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# Effect of the Level of Physical Activity on Prefrontal Cortex Hemodynamics in Older Adults During Single- and Dual-Task Walking

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The present study aimed to examine the impact of the level of physical activity on prefrontal cortex activation in older adults during single- and dual-task walking. Thirty physically inactive and 36 active older adults (60–85 years old) performed six 2-min tasks on a treadmill: two static cognitive tasks, two single-task walking tests, and two dual-task walking tests. Hemodynamics at the level of the prefrontal cortex were measured continuously using functional near-infrared spectroscopy to evaluate cortical activation. The perceived difficulty of the task, cognitive performance, and gait parameters were also measured. During the walking tasks, the level of prefrontal cortex activation, the perceived difficulty of the task, cognitive performance, and motor parameters were not significantly different between active and inactive older adults. This unchanged activation with physical activity was likely the consequence of a similar motor and cognitive load and cardiorespiratory fitness in both active and inactive older adults.

**Keywords:** exercise, PFC, gait, cognition, fNIRS

Normal aging results in decreased motor and cognitive performance (Holtzer et al., 2014), which can be explained, in part, by changes in brain volume and function associated with advanced age (Park & Reuter-Lorenz, 2009; Park et al., 2001). Since the pioneering study of Colcombe et al. (2003) that showed the prophylactic effects of regular exercise on prefrontal cortex (PFC) (Colcombe et al., 2003), numerous transversal and interventional studies showed that physical activity can optimize the volume, integrity, and brain function of certain areas associated with the performance of executive and motor functions, including the PFC (Domingos et al., 2021). In particular, it was shown that high-fit older adults display higher PFC oxygenation during a cognitive task than low-fit older adults (Albinet et al., 2014; Dupuy et al., 2015), particularly under the highest cognitive load, that is, when the task is very demanding (Agbangla et al., 2019). This higher cerebral oxygenation could be partly linked to a higher O<sub>2</sub> delivery to the brain in high-fit older adults as a high cardiorespiratory fitness can be associated with angiogenesis, enhanced vascular plasticity, and vascular health (Agbangla et al., 2021).

Functional near-infrared spectroscopy (fNIRS), which shares the same physiological bases as functional magnetic resonance imaging (Perrey, 2008), is a useful tool to measure regional hemodynamic changes at the cortical level both at rest and during cognitive and/or motor stimulation. NIRS measures variations in blood concentrations of oxygenated hemoglobin (HbO<sub>2</sub>) and de-HbO<sub>2</sub> (HbR) at the cortical level. Based on the neurovascular coupling, this technique can provide information about brain

activation during a task. It allows the easy, quick, silent, inexpensive, and noninvasive study of cortical activity of the PFC in real time (Ekkekakis, 2009; Holtzer et al., 2014).

During normal walking, attention and executive functions (cognitive functions associated with the PFC) are solicited during both gait preparation (Suzuki et al., 2008) and performance (Hamacher et al., 2015; la Fougère et al., 2010). PFC activation increases with the pace of the gait (Suzuki et al., 2004), particularly in older adults (Harada et al., 2009; Stuart et al., 2018), suggesting that PFC activity is intimately related to walking speed. PFC activation is also dependent on the complexity of the task (e.g., precision stepping, crossing obstacles, completing a second walking task), which tends to activate the PFC more than single-task (ST) walking (Pelicioni et al., 2019). The nature of the walking surface (i.e., walking on the floor or on a treadmill) can also influence PFC activation as the PFC appears to be activated more by walking on a treadmill than on the floor (Clark et al., 2014; Herold et al., 2019). Finally, Harada et al. (2009) divided older adults into higher and lower gait capacity groups and found that this grouping has no effect on PFC activation during walking on a treadmill, except at high speed. This result suggests a similar cognitive load during gait in low-fit compared with high-fit older adults when walking at a comfortable speed.

Despite some contradictory results due mainly to methodological differences (Pelicioni et al., 2019), the PFC in older people appears to be activated more during a dual cognitive walking task than during ST walking (Holtzer et al., 2015; Nóbrega-Sousa et al., 2020). Although there is still too little study during natural walking, age appears to increase PFC activity during a dual task (DT; Nóbrega-Sousa et al., 2020). At the same time, a DT often modifies gait parameters in comparison with ST walking (e.g., decrease in gait speed and stride length or increase in spatiotemporal variability), with these changes increasing with age (Pelicioni et al., 2019). There are few studies on the effect of physical activity in older

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adults during DT walking, and those that exist have focused only on the performance of the cognitive task (Tomprowski & Audiffren, 2014). To date, no study has evaluated the effect of physical activity on PFC activation in older people during DT walking as well as ST walking.

