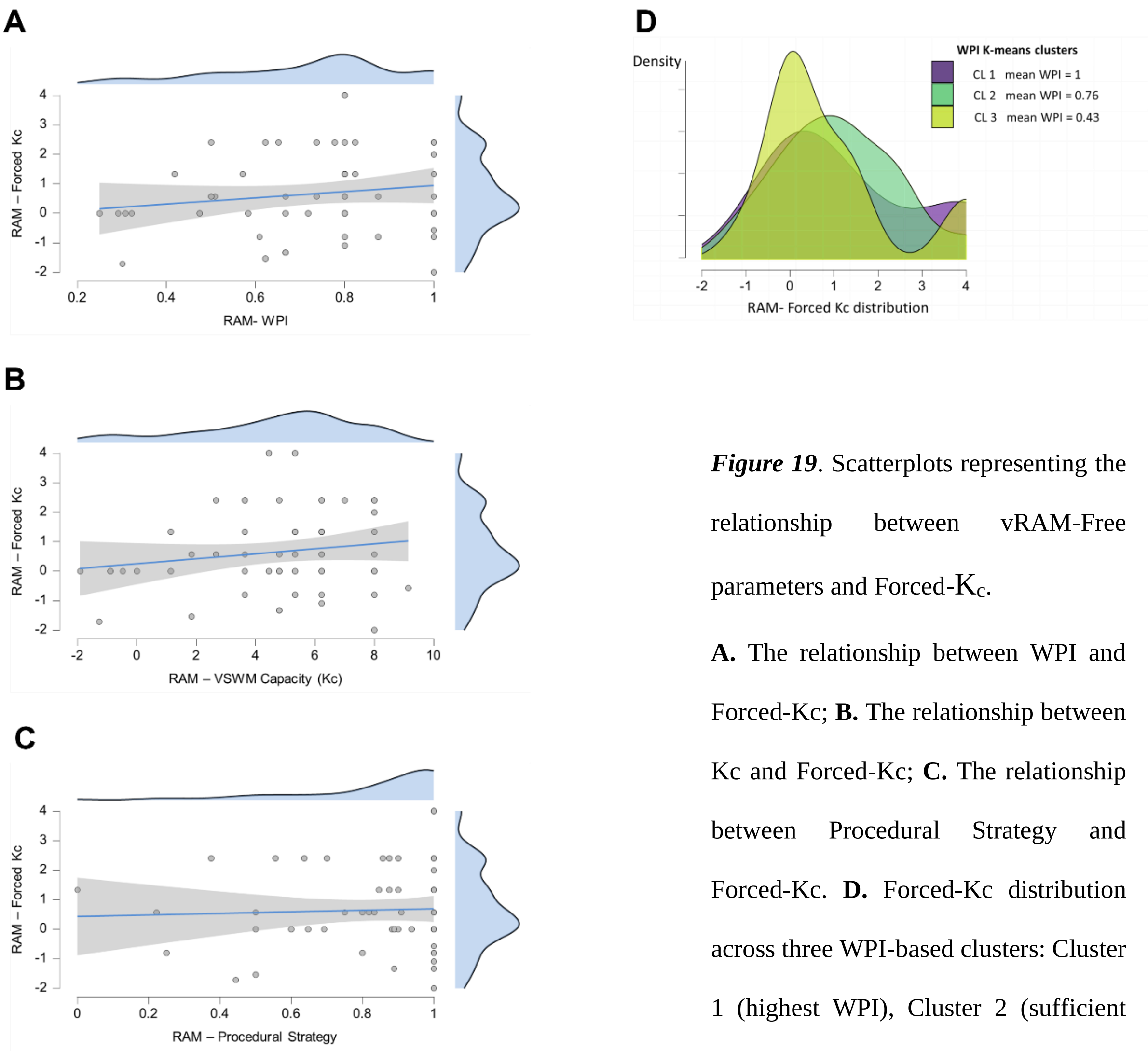

Figure 19. Scatterplots representing the relationship between vRAM-Free parameters and Forced-K_c.

A. The relationship between WPI and Forced-Kc; **B.** The relationship between Kc and Forced-Kc; **C.** The relationship between Procedural Strategy and Forced-Kc. **D.** Forced-Kc distribution across three WPI-based clusters: Cluster 1 (highest WPI), Cluster 2 (sufficient WPI), and Cluster 3 (lowest WPI).

3.4.2. Model 2B

In Model 2B, we employed Bayesian paired t-tests (with a log-normal distribution) to analyse the changes in Forced-K_c between Trial1 and Trial2. Paired t-test revealed an intercept estimate of -0.46 (95% CI [-0.90, 0.018]), indicating a negative but non-significant change in Forced-K_c between trials (*Figure 20*).

