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1 **Full Title:** Biopsychosocial determinants of visuospatial memory performance according to  
2 different spaces

3

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17

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## 26 **Abstract**

27 Visuospatial memory (VSM) performance depends on intrinsic (biopsychosocial parameters)  
28 and extrinsic (space) factors. We aimed at characterizing the determinants of VSM  
29 performance according to space. Young healthy adults, 20 males and 41 females ( $23 \pm 3$  years  
30 old), were assessed for VSM performance through a pathway learning task, in reaching  
31 (eCorsi Block Tapping task) and walking space (Virtual Walking Corsi Task). We evaluated  
32 psychosocial factors through seven questionnaires – Epworth Sleepiness Scale, Pittsburgh  
33 Sleep Quality Index, Fatigue Severity Scale, Profile of the Mood States, 2<sup>nd</sup> edition, short  
34 version, Coping Inventory for Stressful Situations, Measurement of Ambiguity Tolerance,  
35 Motives for Physical Activities Measure-Revised, mental rotation capabilities and locomotor  
36 characteristics (physical activity level through embedded trackers and the International  
37 Physical Activity Questionnaire, and gait parameters). The most explanatory biopsychosocial  
38 determinants of VSM performance were i) mental rotation capabilities and fatigue indicator  
39 in reaching space, and ii) mental rotation capabilities and physical activity level (tracked  
40 active energy expenditure only) in walking space. These results suggest that specific  
41 parameters should be preferred for the evaluation and strengthening of VSM capabilities in  
42 both reaching or walking spaces.

43

## 44 **Keywords**

45 Visuospatial memory; Navigation; Physical activity level; Psychosocial factors; Fatigue;  
46 Mental rotation

47

## 48 **Abbreviations**

49

50 AEE: active energy expenditure

- 51 CISS: coping inventory for stressful situations
- 52 ECBT: e-Corsi block task
- 53 ESS: Epworth sleepiness scale
- 54 FSS: fatigue severity scale
- 55 IPAQ: international physical activity questionnaire
- 56 MAT-50: Measurement of Ambiguity Tolerance
- 57 MAPM-R: motives for physical activities measure, revised
- 58 MRT: mental rotation test
- 59 PA: physical activity
- 60 POMS-2: Profile of the Mood States, 2<sup>nd</sup> edition, short version
- 61 PSQI: Pittsburgh sleep quality index
- 62 SN: step number
- 63 VSM: visuospatial memory
- 64 VWCT: virtual walking Corsi task

## 65 **1. Introduction**

66

67 Visuospatial memory (VSM) is a fundamental cognitive function which maintains a sense of  
68 direction and location during a navigational task. VSM performance depends on extrinsic and  
69 intrinsic factors, such as space (Piccardi et al., 2014) or biopsychosocial parameters including  
70 cognitive (Wolbers & Hegarty, 2010) and motor functions (Merom et al., 2016).

71

72 VSM performance is influenced by the space where the experiment takes place (Coluccia &  
73 Louse, 2004; Piccardi et al., 2014). The effect of space during a pathway learning task is well  
74 known, with better performance found in walking than in reaching space (Piccardi et al.,  
75 2014). Many determinants of VSM performance are influenced by space, such as sex  
76 (Piccardi et al., 2014; Piccardi et al., 2008), age (Perrochon et al., 2018), memory (Lupo et  
77 al., 2018), encoding (Livingstone-Lee et al., 2014; Lupo et al., 2018; Piccardi et al., 2016),  
78 and exploration strategies (Livingstone-Lee et al., 2014). Overall, men perform better than  
79 women, younger better than older people, and people who spontaneously use an allocentric  
80 navigation strategy outperform the egocentric ones. Thus, reaching and walking spaces  
81 involve different cognitive (Piccardi et al., 2014) and motor (Röser et al., 2016) processes.  
82 Indeed, the navigation involved in walking space requires walking, mental rotation and  
83 reorientation.