In this context, the main objective of this study was to examine the impact of the level of physical activity of older adults on PFC activation during ST and DT walking, physical activity being defined as any bodily movement produced by skeletal muscles and resulting in energy expenditure (Caspersen et al., 1985). In line with Harada et al.'s findings (2009), when ST walking with low demands, we expect no difference in PFC activity between active and inactive older adults. We consider that a high cardiorespiratory fitness level could induce greater PFC activation during a static cognitive task in older adults, and physically active lifestyle is favorable for a higher cardiorespiratory fitness level. Therefore, when DT walking, with the added demands of a cognitive task, we expect greater PFC activation in the physically active than the inactive older adults. Those who are physically active are expected to have greater cerebral perfusion capabilities than those who are inactive (Agbangla et al., 2019).

## Methods

### Participants

Sixty-nine individuals aged 60–85 years were included in this study and divided into two experimental groups (33 inactive older adults and 36 active older adults) based on their estimated amount of physical activity during the previous year using the Modifiable Activity Questionnaire (MAQ; Vuillemin et al., 2000). Volunteers were recruited from older adults' communities and/or associations around the metropolis of Orleans using flyers, emails, phone calls, and oral presentations at the place of their activities. The characteristics of the 66 participants are described in Table 1. The

participants were included if they were able to walk for at least 5 min without assistance and if they had no cognitive or psychiatric comorbidity. They were excluded if they had clinically significant medical conditions that could affect motor or cognitive performance, such as Mini-Mental State Examination score <24, resting cardiac abnormalities and postural instability, or depression assessed according to the Geriatric Depression Scale >10. All participants provided informed written consent prior to participation and data collection. The study was approved by an ethics committee (84–18 CPP Ile de France VI) and was performed according to the principles of the Declaration of Helsinki.

### Procedures

All participants participated in two experimental sessions on two different days. During the first session, informed consent was collected, their global cognitive status was assessed by clinical examination and Mini-Mental State Examination, and their functional capacity and balance were determined using a 6-Min Walking Test (6MWT; Rikli & Jones, 2013) and an unipedal station test, respectively. The participants also completed two questionnaires (MAQ and Geriatric Depression Scale). During this session, the cognitive task of random generation of numbers (RNG) to be evaluated during the following experiment was explained to the participants, and they performed a practice trial of this test.

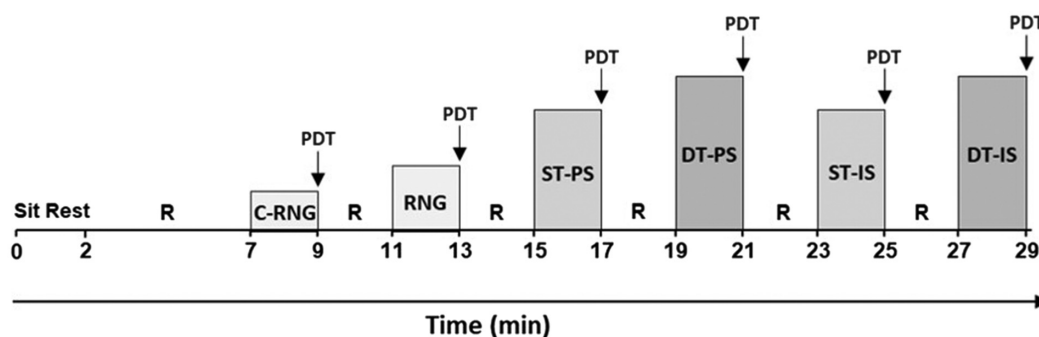
During the second experimental session, the comfortable walking speed (preferred speed [PS]) was determined both on the floor (over 10 m) and on a treadmill. The participants were prepared for the fNIRS recording prior to the performance of the six tasks described next. Then, they were all asked to perform six 2-min tasks on the treadmill separated by 2-min rest periods (including before the first task; Figure 1). The first two tasks were performed while standing still: a control of numbers generation task (without constraints) (C-RNG), then the RNG cognitive task. Then, the subsequent tasks were four random walking tasks: two