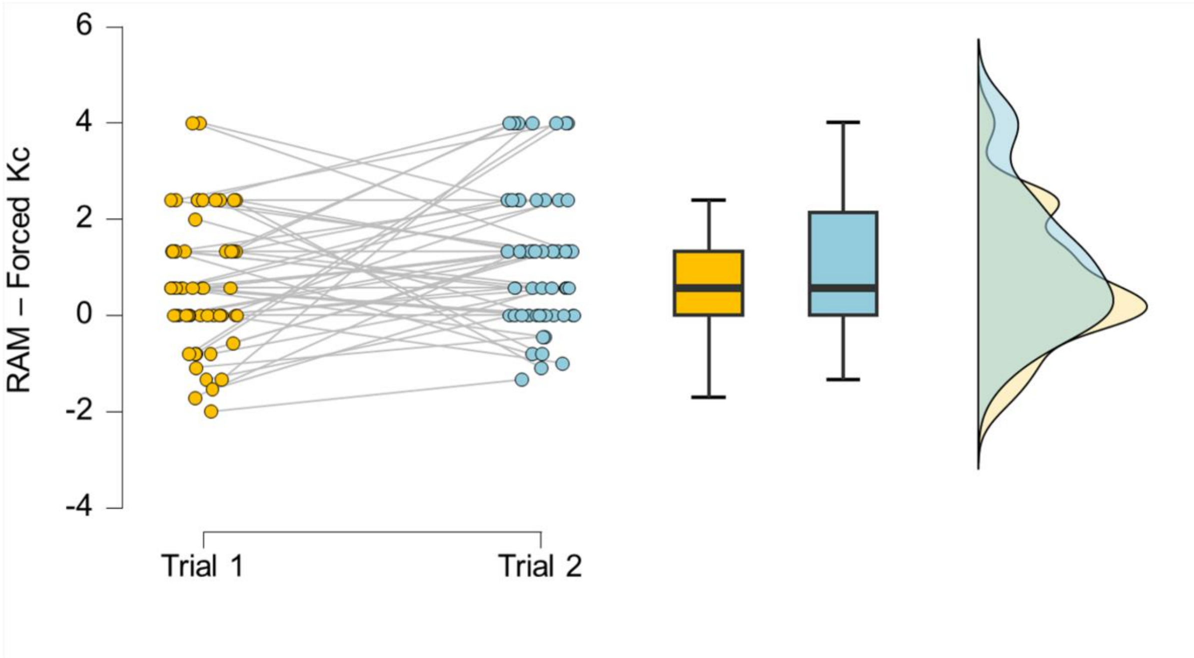

Figure 20. Raincloud plot showing Forced-K_c across trials.

3.4.3. Model 3B

Model 3B aimed to investigate the relationship between neuropsychological measures (CBTT, m-FPT) and the Forced-K_c. The results from the Bayesian Gaussian GLM model suggested that the CBTT backward, was a significant positive predictor of Forced-K_c, with an estimate of 0.30 (95% CI [0.09, 0.68]) (*Figure 21A*). In contrast, the CBTT forward showed a non-significant main effect, with an estimate of 0.11 (95% CI [-0.25, 0.46]) (*Figure 21B*). Similarly, no significant effect was found for m-FPT parameters DSs (estimate of -0.04; 95% CI [-0.11, 0.20]) (*Figure 21C*), UDs (estimate of 0.04; 95% CI [-0.22, 0.15]) (*Figure 21D*), and CSs (estimate of 1.15; 95% CI [-4.25, 6.73]) (*Figure 21E*). The model's sigma was estimated at 1.34 (95% CI [1.11,1.64), reflecting a moderate level of residual variability. The analysis showed a small preference for the simpler log-normal model over the interaction model based on Bayes Factors (BF = 0.003).

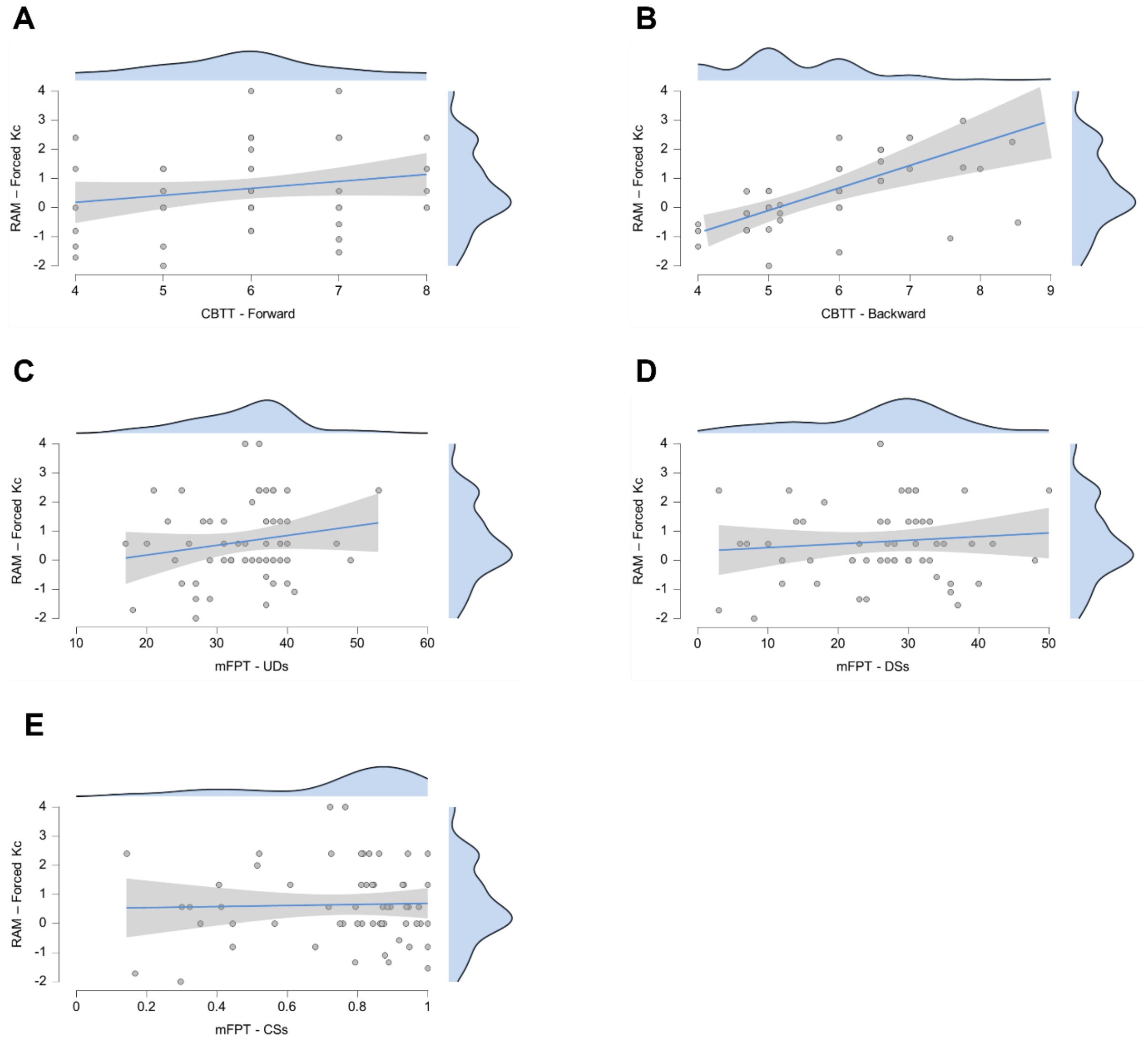

Figure 21. Scatter plots showing the relationship between Forced-K_c and neuropsychological tests: CBTT forward **(A)**; CBTT backward **(B)**; m-FPT UDs **(C)**; m-FPT DSs **(D)**; m-FPT CSs **(E)**.