84

85 In parallel, other factors seems to modify VSM performance, such as biopsychosocial  
86 parameters. On the cognitive aspect, we can mention psychosocial factors such as sleep  
87 (Nakagawa et al., 2016) or motivation (Pazzaglia et al., 2018) (i.e., spatial self-efficacy and  
88 pleasure in exploring) that increase VSM performance, and anxiety and/or stress (Pazzaglia et  
89 al., 2018; Wolbers & Hegarty, 2010) and fatigue that decrease it (Siengsukon et al., 2018).

90 Many other intrinsic parameters, such as recently described personality traits (Carbone et al.,  
91 2019) have an impact on VSM. One can also mention mental rotation capabilities, which  
92 influence environment learning (Pazzaglia & Meneghetti, 2012), as well as navigation and  
93 way-finding capacities (Hegarty et al., 2006; Labate et al., 2014).. With regard to the  
94 locomotor aspect, physical activity (PA) is positively correlated with VSM performance  
95 (Merom et al., 2016). An increase in PA level led to a greater VSM performance in younger  
96 (Stroth et al., 2009) and in older adults (Erickson et al., 2011; Merom et al., 2016; Wang et  
97 al., 2014). Furthermore, environmental factors, such as the type or level of PA practiced,  
98 might be a source of difference in VSM performance, especially sports activities stimulating  
99 the development of spatial capabilities (Coluccia & Louse, 2004; Merom et al., 2016;  
100 Wolbers & Hegarty, 2010).

101

102 Previous studies showed that VSM performance is influenced by many different parameters,  
103 but it remains to be determined which of these determinants contribute the most to  
104 performance, and whether these determinants differ according to space. We therefore  
105 investigated whether, and to what extent, VSM performance in different spaces could be  
106 associated with either cognitive (mental rotation capabilities and psychosocial parameters)  
107 and/or locomotor aspects (PA level, gait parameters). We hypothesised that different  
108 biopsychosocial parameters affecting VSM performance might be influenced by space (i.e.,  
109 mental rotation, psychosocial factors, PA level or gait parameters).