**Table 1** Demographic, Cognitive, Clinical, and Physical Data of Participants

Characteristics	Inactive older adults ( <i>n</i> = 30)	Active older adults ( <i>n</i> = 36)	<i>p</i>
Age (years)	69.2 ± 5.4	69.9 ± 4.9	.56
Sex (male/female)	14/16	18/18	
Height (cm)	165.6 ± 9.6	165.4 ± 8.3	.91
Weight (kg)	77 ± 14.3	68 ± 12.1	.008*
BMI (kg/m <sup>2</sup> )	28 ± 4.7	24.8 ± 3.6	.003*
Education			
ISCED 2011 (0–8)	5.1 ± 1.7	5.1 ± 1.6	.91
Global cognition			
MMSE (0–30)	28.7 ± 1.3	28.7 ± 1.4	.35
Depression			
Geriatric depression scale (0–30)	2.9 ± 3.6	2.4 ± 2.3	.54
Motricity			
Modifiable activity questionnaire (hr/week)	1.8 ± 0.4	10.4 ± 5.8	<.001*
6MWT (m)	584.3 ± 79.7	610.9 ± 77.9	.18
Preferred ground speed 10 m (km/hr)	4.6 ± 0.6	5.1 ± 0.7	.003*
Preferred treadmill speed (km/hr)	3.2 ± 0.5	3.7 ± 0.5	<.001*

*Note.* Data are presented as mean ± *SD*. BMI = body mass index; ISCED = International Standard Classification of Education; MMSE = Mini-Mental State Examination; 6MWT = 6-Min Walking Test.

\*Significantly different between inactive older adults and active older adults.



**Figure 1** — Experimental design for static and randomized walking conditions. R = standing rest; C-RNG = control number generation task; RNG = random number generation task; ST = single task; DT = dual task; PS = preferred speed; IS = imposed speed; PDT = perceived difficulty of the task.

ST walking and two DT walking (i.e., walking while simultaneously performing the cognitive task; DT). One ST and one DT were performed at the imposed speed of 3 km/hr (IS) and one ST and one DT were performed at the treadmill PS. The six tasks were: C-RNG, RNG, ST-IS, ST-PS, DT-IS, and DT-PS. Before each task, the participants were instructed to rest upright on the treadmill while remaining as still as possible and staring at a target in front of them.

### Target Variables

To evaluate the participants' level of physical activity during the previous year, we used the self-administered version of the MAQ (Vuillemin et al., 2000), which is a modified version of the interviewer-administered original version of the MAQ (Kriska & Caspersen, 1997). The investigator was present to guide the participant in completing the questionnaire. To form two distinct groups of older adults based on their level of physical activity, we considered older adults who practiced a physical activity <2 hr/week as inactive and those who practiced a physical activity >4 hr/week as active.

The total distance covered during the 6MWT (Rikli & Jones, 2013) provided an estimation of the participants' functional capacity. We also evaluated PS on the floor using the average of three trials of a 10-m walk. Finally, after walking on the treadmill for few minutes to get accustomed to it, the participants determined their treadmill PS autonomously, without seeing the speed displayed, to allow them to experience sensations similar to those of walking on the floor.

Before the walking evaluation, the participants performed a control cognitive task (C-RNG). For the C-RNG task, they were instructed to count from 1 to 9 out loud at a comfortable speed. Then, the RNG task was performed while standing still and then during DT walking (i.e., three times by each participant). This task is classically associated with executive control (Baddeley, 1996). The instruction for the RNG task was to say the numbers one to nine in a random fashion as quickly as possible without repeating the same number in sequence (e.g., 1–1) or saying a pair of adjacent ascending and descending numbers (e.g., 2–3 or 6–5). Moreover, to encourage natural walking behavior, no special instruction was given regarding the prioritization of task performance.

Under all walking conditions (ST-IS, ST-PS, DT-IS, and DT-PS), the spatiotemporal walking parameters were recorded using a 1-m rail affixed on either side of the treadmill (OptoGait, Microgait). The data from this device were collected and analyzed by the associated software (OptoGait, version 1.12.1.0). We also measured heart rate during each task using a heart rate monitor (RCX5 Polar, Polar Electro Oy).

For each of the six experimental conditions (C-RNG, RNG, ST-IS, ST-PS, DT-IS, and DT-PS), the participants assessed the perceived difficulty of the task using the DP-15 rating scale (Delignières et al., 1994). This scale is composed of 15 levels associated with verbal information (ranging from extremely easy at Level 2 to extremely difficult at Level 14) and is derived from the Borg rating of the perceived effort scale (Borg, 1998). DP-15 was presented to the participant 15 s after the completion of each task (with no reminders of previous ratings).