3.4.4. Model 4B

Model 4B explored the influence of demographic variables (Gender, Age, Education, PA cluster) on Forced-K_c employing a Bayesian gaussian GLM model that included interactions among several predictors. The model revealed a non-significant main effect of Gender, with an estimate of -0.09 (95% CI [-0.62, 0.81]) (*Figure 22A*); a non-significant main effect of Age, with an estimate of -0.08 (95% CI [-0.23, 0.07]) (*Figure 22B*), and a non-significant effect for Education (-0.05, 95% CI [-0.21, 0.11]) (*Figure 22C*). In contrast, a significant positive main effect was found for PA cluster, with an estimate of 0.59 (95% CI [0.07, 1.09]) (*Figure 22D*). The reference level for PA cluster was Cluster 2 (Middle PA), which indicates middle performance. In contrast, Cluster 1 (Low PA) reflects poorer performance, while Cluster 3 (High PA) suggests higher performance. The model's sigma was estimated at 0.35 (95% CI [0.29, 0.44]), indicating moderate variability in the residuals. The analysis favoured the simpler model without interactions over the interaction model based on Bayes Factors (BF = 1237362936.14).

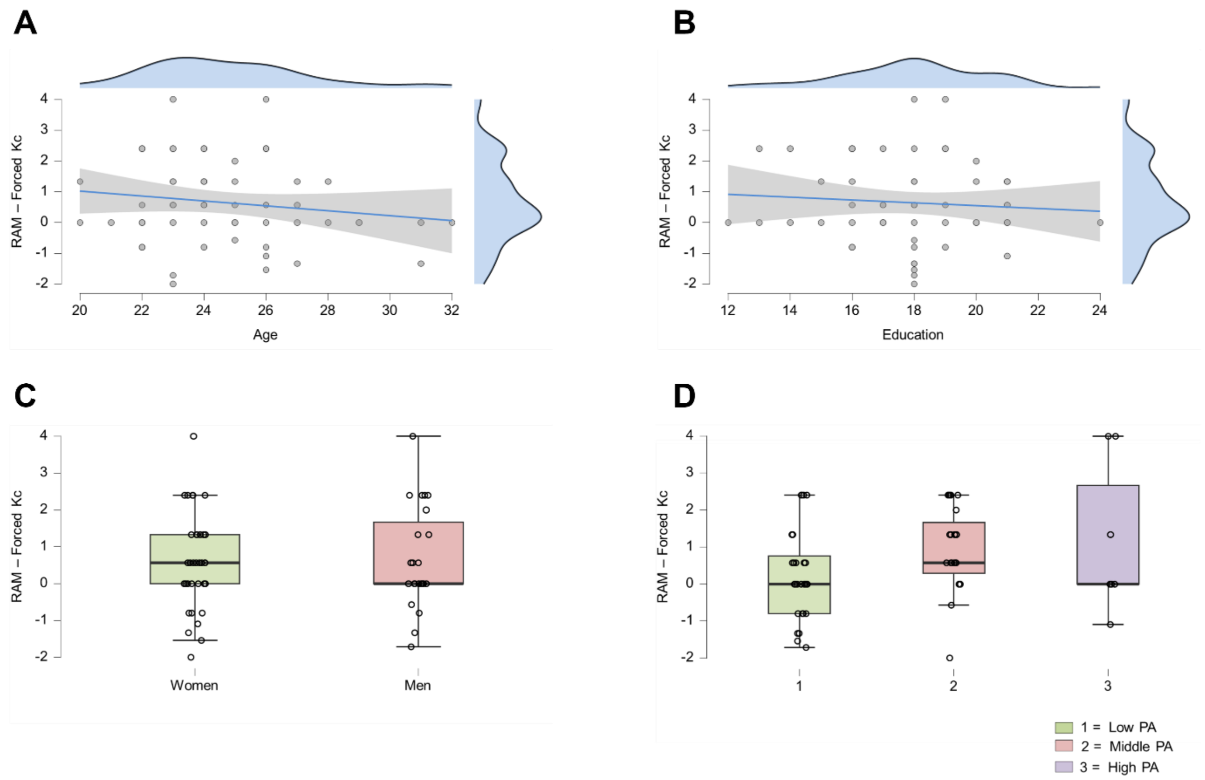

Figure 22. Scatter plots showing the relationship between Forced-K_c and demographic variables (continuous variables): Age **(A)**; Education **(B).** Boxplots illustrating the relationship between Forced-K_c and demographic variables (categorial variables): Gender **(C)**; PA cluster **(D)**.

3.4.5. VR experience

Although investigating the VR experience reports was not the primary focus of our project, we examined participant feedback for potential issues related to motion sickness, immersion, or software usability. These assessments were intended for supplementary studies. In *Table 4*, we present descriptive statistics (mean, standard deviation, minimum, and maximum values) to demonstrate that the overall VR experience was positive, thereby supporting the validity of our behavioural results.

	Median	Mean	SD	Minimum	Maximum
ITQ - Focus	19.5	19.38	4.46	8	28
ITQ - Involvement	16.5	15.71	5.17	6	26
ITQ - Emotions	14	13.43	4.31	5	24
ITQ - Enjoyment	5.5	6.217	4.35	0	16
PQ - Realism	20.5	17.05	12.68	0	40
PQ - Possibility To Act	17	12.58	8.82	0	24
PQ – Quality Interface	11	9.25	6.91	0	18
PQ - Possibility To Examine	11	8.74	6.28	0	18
PQ -Self-evaluation Performance	9	6.65	4.66	0	12
PQ - Sounds	8	7.37	5.86	0	17
PQ - Touch	3	3.67	3.49	0	12
SUS	82.5	82.37	8.11	65	100
CS – Physical Symptoms	5	5.71	4.38	0	15
CS – Eye Symptoms	3	3.95	4.23	0	20
AT - vRAM	3.2	3.18	0.86	1	5

Table 4. Descriptive statistics for the self-report questionnaire on the VR experience. Abbreviations= ITQ: Immerive Tendencies Questionnaire; PQ: Presence Questionnaire; SUS: System Usability Scale; CS: Cyberness Symptoms; AT-vRAM: Attitude Towards vRAM.