110

## 111 **2. Methods**

112

### 113 *2.1. Participants*

114

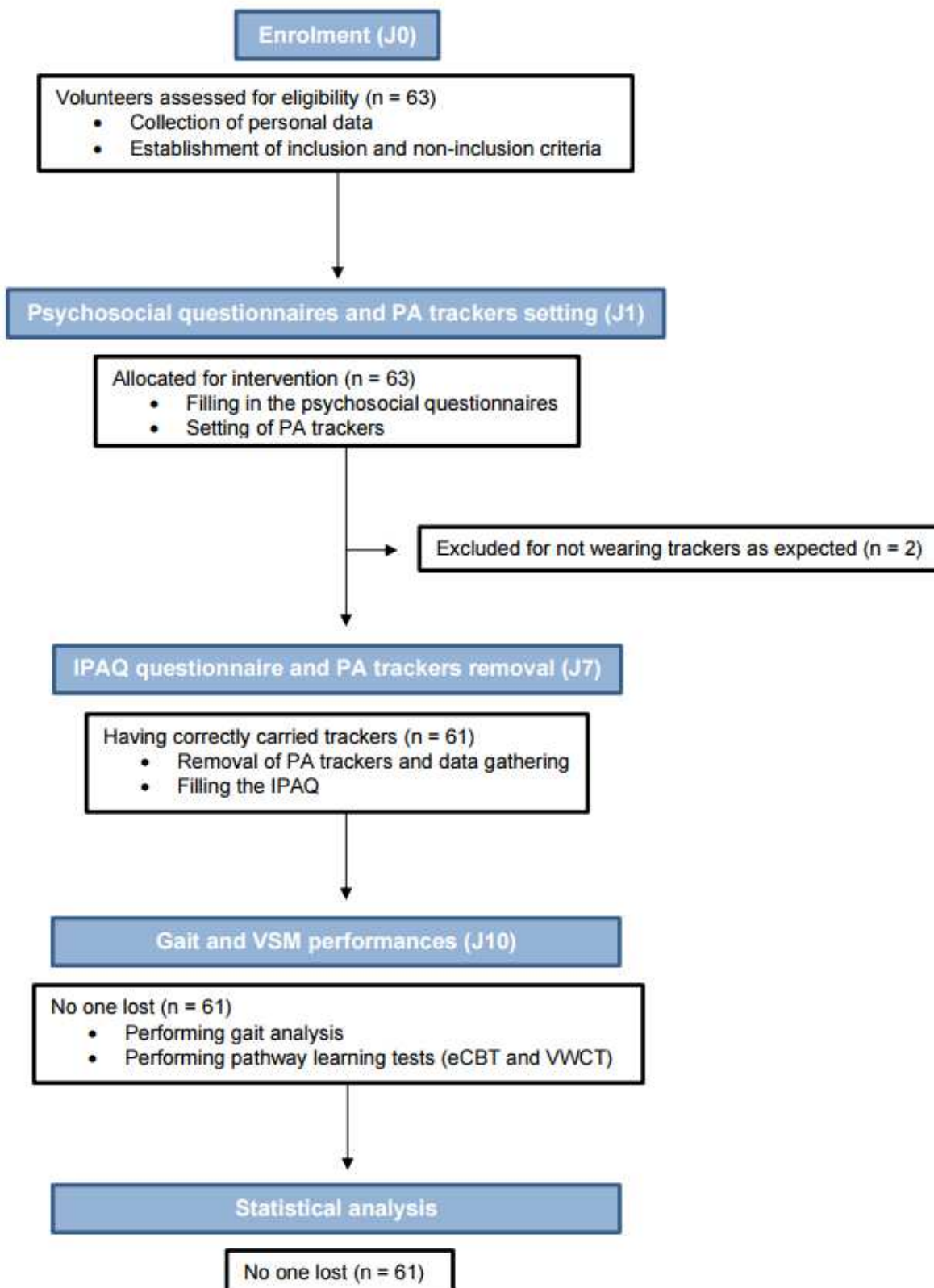
115 63 young healthy subjects volunteered for this cross-sectional study, and 61 were analysed  
116 (20 males, 41 females;  $23 \pm 3$  years old) (Figure 1). The inclusion criteria were age over 18  
117 years and fluent in French. The non-inclusion criteria were any diagnosis of disorders that  
118 could affect memory, perception or walking (physical, visual, perceptual, cognitive,  
119 neurological or psychiatric disorders). The exclusion criteria were to wear the PA tracker less  
120 than 75% of the time over 7 days. Informed consent was obtained from all participants in  
121 accordance with the guidelines of the local ethics committee.

122

## 123 *2.2. Experimental design and outcomes*

124

125 The assessment of subjects' VSM performance, locomotor (PA level, gait parameters) and  
126 cognitive aspects (psychosocial parameters and mental rotation capabilities) required four  
127 appointments scheduled within 10 consecutive days (Figure 1). Two distinct examiners made  
128 evaluations; one was responsible for VSM performance, while the other oversaw  
129 biopsychosocial assessments.



130

131 **Figure 1.** Study design and flow diagram

132

133 We evaluated subjects' VSM performance through a pathway learning task. We used the  
134 Corsi Block-tapping Test in reaching space (e-Corsi Block Task (ECBT)) and in walking  
135 space (Virtual Walking Corsi Task (VWCT)) according to methods described in literature  
136 (Perrochon et al., 2018). The VWCT was performed on the "*Virtual Carpet*", composed of  
137 the association between a projected scene and movement tracking (Perrochon et al., 2018).  
138 The subject had to memorize (*encoding phase*) and then repeat (*recall phase*) a sequence of  
139 elements, pointing on the screen during ECBT and navigating on the projected scene during  
140 VWCT. The validation of a sequence was given by the examiner and led to an increase in the  
141 number of illuminated elements composing the sequence (from 2 to 9). In case the subject  
142 missed twice, the test was stopped and we considered the number of elements of the last  
143 sequence repeated correctly as the span score (Berch et al., 1998). VSM performance was  
144 given by the span score that the subjects achieved in reaching both (ECBT) and walking  
145 (VWCT) space.