The PFC oxygenation was assessed using a continuous-wave NIRS system (OxyMon MKIII, Artinis Medical Systems) utilizing two wavelengths (765 and 855 nm). NIRS signals were measured at 10 Hz. The NIRS probe is composed of two light laser sources and one photodiode detector, resulting in two channels. The source and detector were spaced 38 mm apart, providing a light penetration depth of approximately 14 mm (Patil et al., 2011), which provided an actual measure of oxygenation at the cortex level. The probe was positioned on the PFC based on the 10–20 electroencephalogram maps at a height of 10% of the nasion–inion and at a distance from the nasion of 5% of the circumference of the head to the left of the midline (Klem et al., 1999). These locations roughly target the left Brodmann's Area 10, corresponding to the dorsolateral and anterior PFC. To optimize the signal-to-noise ratio during fNIRS recording, the two optodes were protected from ambient light on the target areas using a black swimming cap. All of the cables were suspended to minimize movement artifacts. During the resting phases, the participants were asked to stand as still as possible (in particular, avoiding head and eye movements by staring at targets) and to try not to think ("try to empty your mind as much as possible"). During the tasks, the same instructions were given concerning eye and head movements. The aim of all of these instructions was to minimize the risk of bias as much as possible (physiological and nonphysiological responses to movements and brain activity for thoughts). During data collection, signal quality and the absence of movement artifacts were checked constantly.

### Cognitive Task Analysis

Each RNG task was recorded and analyzed using Towse and Neil's RgCalc software (1998). We evaluated cognitive performance by the number of digits spoken in 2 min (number/2 min) and by the adjacency score, which reflected counting inhibition. This adjacency score, expressed as a percentage, was the number of pairs of ascending and descending adjacent numbers relative to the total

number of pairs of responses produced by the participant. Thus, adjacency scores ranged from 0% (no adjacent pairs) to 100% (only adjacent pairs generated), indicating, in this case, poor executive performance. The adjacency score was chosen for its reliability in measuring inhibition under time constraints (Miyake et al., 2000; Towse & Neil, 1998) and its sensitivity to the effects of aging and physical condition (Abou-Dest et al., 2012; Albinet et al., 2014; Boucard et al., 2012).

### Gait Analysis

Measurements were selected over 100 s of walking out of a total of 120 s (i.e., during the plateau phase of the target walking speed [IS or PS] when the participants were not holding onto the treadmill and were swinging their arms normally).

The index chosen to assess gait variability was the coefficient of variation (CV) of the stride length (Hausdorff, 2005) and cadence ( $(SD/\text{mean}) \times 100$ ).

### Near-Infrared Spectroscopy Analysis

Oxysoft software (Artinis) provided data on the intensity changes of light at 765 and 855 nm. These NIRS data were preprocessed using Homer 2 software (version 2.1), a MATLAB-based toolbox (Huppert et al., 2009). Raw intensity was converted to optical density. Motion artifacts were detected using an *SD* range of 20, and data were corrected using a spline interpolation (Brigadoi et al., 2014). A low-pass filter was employed with a cutoff frequency at 1 Hz. Finally, optical density was converted into relative concentrations of HbO<sub>2</sub> and HbR via the modified Beer–Lambert law (Obrig & Villringer, 2003) after correcting for a differential path-length factor of 6.61. After this preprocessing step, data were averaged over 1 min (between 45 s and 1 min 45 s) during the resting period preceding each task and over the 2 min of each task. Then, the differences between the averaged data during the task (activation values) and the resting state were calculated both for HbO<sub>2</sub> and HbR ( $\Delta\text{HbO}_2$  and  $\Delta\text{HbR}$ ).

### Statistical Analysis

Data are presented as mean values  $\pm$  *SD* of the mean (*SD*). A Student's *t* test was used to identify characteristics differences between groups, and a Student's paired *t* test was used to compare  $\Delta\text{HbO}_2$  and  $\Delta\text{HbR}$  with zero in each group.

A repeated-measures analysis of variance with two factors, group (physically active and inactive older adults) and task (C-RNG, RNG, ST-IS, ST-PS, DT-IS, DT-PS), was also used. When a significant effect was observed, a post hoc Fisher's least significant difference test was used to locate the differences. Analyses were performed in STATISTICA, a statistics software for Windows (version 7.1, StatSoft Inc.), and the differences were considered significant at  $p < .05$ .