3.5. Discussion

In previous chapters, we extensively discussed the importance of studying visuospatial working memory (VSWM) processes in contexts that more accurately reflect real-world navigation and spatial learning (Palombi et al., 2022; Passarello et al., 2024a). We emphasized that environments requiring exploration offer an ideal context for assessing VSWM in a more ecological and realistic way (Fialho et al., 2023). When encountering new environments, individuals rely on VSWM to store and update spatial representations, a process crucial to understanding how memory and cognition work in real-time navigation (Wang & Spelke, 2002). For this to be properly studied, it is essential that individuals feel fully immersed in the environment, as immersion plays a key role in engaging the cognitive processes associated with spatial memory (Palombi et al., 2023).

With this in mind, we developed a Virtual Reality (VR) version of the well-established Radial Arm Maze (RAM) (Olton et al., 1979), aiming to enhance immersion and simulate a more authentic navigational experience. VR allows participants to actively engage with a dynamic, changing environment, providing a more accurate setting for studying VSWM than traditional, static tasks (Cipresso et al., 2018).

Our first aim was to identify a parameter that could capture not just basic performance (such as accuracy or speed), but also key aspects of VSWM and spatial exploration. This required a metric that accounted for both memory capacity (i.e., how much information participants can hold and manipulate in their VSWM) and their exploratory behaviour (i.e., what strategies they use and what movement patterns they follow). Additionally, we sought to explore how VSWM influences the ability to navigate new environments—how the spatial representation that an individual holds in their memory can assist them in making decisions during exploration. To achieve this, we introduced the Weighted Performance Index (WPI). This new measure was designed to capture all of these factors in a single, comprehensive parameter. The WPI not only assesses how accurately participants complete the task, but also integrates information about the significance of each entry into the maze, reflecting both their VSWM capacity and the strategies employed during exploration. By doing so, the WPI allows us to understand how well participants can hold and use spatial information to guide their actions in an immersive environment.

After creating the WPI, we tested its composition in Experiment 1 by examining whether established VSWM indices, like Cowan's K (K_c), could predict WPI. We used the *free-choice* version of the Radial Arm Maze (vRAM-Free), which allowed participants to explore the environment freely, making it ideal for studying the exploration process in depth. In Model 1A, we demonstrated that K_c is positively associated with WPI, indicating that VSWM capacity plays a role in performance on the vRAM-Free task. This was further supported by our clustering analysis, where participants grouped as top (cluster 1), middle (cluster 2), or low (cluster 3) performers based on WPI were also found to have correspondingly high, middle, and low K_c values. However, we also observed that not all top performers based on WPI had the highest K_c scores. When we analysed the mean and standard deviation of K_c across the clusters, the distinction between groups was not as clear as we might have expected. This suggests that while K_c (VSWM capacity) is important for better performance in the vRAM-Free, WPI and K_c are measuring different aspects of the task. VSWM capacity is a necessary but not sufficient condition for superior performance in a free exploration task, as WPI likely captures additional cognitive processes involved in navigation and strategy use beyond just memory capacity. The distinction between WPI and K_c underscores that WPI likely captures cognitive processes beyond VSWM capacity alone. While K_c reflects the number of items that can be maintained in VSWM (Cowan, 2008), WPI incorporates both memory capacity and the strategic elements of navigation—factors that extend beyond simple recall. For instance, research in reinforcement learning, such as the Variational Information Maximizing Exploration (VIME) strategy, shows that successful exploration depends not just on memory but also on adaptive strategies aimed at maximizing information gain about the environment (Houthooft et al., 2016). Similarly, in our study, WPI may reflect this strategic exploration component, which is not directly measured by Kc, offering a more comprehensive understanding of how participants navigate and interact with dynamic environments. In Model 1A, we found no significant association between WPI and Procedural Strategy. The cluster analysis, which categorized participants into top, middle, and low performers based on WPI, revealed that this division remained consistent when we analysed the mean and standard deviation of Procedural Strategy across WPI clusters. However, the differences between clusters were minimal, suggesting that while procedural strategies are common across performance levels, they neither enhance nor detract from task performance. The concept of procedural strategy has been explored in various contexts. For instance, rhesus monkeys have been shown to use distance-minimizing search strategies in spatial tasks, reducing their working memory load and increasing accuracy (Taffe & Taffe, 2011). Similarly, procedural strategies have been integrated into robotic systems, where combining procedural knowledge with topological modelling and metric information enables robust spatial learning in unfamiliar environments (Kuipers & Byun, 1988). In animals, procedural strategies can compensate for deficits in declarative memory. Research on vestibular loss in rats demonstrated that the animals shifted from declarative to procedural memory when performing spatial tasks, likely due to the involvement of the striatum and motor learning (Machado et al., 2014). This link between procedural strategies and spatial navigation also extends to human behaviour. Studies such as Mandolesi et al. (2009) and Foti et al. (2020)have shown that individuals with Williams syndrome display deficits in spatial processing, including impaired procedural abilities and working memory, when tested with the Radial Arm Maze (RAM). These findings suggest that procedural strategies—like visiting adjacent arms in sequence—may allow individuals to explore a maze without relying heavily on VSWM. By systematically visiting adjacent arms, participants could potentially complete the task faster and simply recognize when there are no more rewards left to collect, without needing a detailed spatial representation of the environment.

However, our findings indicate that the widespread use of procedural strategies does not necessarily predict better or worse performance. It may reflect a natural tendency in human behaviour, rather than a reliable predictor of performance. Moreover, it is possible that what we labelled as "procedural strategy," such as moving from one adjacent arm to another, may not even represent a cognitive strategy per se, but rather a simple movement preference that some individuals adopt. This distinction could explain why procedural strategy did not emerge as a significant factor in influencing WPI, as it may be more of a habitual movement pattern than a deliberate strategy aimed at enhancing task performance.