146

#### 147 2.1.1. Locomotor aspects

148

149 We evaluated subjects' PA level according to self-reports and tracker records. We used a  
150 validated questionnaire, the International Physical Activity Questionnaire (IPAQ) (Craig et  
151 al., 2003), estimating the time spent resting or in activity during these last 7 days. The  
152 continuous record consisted in wearing a PA tracker, the Armband ® (Bodymedia,  
153 Pittsburgh, USA) on the left triceps muscle for 7 days. This embedded tool, which is  
154 automatically activated in contact with skin, has been validated in the ongoing daily  
155 evaluation of steps and energy expenditure (Alharbi et al., 2017). We analysed the active  
156 energy expenditure (AEE) and the step number (SN) as a daily average calculated over 7

157 days. This information was provided by the Armband ® data gathering (*software* SenseWear  
158 Professional ® 7.0).

159

160 We analysed subjects' gait over 20 meters with motion sensors MTi-1® (XSens, Enschede,  
161 Netherlands), which informed us about subjects' gait speed ( $\text{m}\cdot\text{s}^{-1}$ ) and gait cycle time  
162 variability(ies). Each subject had to walk over 10 meters back and forth with a half-turn  
163 around a post halfway, at a spontaneous speed, wearing two sensors on the feet, one on the  
164 back, and one on the forehead.

165

### 166 *2.2.1. Cognitive aspects*

167

168 To assess subjects' psychosocial factors, we used seven questionnaires focusing on i) sleep  
169 (Epworth Sleepiness Scale (ESS) (Johns, 1991), Pittsburgh Sleep Quality Index (PSQI)  
170 (Buysse et al., 1989)), ii) fatigue (Fatigue Severity Scale (FSS) (Krupp et al., 1989), Profile  
171 of the Mood States, 2<sup>nd</sup> edition, short version (POMS-2) (Heuchert & McNair, 2012)), iii)  
172 stress (Coping Inventory for Stressful Situations (CISS) (Endler & Parker, 1990)), iv)  
173 flexibility as personality trait (Measurement of Ambiguity Tolerance (MAT-50) (Norton,  
174 1975)), and v) motivation (Motives for Physical Activities Measure-Revised (MPAM-R)  
175 (Ryan et al., 1997)). All these questionnaires were provided by the examiner and completed  
176 by the subject through the SphinxOnline® platform in the presence of the examiner, who  
177 answered questions.

178

179 To evaluate the subjects' mental rotation capabilities, we used the Mental Rotation Test  
180 (MRT) (Peters et al., 1995). The MRT is a paper and pencil test consisting of 24 items, in

181 which the candidate must recognize, among 4 forms, the one corresponding to the presented  
 182 model.

183

## 184 *2.2. Statistical analysis*

185

186 Univariable linear regressions were performed to examine relationships between PA level,  
 187 psychosocial factors, gait parameters or mental rotation capabilities (independent variables)  
 188 and span scores in ECBT and VWCT (dependent variables) to determine which of these  
 189 should be integrated in the subsequent multivariable regression models. Separate  
 190 multivariable linear regressions were run to examine whether biopsychosocial variables  
 191 would predict VSM performances in different spaces. We controlled the multicollinearity by  
 192 deleting the predictors whose variance inflation factors value  $< 5$ . The statistical analysis was  
 193 performed using IBM SPSS ® Statistics version 22 (IBM Corp, Armonk, USA), and result  
 194 significance was set with  $p < 0.05$ .

195

## 196 **3. Results**

197

### 198 *3.1. Participant data*

199

200 Participant characteristics; VSM performance, PA level (self-reported and tracked), gait  
 201 parameters, psychosocial factors, and mental rotation capabilities are summarized in Table 1.