## Results

### Participants

Three inactive older adults did not complete the study, one due to tendonitis, a second due to a lack of availability, and the third due to a vagal malaise at the start of the second experimental visit. Age, height, education, cognition, depression, and distance at the 6MWT were not significantly different between groups, whereas weight and body mass index were significantly higher in inactive

adults than in active older adults (Table 1). Compared with active older adults, inactive older adults practiced significantly fewer hours of physical and sports activity per week ( $1.76 \pm 0.43$  vs.  $10.42 \pm 5.80$  hr/week) and had a significantly lower preferred walking speed both on the floor ( $4.6 \pm 0.6$  vs.  $5.1 \pm 0.7$  km/hr) and on the treadmill ( $3.2 \pm 0.5$  vs.  $3.7 \pm 0.5$  km/hr).

### PFC Hemodynamic

$\Delta\text{HbO}_2$  was significantly higher than zero during RNG, DT-IS, and DT-PS in both groups, and  $\Delta\text{HbR}$  was significantly lower than zero during RNG and ST-IS in inactive older adults and during RNG, ST-IS, ST-PS, DT-IS, and DT-PS in active older adults (Table 2). There was no significant effect of group or interaction (Group  $\times$  Task) for  $\Delta\text{HbO}_2$  ( $p = .98$  for both) and  $\Delta\text{HbR}$  ( $p = .52$  and  $.92$ , respectively). However, a significant effect of task was observed for  $\Delta\text{HbO}_2$  ( $p < .001$ ) and  $\Delta\text{HbR}$  ( $p = .02$ ). Post hoc testing revealed that HbO<sub>2</sub> was significantly higher during RNG compared with C-RNG and was significantly higher during DT-PS compared with ST-PS in both groups. HbO<sub>2</sub> during DT-IS was higher than during ST-IS but did not reach significance ( $p = .054$  and  $p = .053$  for inactive and active older adults, respectively). No significant difference was found in the speed of the walking task for  $\Delta\text{HbO}_2$  and  $\Delta\text{HbR}$  for either group. Regarding HbR, post hoc testing revealed that HbR was significantly lower during RNG compared with C-RNG only in active older adults.

### Perceived Difficulty

There was no significant effect of group or interaction (Group  $\times$  Task) for perceived difficulty of the task ( $p = .43$  and  $.41$ , respectively), but there was a significant effect of task ( $p < .001$ ). Post hoc testing revealed that the perceived difficulty of the task was significantly higher during RNG compared with C-RNG and was significantly higher during DT compared with ST in both groups. No significant difference was observed for the speed of the walking task in either group.

### Cognitive Task Performance

There was no significant effect of group or interaction (Group  $\times$  Task) for RNG number/2 min ( $p = .36$  and  $.63$ , respectively) and RNG adjacency ( $p = .12$  and  $.57$ , respectively), whereas there was a significant effect of task for RNG-number/2 min ( $p < .05$ ). Post hoc testing revealed that RNG-number/2 min was significantly higher during DT-IS compared with RNG.

### Gait Performance

There was no significant effect of group for stride length CV and cadence CV ( $p = .08$  and  $.10$ , respectively), but there was a significant interaction (Group  $\times$  Task) ( $p < .05$ ). There was also a significant effect of task for cadence CV ( $p < .001$ ). In active older adults, post hoc testing revealed that stride length CV was significantly lower during DT-PS than during DT-IS ( $p < .05$ ) and that cadence CV was significantly lower during ST-PS than during ST-IS ( $p < .01$ ) and during DT-PS than during DT-IS ( $p < .001$ ).

## Discussion

To our knowledge, this is the first study to explore the effect of the level of physical activity on PFC activation in older people during