We maintain that having an integrated spatial representation of the environment significantly influences performance. To explore this concept further, we sought additional behavioural parameters that could indicate whether participants possessed this representation in their VSWM. Drawing from previous research (Foti et al., 2020; Mandolesi, Addona, et al., 2009; Passarello et al., 2024a)we observed that after completing the exploration phase and collecting all available rewards, some participants continued to search for more rewards instead of stopping. This behaviour, which we termed "checking behaviour," prompted us to record three specific variables. First, we introduced a binary variable indicating whether the participant engaged in checking behaviour (Yes/No) (Checking Tendency). Second, we recorded a continuous variable capturing the total number of checks made (Number of Checks). Finally, we implemented a second binary variable that indicated whether the participant revisited the first arm they had explored during their search (Yes/No) (First Entry Check). Revisiting the first arm could suggest a strategic or cautious approach, possibly driven by expectations regarding the task, such as anticipating a game-over signal. In contrast, not returning to the first arm, but still checking other arms, might indicate a less integrated spatial representation. In Model 2A, we analysed these three indexes and found that the tendency to check did not significantly influence performance as measured by the WPI. However, the number of checking negatively affected the WPI. This indicates that checking behaviour is only impactful when it becomes repetitive; simply returning to check does not necessarily indicate a lack of spatial representation. Additionally, the tendency to check the first arm entered positively predicted WPI, reinforcing the notion that checking is a normal behaviour rather than a sign of diminished capacity.

We then used Model 3A to analyse the association between vRAM-Free performance, as measured by the WPI, and scores obtained from classic VSWM tasks, such as the Corsi Block Tapping Test (CBTT), as well as another neuropsychological test that considers both working memory and spatial aspects, the Modified Five-Point Test (m-FPT). Our findings indicated a positive association only with the m-FPT.

As previously mentioned, traditional VSWM tasks like the CBTT do not capture the dynamic aspects of VSWM, particularly those relevant to spatial orientation tasks (Driver et al., 1999). In the CBTT, participants are presented with a fixed sequence of spatial representations that they must memorize and later reproduce. While there is some manipulation involved—especially in the backward version—this does not adequately address the complexity of VSWM engagement in spatial orientation. The CBTT primarily measures a more static type of information, akin to capturing a photograph. This aligns with the task's goal of assessing how many visuospatial items one can hold in working memory, focusing on capacity rather than process. In contrast, our WPI reflects the dynamic formation of VSWM, particularly in the context of spatial orientation. It embodies the concept that the spatial representation held in

VSWM is continually created and updated as individuals navigate their environment (Allen et al., 2006).

On the other hand, in the m-FPT, participants are required to produce unique drawings within a limited timeframe. Each time they create a drawing, they must store that visuospatial element in VSWM to avoid repetition (Cattelani et al., 2011). This dynamic process closely resembles the one involved in WPI. Further, it is the strategy index parameter (CSs) that predicts WPI. This index reflects the proportion of drawings made by altering only one or two elements from the previous drawing. To achieve this, participants must clearly remember what they have drawn before, which underscores the connection between these two tasks.

We then aimed to analyse the effect of demographic variables on WPI in Model 4A. Our analysis revealed no association between WPI and age or education, which was expected given that our sample comprised healthy young adults, with a balanced distribution of education years. The majority of participants were students, leading to a relatively uniform cognitive level, as confirmed by their scores on the Raven's Advanced Progressive Matrices (APM). Therefore, it is not surprising that the WPI was unaffected by these two variables.

However, we anticipated observing some gender differences based on previous research involving RAM tasks. The literature on gender differences in visuospatial memory tasks has yielded mixed findings. For instance, in a similar maze task, women made fewer errors than men, particularly in object memory tasks (Weiss et al., 2003). In contrast, studies using Virtual Morris Water Maze found that men outperformed women in the task, but this result was not replicated when the virtual Radial Arm Maze was used (Astur et al., 2004). Interestingly, research examining children's performance in the radial arm maze revealed that female children developed spatial competencies earlier than male ones, with 4.5-year-old girls performing comparably to 6-year-old boys (Mandolesi et al., 2009). These findings suggest that gender differences in visuospatial memory may be task-specific and influenced by various factors, including age, strategy selection, and brain organization. While the existing literature provides valuable insights, it also emphasizes the need for caution in interpreting gender differences in visuospatial memory. Variability in results may arise from small sample sizes and limited generalizability in human studies.

In our study, we found no association between gender and vRAM-Free performance. Although our sample was balanced in terms of gender proportions, it may still be somewhat small to draw robust conclusions regarding the lack of influence of gender on visuospatial abilities. We also anticipated differences based on Physical Activity level (PA). As emphasized in Chapter 1, PA is a significant environmental factor that influences various cognitive processes (Mandolesi et al., 2018; Passarello, Varini, et al., 2022; Voss et al., 2010). Our previous research has demonstrated the effects of PA on a range of cognitive abilities, including executive functioning, motor imagery, and even VSWM as measured by a table version of the radial arm maze (table-RAM) (Mandolesi et al., 2023; Passarello et al., 2024a). While some studies have found correlations between spatial abilities and sport activities (Pietsch & Jansen, 2012), others have reported no significant differences in spatial ability between athletes and non-athletes (Cynthia et al., 2016). However, elite athletes have shown greater efficiency in mental rotation tasks compared to novices, suggesting a link between sports performance and spatial abilities (Moreau et al., 2011). These findings underscore the complex relationships between sports, spatial cognition, and related skills.

In our analysis, we found no association between PA and WPI. It is important to note that rather than categorizing the sample based on a fixed criterion, we employed clustering analysis to determine participants PA. This approach was necessary because while it is straightforward to distinguish between athletes and non-athletes, classifying individuals based on physical activity is more challenging (Mandolesi et al., 2018). It is possible that the findings from previous studies primarily relate to structured sport practice rather than general PA. Alternatively, it may suggest that VSWM related to spatial navigation is not significantly influenced by PA at all. Our final Model 5A, for Experiment 1, aimed to identify differences in performance between vRAM-Free Trial 1 and Trial 2 to assess any learning effects. Given that the free-choice paradigm has traditionally been utilized as a means of habituation to the environment—especially in animal models and clinical studies—we anticipated observing a learning effect between trials (Olton et al., 1979).

Indeed, we found improvements in both WPI and K_c. Since the spatial layout remained constant across trials, participants likely had a complete representation of the space stored in their VSWM by Trial 2, which may have facilitated exploration. Interestingly, we also observed an increase in the use of procedural strategy, indicating a tendency to rely on more automated navigation methods that reduce cognitive fatigue during environmental exploration. As mentioned earlier, the strategy of moving from one arm to the immediately adjacent one may reflect just a simpler way to navigate the environment. Once participants integrated their spatial representation, they likely felt less compelled to explore and could instead follow a more organized pattern to collect rewards. This is further supported by the observation that the tendency to check, particularly the first arm visited, remained consistent across trials. It is noteworthy that the number of checks decreased in Trial 2, suggesting that participants relied more on automated navigation strategies, moving from adjacent arm to adjacent arm until they observed that no rewards were left. However, they still possessed a more integrated spatial representation from Trial 1, as evidenced by their tendency to check mostly the first arm they visited, stopping after just one check. This behaviour could indicate fatigue or a diminishing interest in the task during the second trial.