202

203

Mean ± SD	<i>r</i> -value	
	e-CBT	VWCT

<b>Demographic characteristics</b>			
Males/Females (n = 61)	20 / 41	0.17	<b>0.43**</b>
Age (years)	23 ± 3	0.02	-0.09
BMI (kg/m <sup>2</sup> )	23 ± 3	-0.07	0.00
<b>Visuospatial Memory Performance</b>			
<i>Reaching space</i>			
ECBT span score (/9)	7.64 ± 0.93	-	<b>0.46**</b>
<i>Walking space</i>			
VWCT span score (/9)	6.62 ± 1.27	<b>0.46**</b>	-
<b>LOCOMOTOR</b>			
<b>Physical Activity Level</b>			
<i>Tracked</i>			
Armband ®			
AEE (kcal)	840 ± 457	<b>0.38**</b>	<b>0.49**</b>
SN	8367 ± 3722	0.22	<b>0.34**</b>
<i>Self-reported</i>			
IPAQ score (MET/min)	1970 ± 2067	-0.15	0.06
<b>Gait</b>			
Gait speed (m/s) ‡	1.13 ± 0.18	<b>0.29*</b>	0.12
Gait cycle time variability (s)	0.19 ± 0.03	0.06	0.19
<b>COGNITIVE</b>			
<b>Psychosocial Factors</b>			
<i>Fatigue and sleep</i>			
ESS (/24)	9.5 ± 4	0.01	-0.08
PSQI (/21)	7.2 ± 2.7	<b>-0.27*</b>	<b>-0.32*</b>
FSS (/7)	2.9 ± 1	<b>-0.44**</b>	<b>-0.40**</b>

POMS-2 (/200)	31.8 ± 29	0.00	-0.16
Fatigue (/28)	9.8 ± 4.9	-0.11	<b>-0.37**</b>
<i>Flexibility</i>			
MAT-50 (/427)	267.7 ± 29.2	-0.02	0.05
<i>Stress</i>			
CISS			
Task items (/80)	57.3 ± 9.1	0.15	0.19
Emotion items (/80)	46.6 ± 10.8	-0.10	-0.22
Avoidance items (/80)	42.3 ± 10.1	0.11	-0.03
<i>Motivation</i>			
MPAM-R			
Intrinsic motivation (/21)	5.4 ± 1.6	0.02	0.01
Extrinsic motivation - Integrated (/21)	4.8 ± 1.9	0.17	0.18
Extrinsic motivation - Identified (/21)	5.6 ± 1.5	0.02	-0.03
Extrinsic motivation - Introduced (/21)	4.7 ± 1.6	-0.01	0.01
Extrinsic motivation - External regulation (/21)	1.3 ± 0.7	-0.18	-0.14
Amotivation (/21)	1.2 ± 0.7	0.02	-0.11
<b>Mental Rotation</b>			
MRT (/24) §	4.6 ± 2.6	<b>0.26*</b>	<b>0.37**</b>

204

205 **Table 1: Relationship between VSM performance and biopsychosocial parameters in**  
206 **different spaces.**

207

208 *ns*: non-significant; \*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$ . Body mass index (BMI); e-Corsi  
209 Block Task (ECBT); Virtual Walking Corsi Task (VWCT); Active energy expenditure  
210 (AEE); Number of steps (SN); International Physical Activity Questionnaire (IPAQ);

211 Epworth Sleepiness Scale (ESS); Pittsburgh Sleep Quality Index (PSQI); Fatigue Severity  
212 Scale (FSS); Profile of the Mood States, 2<sup>nd</sup> edition, short version (POMS-2); Coping  
213 Inventory for Stressful Situations (CISS); Measurement of Ambiguity Tolerance (MAT-50);  
214 Motives for Physical Activities Measure-Revised (MPAM-R); Mental Rotation Test (MRT).  
215 ‡: N = 60; §: N = 59.

216

### 217 3.2. Univariable linear regression

218

219 Significant correlations between VSM performance and biopsychosocial parameters are  
220 shown in Table 1. Gender was associated with VWCT ( $r = 0.43$ ,  $p < 0.001$ ), but not with  
221 ECBT. As expected, there was a significant correlation between ECBT and VWCT span  
222 scores ( $r = 0.46$ ,  $p < 0.01$ ).