**Table 2 Parameters During Each Task in Inactive and Active Older Adults**

Measure	Group	C-RNG	RNG	ST-IS	ST-PS	DT-IS	DT-PS
<b>fNIRS</b>							
$\Delta\text{HbO}_2$ ( $\mu\text{M}$ )	Inactive older adults	0.126 $\pm$ 0.732	1.645 $\pm$ 2.018*** aaa	0.148 $\pm$ 1.422	0.065 $\pm$ 1.418	0.829 $\pm$ 2.314*	0.965 $\pm$ 1.484*** <sup>a</sup>
	Active older adults	0.163 $\pm$ 1.190	1.393 $\pm$ 1.228*** aaa	0.213 $\pm$ 1.163	0.159 $\pm$ 1.736	0.836 $\pm$ 1.814**	1.048 $\pm$ 1.695*** aa
$\Delta\text{HbR}$ ( $\mu\text{M}$ )	Inactive older adults	-0.066 $\pm$ 0.452	-0.331 $\pm$ 0.888*	-0.205 $\pm$ 0.570*	-0.172 $\pm$ 0.605	-0.369 $\pm$ 1.202	-0.396 $\pm$ 1.340
	Active older adults	-0.133 $\pm$ 0.444	-0.472 $\pm$ 0.750*** a	-0.219 $\pm$ 0.597*	-0.381 $\pm$ 0.650**	-0.343 $\pm$ 0.756**	-0.495 $\pm$ 0.787***
PDT (1–15)	Inactive older adults	2.6 $\pm$ 1.3	8.6 $\pm$ 1.8 <sup>aaa</sup>	4.4 $\pm$ 2.5	4.2 $\pm$ 2.2	9.0 $\pm$ 2.0 <sup>aaa</sup>	8.8 $\pm$ 2.1 <sup>aaa</sup>
	Active older adults	3.1 $\pm$ 1.6	8.4 $\pm$ 1.8 <sup>aaa</sup>	4.0 $\pm$ 2.2	3.7 $\pm$ 1.6	8.5 $\pm$ 1.9 <sup>aaa</sup>	8.6 $\pm$ 1.8 <sup>aaa</sup>
Heart rate (mean, bpm)	Inactive older adults	80.8 $\pm$ 15.2	83.5 $\pm$ 17.3	92.0 $\pm$ 15.4	92.0 $\pm$ 17.5	93.4 $\pm$ 15.2 <sup>bbb</sup>	95.0 $\pm$ 15.9 <sup>bbb</sup>
	Active older adults	81.8 $\pm$ 16.3	84.5 $\pm$ 21.8	88.7 $\pm$ 14.3	92.6 $\pm$ 15.4 <sup>cc</sup>	92.6 $\pm$ 18.1 <sup>aa,bbb</sup>	93.3 $\pm$ 15.1 <sup>bbb</sup>
<b>Cognition</b>							
RNG number/2 min	Inactive older adults		85.8 $\pm$ 22.9			93.2 $\pm$ 24.4 <sup>b</sup>	91.7 $\pm$ 25.7
	Active older adults		93.1 $\pm$ 17.9			99.1 $\pm$ 27.4 <sup>b</sup>	95.1 $\pm$ 29.3
RNG adjacency (%)	Inactive older adults		11.4 $\pm$ 8.1			12.2 $\pm$ 8.3	11.6 $\pm$ 7.5
	Active older adults		16.3 $\pm$ 13.6			15.5 $\pm$ 13.6	14.9 $\pm$ 12.1
<b>Walking</b>							
Stride length CV (%)	Inactive older adults			4.3 $\pm$ 1.4	4.6 $\pm$ 2.3	4.5 $\pm$ 2.0	4.9 $\pm$ 2.9
	Active older adults			4.1 $\pm$ 1.2	3.8 $\pm$ 1.2	4.4 $\pm$ 1.1	3.8 $\pm$ 1.0 <sup>c</sup>
Cadence CV (%)	Inactive older adults			15.3 $\pm$ 14.6	13.7 $\pm$ 15.9	14.5 $\pm$ 15.2	12.0 $\pm$ 13.5
	Active older adults			11.6 $\pm$ 13.0	5.7 $\pm$ 7.2 <sup>cc</sup>	15.1 $\pm$ 15.2	6.6 $\pm$ 10.1 <sup>ccc</sup>

Note. Data are presented as mean  $\pm$  SD. C-RNG = control number generation task; RNG = random number generation task; ST = single task; DT = dual task; PS = preferred speed; IS = imposed speed; fNIRS = functional near-infrared spectroscopy;  $\Delta\text{HbO}_2$  = delta of oxygenated hemoglobin;  $\Delta\text{HbR}$  = delta of deoxygenated hemoglobin; PDT = perceived difficulty of the task; CV = coefficient of variation; bpm = beats per minute.

<sup>a</sup> $p < .05$ . <sup>aa</sup> $p < .01$ . <sup>aaa</sup> $p < .001$  is significantly different with the control condition (RNG vs. C-RNG, DT-IS vs. ST-IS, and DT-PS vs. ST-PS). <sup>b</sup> $p < .05$ . <sup>bbb</sup> $p < .001$  is significantly different with RNG. <sup>c</sup> $p < .05$ . <sup>cc</sup> $p < .01$ . <sup>ccc</sup> $p < .001$  is significantly different between gaits (ST-PS vs. ST-IS and DT-PS vs. DT-IS).