Experiment 2 aimed to analyse the same participants in a different version of the task, specifically the *forced-choice* paradigm. Traditionally, this version is considered more difficult and relies heavily on VSWM (Oberauer, 2009). We expanded on this by proposing that the vRAM-Forced task can be viewed as a classical VSWM task, similar to the CBTT. In this version, participants first explore a spatial pattern composed of four arms, have time to consolidate this spatial representation in memory, and then must reproduce it by visiting arms that were previously inaccessible. While there is some spatial exploration and manipulation of information, the task predominantly relies on VSWM to successfully complete. For this reason, we calculated Cowan's K (Forced- K_c) to determine performance. In our first Model (1A), we aimed to examine whether performance in vRAM-Free could predict performance in vRAM-Forced. Our findings showed that none of the performance indices from the free-choice version predicted Forced-Kc. This supports the idea that these two tasks measure different cognitive processes. Furthermore, the clusters based on WPI performance in the free version were not consistent in the forced version. Participants who were mid-performers based on WPI in the free task emerged as top performers in the forced task based on their Forced-K_c scores.

These results highlight the distinction between performing a VSWM task and engaging in spatial navigation (Cowan, 2005). While VSWM plays a critical role in spatial navigation, the processes involved in exploring an environment differ from those required to perform a purely VSWM-dependent task. This conclusion is further supported by the results of Model 3B, which showed a positive association between Forced-K_c and performance in the backward version of the CBTT. This makes sense, as the vRAM-Forced task involves a similar cognitive manipulation—reproducing a spatial sequence in reverse, akin to the backward CBTT (Kessels et al., 2000).

In Model 2B, we aimed to analyse the potential effect of learning by comparing Forced-K_c scores between Trial 1 and Trial 2 of the vRAM-Forced task. Contrary to our findings in the vRAM-Free task, where we observed an improvement in K_c across trials, we found no significant difference in Forced-K_c between trials in the vRAM-Forced task. This could be explained by the fact that participants did not have a fixed spatial pattern to memorize, as the sequence of closed arms changed randomly between trials (Foti et al., 2020). As a result, previous exposure to the space provided no advantage in performance.

Similarly, research suggests that learning can improve performance on VSWM tasks like the CBTT. For example, a single training session on a computerized version of the Corsi task led to faster reaction times on a mental rotation test (Schaefer et al., 2022). However, these effects are not replicated in the backward version of the CBTT, where no significant learning effects are observed (Mammarella & Cornoldi, 2005). This may suggest that the backward Corsi task, like the vRAM-Forced task, involves unique spatial processes that do not benefit from repeated exposure or learning across trials.

Lastly, in Model 4C we found no association between age, education, and Forced-K_c, nor did we observe any significant gender differences. The research on gender differences in VSWM has produced mixed findings. Some studies suggest that men outperform women, especially in tasks requiring more active processing (Cattaneo et al., 2006). However, other studies report no significant differences in spatial orientation tasks, implying that the observed effects may be more related to differing cognitive strategies than to inherent abilities (Bosco et al., 2004).These findings illustrate the complexity of gender differences in VSWM and suggest that factors such as task design, and individual differences should be considered when interpreting results. Importantly, many of these studies involve small sample sizes, and larger studies may be necessary to reliably identify gender differences.

Interestingly, we did find a significant association between PA and performance in the vRAM-Forced task, with more physically active individuals performing better. This result contrasts with our findings in the vRAM-Free task, reinforcing the idea that these tasks likely measure different cognitive processes. While we expected to find that active individuals would perform better in tasks involving spatial orientation (Jansen & Pietsch, 2022), our findings suggest that physical activity may be more strongly related to specific VSWM capacity. This could indicate that it is not merely PA that improves spatial navigation, but rather participation in specific sports, particularly open-skill sports that require spatial awareness (Moreau et al., 2011). However, our findings could suggest that either more realistic, ecologically valid tasks are needed to measure the influence of PA on VSWM, or that participants need to be more precisely categorized based on their physical activity level.

Overall, our study demonstrates that the virtual Radial Arm Maze (vRAM), in both its free-choice and forced-choice versions, is a valuable tool for exploring spatial navigation processes, visuospatial working memory (VSWM), and the interaction between them. The free-choice version holds greater potential as it allows us to examine how VSWM and spatial orientation influence each other dynamically.

3.6. Limitations and Future Directions

While our results were numerous and informative, it is important to acknowledge certain limitations. First, the relatively long duration of the test session may have contributed to fatigue effects. This is evident in the vRAM-forced condition, where some participants showed notably low K_c values. According to Cowan's research, K_c—representing the capacity of VSWM—should typically hover around 4 (Cowan, 2001)The low values observed in our study may indicate that the task was either too difficult or that participants were fatigued by the time they completed it. Another potential explanation lies in the time gap between phase 1 (memorizing the sequence with blocked arms) and phase 2 (reproducing the sequence with all arms open). There has been ongoing debate in the literature regarding how long information can be retained in VSWM, and no consensus has been reached (Cowan, 2008). While we used a pause duration commonly employed in similar tasks(Foti et al., 2020; Mandolesi, Addona, et al., 2009)), it may be worthwhile in future studies to modulate this timing and examine its effects on performance.

Looking ahead, we aim to investigate how factors related to participants' VR experience, which we recorded via self-report measures, could impact their performance. Additionally, we plan to introduce a version of the task that includes clear external landmarks, allowing us to assess how these environmental cues influence navigation and memory strategies. There is also potential to explore how varying the number of arms in the task affects performance. Finally, a key future direction will be to administer this task to children or clinical populations, such as individuals with cognitive impairments and neurodevelopmental disorders, to better understand what the vRAM truly measures across different groups. These extensions will help us further clarify the cognitive mechanisms underlying performance on the vRAM task and its broader applicability.