223

224 In reaching space (i.e., ECBT), VSM performance was correlated with AEE ( $r = 0.38$ ,  $p <$   
225  $0.001$ ), gait speed ( $r = 0.29$ ,  $p < 0.05$ ), fatigue factor PSQI ( $r = -0.27$ ,  $p < 0.05$ ), indicator FSS  
226 ( $r = -0.44$ ,  $p < 0.001$ ), and MRT ( $r = 0.26$ ,  $p < 0.05$ ). ECBT was most strongly correlated with  
227 FSS.

228

229 In walking space (i.e., VWCT), VSM performance was significantly correlated with AEE ( $r =$   
230  $0.49$ ,  $p < 0.001$ ), SN ( $r = 0.34$ ,  $p < 0.001$ ), fatigue factor PSQI ( $r = -0.32$ ,  $p < 0.05$ ) and  
231 indicators FSS ( $r = -0.40$ ,  $p < 0.001$ ), POMS-2 fatigue ( $r = -0.37$ ,  $p < 0.001$ ), and MRT ( $r =$   
232  $0.37$ ,  $p < 0.001$ ). VWCT was most strongly correlated with AEE, FSS, POMS-2 fatigue and  
233 MRT.

234 All other psychosocial variables were not associated with VSM performance in two spaces.

235

236        *3.3. Multivariable linear regression*

237

238    In the multivariate linear regressions, we integrated gender in the model as a control variable,  
239    and the main significant variables significant in both spaces from the univariate linear  
240    regression to predict VSM performance in the ECBT and VWCT.

241    Results in Table 2.a show that only MRT and FSS were significantly associated with ECBT  
242    ( $p < 0.05$ ). Other biopsychosocial variables were not related with ECBT. We performed a  
243    similar hierarchical linear regression for walking space, and we determined that AEE and  
244    MRT remained significant predictors of VWCT ( $p < 0.05$ ), as can be seen in Table 2.b. Other  
245    biopsychosocial variables were not associated with VWCT.

246

Category	$\beta$	[95% CI]	p		Category	$\beta$	[95% CI]	p	
Gender	-0.288	[-0.834, 0.257]	0.293	249	<b>a) E</b>  <b>CB</b>  <b>T</b>	Gender	0.303	[-0.393, 1.000]	0.387
AEE	0.001	[0.000, 0.001]	0.065	250		AEE	0.001	[0.000, 0.002]	<b>0.028*</b>
MRT	0.105	[0.022, 0.187]	<b>0.015*</b>	251		MRT	0.131	[0.021, 0.242]	<b>0.021*</b>
FSS	-0.228	[-0.444, -0.012]	<b>0.039*</b>	252		FSS	-0.271	[-0.562, -0.021]	0.079
PSQI	-0.012	[-1.390, 0.253]	0.780	253		PSQI	0.026	[-0.141, 0.089]	0.649
				254	adju				

255       sted  $R^2 = 0.285$

**b) VWCT**

adjusted  $R^2 = 0.406$

256 **Table 2. Multivariate linear regression to determine biopsychosocial variables which predict visuospatial memory performance in**  
 257 **reaching (a) and walking space (b) (n=59).**

258

259  $\beta$  = Unstandardized beta coefficient; \*  $p < 0.05$ . Active energy expenditure (AEE); mental rotation test (MRT); fatigue severity scale (FSS);

260 Pittsburgh Sleep Quality Index (PSQI).

261  
262 We found that PA level and mental rotation significantly predicted VSM performance in  
263 walking space, whereas fatigue and mental rotation predicted VSM performance in reaching  
264 space. Interestingly, the total variance accounted for was 28.5% in reaching space (i.e., e-  
265 CBT), whereas it was above 40.6% in walking space (i.e., VWCT) (Tables 2.a and 2.b).