\* $p < .05$ . \*\* $p < .01$ . \*\*\* $p < .001$  is significantly different from 0.

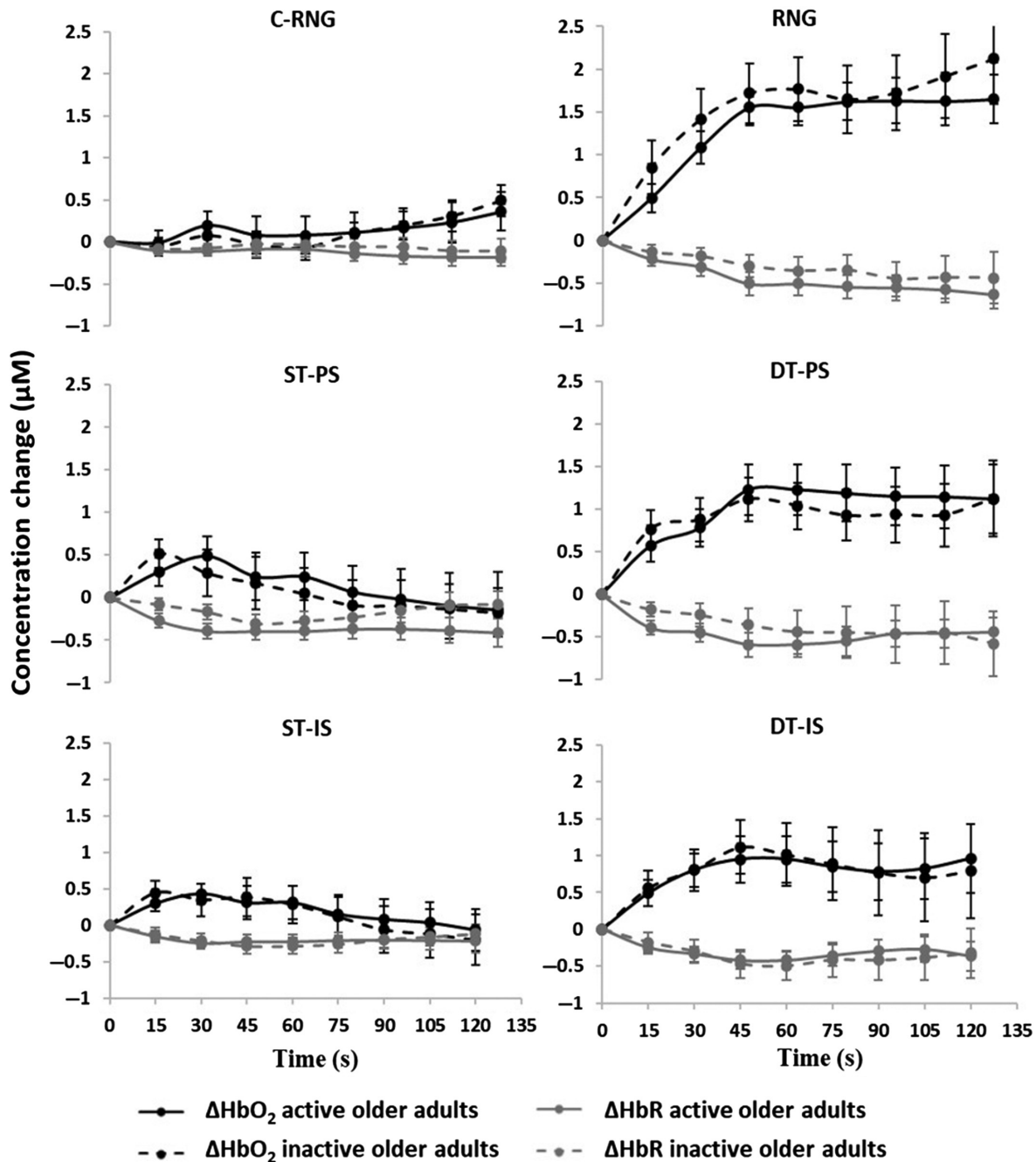
ST and DT walking at different moderate speeds (i.e., at PS and at 3 km/hr). Our first hypothesis was supported as there was no significant difference in PFC activity between inactive and active older adults during ST walking. Our second hypothesis was not supported as PFC activation in inactive and active older adults was not significantly different during DT walking.