Final Discussion

Cognitive functions not only help us acquire knowledge but also enable us to interpret the world around us and respond appropriately to various stimuli. Recent research has increasingly focused on the interaction between cognitive functions and the external environment, challenging traditional views of cognition as an entirely internal process. Rowlands (1999) and Clark & Chalmers (1998) propose that cognition extends beyond the brain, involving the manipulation of environmental objects and active engagement with the world. Kirsh (1999) further emphasizes the importance of interactivity and distributed cognition in designing work environments.

This interplay between cognition and the environment is essential to our ability to adapt and function effectively across different contexts. Stimulus-rich environments, or those with specific characteristics, can either enhance or hinder cognitive performance. Moreover, this relationship is not unidirectional—cognitive functions are shaped by the environment, but they also actively shape how we experience it. The continuous feedback loop between cognitive processes and environmental conditions underscores the need to study this interaction to improve our understanding of cognition and develop strategies to optimize cognitive performance.

The bidirectional nature of this relationship means that while cognitive functions enable us to perceive and respond to environmental demands, the environment also influences and shapes our cognitive processes (Gelfo et al., 2018; Serra et al., 2022). Environmental conditions can have immediate, real-time effects on cognition. Research shows that external feedback and environmental factors significantly impact cognitive functions during tasks. For instance, false cognitive feedback can alter subsequent performance, though the extent of its influence varies depending on the specific executive function being assessed (Clark et al., 2024). Providing feedback during tasks has been shown to enhance cognitive control, improve behavioural outcomes, and modulate brain activity related to anticipation, perceptual awareness, and selective attention (Mussini et al., 2022).

Motor experiences, particularly physical activity and sport practice, play a vital role in shaping cognitive functions. Activities like running, swimming, and team sports enhance cognitive processes by increasing blood flow to the brain and promoting neurogenesis, particularly in regions associated with memory and learning (Kramer & Erickson, 2007). This physiological impact boosts cognitive functions such as working memory, attention, and executive control. The combination of physical activity, cognitive engagement, and social interaction in sports creates a stimulating environment that supports both immediate cognitive benefits and long-term cognitive health and resilience (Erickson et al., 2022). Research also indicates that sports participation positively affects cognitive functions in children and young adults. Open-skill sports, which require adapting to changing environments, are especially beneficial for cognitive development compared to closed-skill sports or inactivity (Pacesova et al., 2019). Physical activity during childhood and adolescence has been linked to improvements in attention, language, learning, and memory (Passarello et al., 2024a).

In the first part of this thesis, we investigated the impact of structured sports practice and physical activity on cognitive functioning, with a focus on executive functions due to their importance in goal-directed behaviour, problem-solving, and adaptability. We found that individuals who engage in regular sports, particularly those that require significant mental effort, show superior performance in tasks measuring executive functions such as verbal and graphic fluency. These findings align with existing research, which shows that sports participation enhances cognitive abilities in both children and adults (Passarello et al., 2024a; Passarello, Varini, et al., 2022).

Our studies revealed that different types of sports affect cognitive functions differently.

Multimodal sports, which require the integration of physical and cognitive components, such as decision-making and spatial awareness, have a stronger impact on cognitive functions compared to unimodal sports, which primarily involve repetitive physical movements. This suggests that the cognitive demands of multimodal sports stimulate neuroplasticity, enhancing brain regions responsible for executive functions, working memory, and attention. Additionally, physical fitness, motor skills, and sports proficiency emerged as independent predictors of various executive functions, with specific activities benefiting different cognitive domains (Fernandes et al., 2017).

Furthermore, we extended our research to older adults, showing that physical activity helps prevent cognitive decline and may mitigate the effects of neurodegenerative diseases. Physically active older individuals performed better in cognitive tasks, suggesting that regular physical exercise supports cognitive resilience and brain health as people age (Chang et al., 2013).

Our research also highlighted the role of motor imagery in enhancing performance, particularly in athletes engaged in complex motor tasks such as backward walking. These athletes demonstrated better mental rehearsal abilities, which are essential for skill acquisition and motor learning. Motor imagery is not only beneficial for athletes, but also for non-athletes, including those in rehabilitation or individuals looking to improve everyday activities (Mandolesi et al., 2023).

In conclusion, our research demonstrates that environmental factors, particularly sports and physical activity, have a significant influence on cognitive abilities. All our findings underscore the important role that physical activity plays in enhancing and maintaining cognitive health throughout life, highlighting its potential as a key factor in cognitive development and resilience.

In the second part of this dissertation, we explored how VSWM stands out as a key cognitive function that is significantly influenced by environmental factors like physical activity, education, and social engagement. VSWM plays a central role in tasks requiring problem-solving, decision-making, and spatial navigation by allowing individuals to temporarily store and manipulate spatial information, crucial for effectively interacting with dynamic environments (Allen et al., 2006).

Research shows that enriched environments, which promote neuroplasticity, have a direct positive impact on working memory. For instance, physical activity enhances the brain's adaptability to external stimuli, highlighting the role of VSWM in how we interact with and adapt to our surroundings. VSWM is particularly important in spatial navigation, where it supports the encoding and processing of landmarks, routes, and spatial relationships. Individuals with superior VSWM tend to perform better in navigation tasks and other activities requiring cognitive flexibility and spatial awareness (Garden et al., 2002). However, traditional assessments of VSWM have typically been carried out in static and controlled settings, which may not fully capture the complexity of real-world memory functioning. Dynamic environments, where spatial information changes in real time, better represent the conditions in which VSWM operates. The ability of working memory to adapt to such changes is critical for maintaining high cognitive performance.

The dynamic systems theory further supports the notion that memory is continuously shaped by interactions with a changing environment (Thelen & Smith, 2007). Studies show that exposure to dynamic environments—whether physical or virtual—enhances VSWM performance, underscoring its adaptability. This suggests that the environments in which individuals operate, and the demands placed on memory during spatial navigation, play a crucial role in shaping the efficiency of working memory processes.

Overall, these findings demonstrate that working memory, especially VSWM, is highly responsive to environmental influences, reinforcing the importance of studying cognitive functions in dynamic, ecologically valid settings (Passarello et al., 2024a)This understanding laid the groundwork for our study, which aimed to develop a more ecologically valid assessment for VSWM in children, utilizing the Bricks Game Task (BGT). The BGT adapts the Corsi Block-Tapping Test by incorporating real-world navigation elements and features a small platform with three configurations: Matrix, Cluster, and Cross.