266

#### 267 **4. Discussion**

268

269 In this study, we investigated the determinants of VSM performance during a pathway  
270 learning task in different spaces. The most explanatory biopsychosocial determinants of VSM  
271 performance were mental rotation capabilities and fatigue indicator (i.e., MRT and FSS) in  
272 reaching space, and mental rotation capabilities and PA level (i.e., MRT and AEE) in walking  
273 space.

274

##### 275 *4.1. Determinants of VSM performance in different spaces*

276

277 In view of our results, we can suggest that mental rotation capabilities are specifically  
278 associated with the nature of the VSM task (i.e., pathway learning) (Muffato et al., 2019;  
279 Pazzaglia et al., 2018), while fatigue and PA level are more specific to space.

280

##### 281 *4.1.1. Mental rotation in both spaces*

282

283 We found that mental rotation capabilities were associated with VSM performances in both  
284 spaces, and these relationships were resistant in the multivariable linear regression models.  
285 Mental rotation capabilities seemed to represent a determining parameter of VSM  
286 performance in reaching space and in navigation. This is in line with the literature, in which

287 mental rotation capabilities are known to play a role in environment learning (Pazzaglia &  
288 Meneghetti, 2012), and way-finding capacities (Hegarty et al., 2006; Labate et al., 2014) in  
289 reaching space. Mental rotation capabilities are also known to play a role during acquisition  
290 and navigation in walking space (Labate et al., 2014): beyond motor and posture control,  
291 mental rotation is an important cognitive task needed for spatial updating during a Corsi  
292 Block-tapping Test in navigation (i.e., VWCT) (Röser et al., 2016).

293

#### 294 *4.1.2. Fatigue in reaching space, PA level in walking space*

295

296 We found that PA level (i.e., AEE) was associated with VSM performance in navigation  
297 (VWCT). This relationship is usually demonstrated in reaching space (Erickson et al., 2011;  
298 Merom et al., 2016; Wang et al., 2014), but was unexplored in walking space. We did not find  
299 this result because we studied more explanatory determinants of VSM performance in  
300 reaching space (i.e., fatigue that statistically exceeds the PA level in the multivariable model).  
301 Furthermore, we observed that this relationship between VSM performance and PA level  
302 appears for the tracked PA level only, and never for the self-reported PA level. This  
303 difference can be explained by the varying level of reliability of these two instruments. The  
304 self-reported perceived PA level is often overestimated (Dyrstad et al., 2014), whereas the  
305 AEE parameter was obtained by a validated activity tracker (Alharbi et al., 2017). PA level,  
306 measured by PA tracker, seemed to represent a determining parameter of VSM performance  
307 in walking space. We believe that walking represents an important part of the PA tracked in  
308 our subjects, inducing navigation and soliciting spatial cognition (spatial updating,  
309 reorientation, mental rotations). The underlying mechanism seems to be that the individual  
310 fitness level has an impact on brain region activation associated with spatial learning  
311 (Holzsneider et al., 2012). More generally, PA encourages brain plasticity, increasing

312 cerebral blood flow and oxygenation (Cameron et al., 2015), as well as the size of the anterior  
313 hippocampus, leading to improvements in spatial memory (Erickson et al., 2011). PA could  
314 even be an epigenetic modulator of brain plasticity and cognition, influencing long-term brain  
315 function and behaviour (Fernandes et al., 2017).

316

317 On the other hand, we found that VSM performance in reaching space was negatively  
318 associated with the fatigue indicator (i.e., FSS), assessing the effect of fatigue on different  
319 activities. Previous studies have demonstrated the relationship between sleep (Nakagawa et  
320 al., 2016) or fatigue (Siengsukon et al., 2018) and VSM performance in reaching space. This  
321 is the first study which demonstrates a relationship between fatigue and pathway learning in  
322 reaching space. An increase in subjects' fatigue level during continuous performance of  
323 cognitive tasks has already been shown (Sengupta et al. 2017). In our study, ECBT and  
324 VWCT are particularly long and uninterrupted cognitive tasks that seem to be sensitive to  
325 fatigue. Indeed, the ECBT and VWCT tests required encoding and restoring spans ranging  
326 from 2 to 9 elements. During the encoding phase, the sequence was presented with a 1.5  
327 second illumination and 1 second extinction frequency. During the restitution phase, the  
328 subject was asked to respect an equivalent frequency. In addition, the average performance  
329 score is greater than 6, and each span level could be achieved once, or twice in the event of  
330 failure. Thus, each participant performed a continuous cognitive task for approximately 20  
331 minutes. Nevertheless, fatigue was not resistant in the multivariable linear regression model in  
332 walking space, because of more explanatory determinants of VSM performance (i.e., MRT  
333 level).

334

335 *4.2. The least explanatory biopsychosocial parameters of VSM performance*

336

337 Beyond the most explanatory biopsychosocial parameters of the VSM performance  
338 previously discussed, it is worth noting that we evaluated a certain number of parameters that  
339 do not emerge from the univariate or multivariate statistical analysis. Thus, in this study, age,  
340 body mass index, self-reported PA level (IPAQ), sleepiness (ESS), flexibility (MAT-50),  
341 stress (CISS), and motivation (MPAM-R) were not associated with VSM performance in  
342 reaching or walking space. It is worth noting that our results are probably not due to chance  
343 nor to the amount of variables introduced in the model, because the most explanatory  
344 biopsychosocial parameters of the VSM performance we found are in line with the literature  
345 (mental rotation, physical activity level) and vice-versa for those not correlated (body mass  
346 index, gait parameters). Furthermore, we are only discussing the most explanatory  
347 biopsychosocial parameters of VSM performance, and other parameters participate to a lesser  
348 extent, but do not appear in the multivariate model. For example, gender was correlated with  
349 VSM performance but became nonsignificant after controlling other variables in multivariate  
350 regressions. This may be because these parameters are usually studied independently, and not  
351 grouped together. In addition, some parameters are cofactors, such as gender and mental  
352 rotation capabilities, in which men outperform women (Coluccia & Louse, 2004).  
353 Nevertheless, we can argue that the nature of the task may be the reason why gait was not  
354 associated with VSM performance: the spontaneous gait used during the walking test was not  
355 the one used during VWCT, which contained an additional cognitive task, the need to reorient  
356 oneself, and no time constraint. Regarding motivation, anxiety and depression, they were not  
357 resistant in the multivariable linear regression models, while they are described as associated  
358 with VSM performance (Pazzaglia et al., 2018; Wolbers & Hegarty, 2010). This may be  
359 because we did not use the same scales nor assessed the same parameter dimensions. These  
360 authors investigated motivation and anxiety related to navigation (including anxiety and

361 pleasure in exploring), while we measured motivation for physical activity and general  
362 stressful situations.

363

#### 364 *4.3. Methodological considerations*

365

366 VSM and navigation performance are influenced by encoding strategies or reorientation  
367 (Coluccia & Louse, 2004; Wolbers & Hegarty, 2010). We could also mention the gender  
368 effect, navigation strategies, as well as certain hormone levels known to influence orientation  
369 and navigation performance (Brake & Lacasse, 2018; Scheuringer & Pletzer, 2017). Further  
370 research might benefit from including all these known factors to refine the results, in  
371 particular regarding the total variance, and therefore the explanatory part of the different  
372 determinants studied. In addition, it would be interesting to measure brain activity to better  
373 understand the areas involved in each space.

374

#### 375 **Conclusion**

376

377 In both spaces, VSM performance during a pathway learning task was associated with mental  
378 rotation capabilities. Among various psychosocial factors, VSM performance was associated  
379 with a fatigue indicator in reaching space, and with active energy expenditure, not self-  
380 reported PA level, in walking space. Taken together, these results suggest that specific  
381 parameters should be preferred for the evaluation and strengthening of VSM capabilities in  
382 subjects to increase their navigation capabilities; i.e., their mental rotation capabilities, and  
383 their actual level of PA.

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399 All authors declare to have seen and approved the final version.

400

401 **Open Practices Statement**

402 None of the data or materials for the experiments reported here is available, and none of the

403 experiments were preregistered.

404

405

406 **References**

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