Involving 228 Italian children, the study found strong correlations between BGT scores and traditional neuropsychological assessments. The results indicated age-related improvements in performance, with the Matrix configuration being the most accessible. Overall, the BGT proved to be a reliable tool for measuring children's VSWM, highlighting the significance of ecological tasks in developmental evaluations (D'Aurizio et al., 2023).

While the BGT represents a significant advancement, challenges persist, particularly in assessing spatial orientation and visuospatial working memory (VSWM) in environments that are continuously changing— contexts that closely resemble real-life situations where individuals must constantly adapt to their surroundings.

These unresolved questions set the stage for the third part of this thesis, in which we introduce a novel assessment tool aimed at addressing these concerns. The application of virtual reality (VR) as a medium for assessing cognitive functions, including VSWM has been a highly popular topic in recent years. By integrating the elements of immersion, presence, and interaction, VR systems provide a highly effective and engaging platform for simulation, learning, and experience enhancement. VR demonstrates great potential as a tool for assessing VSWM in realistic spatial orientation scenarios. By creating immersive environments, VR can replicate complex situations that reflect real-world navigation challenges, thereby enhancing ecological validity and offering valuable insights into cognitive processes (Palombi et al., 2022). This innovative approach could significantly deepen our understanding of VSWM and inform interventions for individuals experiencing difficulties with spatial awareness.

Following this line, the study aimed to enhance the assessment of visuospatial working memory (VSWM) through a virtual reality (VR) adaptation of the traditional Radial Arm Maze (vRAM) (Olton et al., 1979). While existing VR tools for spatial navigation have made significant contributions, they often lack intuitive interfaces, detailed data collection, and the immersive qualities needed for an engaging participant experience.

The limitations of traditional evaluation methods for RAM, which primarily measure total time, latency of first visit, number of entries, and errors, do not adequately capture the exploratory dynamics of spatial navigation. Previous research has failed to account for how participants dynamically update their spatial representations during exploration, leading to potential misinterpretations of their VSWM capabilities.

To address these gaps, the study focused on developing a more comprehensive assessment of VSWM in a dynamic environment by employing two versions of the vRAM: a *free-choice* version (vRAM-Free) that promotes exploratory behaviour and a *forced-choice* version (vRAM-Forced) that aligns with conventional VSWM paradigms.

The study involved 60 participants and introduced a Weighted Performance Index (WPI) to assess navigation and VSWM capacity. The results from Experiment 1 indicated that WPI is primarily associated with Cowan's K (K_c), capturing aspects that K_c overlooks, since it mainly reflects VSWM capacity. While WPI did not show a direct association with procedural strategies, it highlighted the ability to create a complete spatial representation, as evidenced by the inverse relationship between WPI and checking behaviour. Additionally, WPI correlated with the modified Five-Point Test (m-FPT), emphasizing similar dynamic processes in creating VSWM representations. A learning effect was observed for WPI.

In Experiment 2, which was more aligned with traditional VSWM tasks, performance was still linked to information manipulation, particularly through backward Corsi tasks. However, there was no learning effect due to different spatial configurations, and prior experience in the vRAM did not influence outcomes. Among demographic variables, only physical activity impacted performance in the vRAM-Forced, underscoring the relationship between physical activity and VSWM tasks.

Overall, this study deepens the understanding of how VSWM interacts with spatial navigation and identifies new performance parameters that reflect the cognitive processes involved in these tasks.

At this point, it is crucial to identify the neural correlates that specifically describe the dynamic processes involved in VSWM. This investigation aligns with my current research at Utrecht University, where I am studying the role of the Contralateral Delay Activity (CDA). The CDA is an event-related potential (ERP) observed in EEG recordings during tasks involving visual short-term memory (VSWM) (Tsubomi et al., 2013). It manifests as a sustained, negative voltage potential over parietal-occipital brain regions contralateral to the visual field where items are maintained in memory.

Key features of the CDA include its topographical location over parietal and occipital regions, with amplitude correlating to the number of items in memory. The CDA's amplitude is greater over the hemisphere opposite to the visual field where the memorized items are located, reflecting active storage. It serves as an electrophysiological marker for maintaining information in VSWM, increasing in amplitude as more items are held in memory until reaching an individual's VSWM capacity (Drew et al., 2009).

Importantly, my research aims to explore whether the CDA after eye movement reflect the memoranda's original retinotopic locations or their updated spatiotopic locations. By investigating these neural processes, we can deepen our understanding of how VSWM operates in dynamic contexts, paving the way for future research in cognitive functions and potential interventions for individuals with spatial awareness difficulties.

Conclusions

This dissertation has explored the intricate dynamics of environment and cognitive functioning, with a focus on visuospatial working memory (VSWM) through a series of innovative studies that bridge ecological validity with experimental rigour. We first studied extensively the relationship between environmental factors like physical activity and sport practice on cognitive functioning. Then we developed the Bricks Game Task (BGT) to assess VSWM in children, emphasizing the significance of ecologically valid assessments in understanding cognitive functions. Our findings highlight that VSWM is highly responsive to environmental influences, suggesting that traditional assessments may overlook crucial aspects of cognitive performance in real-world contexts.

Following this, we introduced a virtual reality adaptation of the Radial Arm Maze (vRAM), which allowed us to investigate the interplay between VSWM and spatial navigation more comprehensively. The inclusion of a Weighted Performance Index (WPI) proved instrumental in capturing the cognitive processes underlying spatial navigation, demonstrating significant associations with Cowan's Kc while reflecting participants' ability to create complete spatial representations. Additionally, we identified learning effects and distinct relationships between performance and demographic factors, such as physical activity levels.

The exploration of VSWM's dynamic nature has opened avenues for future research, particularly regarding the neural correlates that underlie these processes. My current work at Utrecht University, focusing on the Contralateral Delay Activity (CDA), aims to elucidate how VSWM operates in ever-changing environments, providing insights into the mechanisms of spatial awareness and memory recall.

In conclusion, this thesis underscores the importance of integrating immersive and dynamic methodologies in cognitive research to enhance our understanding of VSWM and its implications for interventions in individuals experiencing spatial awareness challenges. By bridging theoretical frameworks with practical applications, we can develop more effective tools for assessing and supporting cognitive functioning in diverse populations.

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