### PFC Activation During the ST Walking

During ST walking (ST-IS and ST-PS), HbR decreased significantly except in inactive older adults at the PS, but we did not observe any significant increase in HbO<sub>2</sub>. Although it is generally considered that HbO<sub>2</sub> is more sensitive to locomotion-related activities than HbR (Hoshi et al., 2001; Strangman et al., 2002; Suzuki et al., 2004), the decrease in HbR suggests PFC activation during ST walking in older adults. These data confirm previous

observations showing PFC activation during ST walking in healthy adults over 60 years of age (Hawkins et al., 2018; Mirelman et al., 2017; Nóbrega-Sousa et al., 2020). As walking may become less automatic with aging, older adults might rely on executive resources to compensate for the loss of automaticity, the greater reliance on executive control leading to greater PFC activation during gait (Nóbrega-Sousa et al., 2020). Moreover, in older adults, the PFC is activated more during walking on a treadmill than on the floor (Clark et al., 2014), which might be especially true during the first seconds of gait (Figure 2). So, the walking condition (i.e., on a treadmill) could partially explain our results. Finally, we saw no difference in HbO<sub>2</sub> or HbR between the groups, meaning that, in this sample, physical activity had no influence on this activation.

This result is in accordance with those obtained by Harada et al. (2009), who showed that gait capacity did not alter PFC activation during walking on a treadmill at a speed similar to the



**Figure 2** — Concentration for left PFC during the experimental tasks in inactive and active older adults. Concentration change presented as mean  $\pm$  standard error of the mean. 0 is the baseline value obtained during the standing rest before the task. C-RNG = control generation of numbers task; RNG = random generation of numbers task; ST = single task; DT = dual task; PS = preferred speed; IS = imposed speed;  $\Delta\text{HbO}_2$  = delta of oxygenated hemoglobin;  $\Delta\text{HbR}$  = delta of deoxygenated hemoglobin.

speed used in this study. They reported greater PFC activity in older adults with lower gait capacity only at a high velocity. Higher cognitive demand due to reduced motor and cognitive control of gait would occur at this high velocity for these older adults with low gait capacity. In our study, the treadmill speed was likely too low to have induced prefrontal hyperactivation in inactive older adults.

In our study, participants walked at two different speeds. In active older adults, the PS was significantly higher than the imposed speed of 3 km/hr ( $p < .001$ ), and PFC activation was similar. It should

be noted that, although the physiological demand was higher (higher heart rate), walking at this PS led to a reduction in the variability of the gait as indicated by the decrease of the cadence CV. It can be interpreted as an improvement in gait performance when older people are free to choose their speed on a treadmill.

#### PFC Activation During the Static Cognitive Task

The significant increase in  $\text{HbO}_2$  and the decrease in  $\text{HbR}$  illustrate activation of the PFC during the static cognitive task (RNG), but we

found that PFC activation was similar in both groups. This result appears to contradict previous studies that showed that older adults with high physical fitness had higher levels of PFC activation (Agbangla et al., 2019; Albinet et al., 2014) and/or cognitive performance (Abou-Dest et al., 2012; Albinet et al., 2014; Boucard et al., 2012) during a cognitive task compared with inactive older adults. As cognitive performance and the perceived difficulty of the cognitive task were not different in inactive and active older adults, we may consider that the cognitive load was similar, partially explaining the lack of difference in PFC activation. It is also possible that the RNG task was not difficult enough to induce any difference in PFC activation between the two groups. Indeed, it has already been shown that PFC activation is dependent on cognitive load and that cardiorespiratory fitness has a different impact on PFC activation with the increasing cognitive load, with inactive older adults demonstrating lower hemodynamic variations as a function of the cognitive load (Agbangla et al., 2019). Finally, cardiorespiratory fitness was not evaluated in the present study, so it is possible that inactive and active older adults had a similar cardiorespiratory fitness, explaining why we did not observe any difference in PFC activation and/or performance during the static cognitive task.

### PFC Activation During DT Walking

During DT walking (DT-IS and DT-PS), there was activation of PFC as indicated by the significant increase in HbO<sub>2</sub> and/or decrease in HbR. As suggested by the higher HbO<sub>2</sub> during DT walking than during ST walking, performing a cognitive task while walking led to higher activation of the PFC. This result is in accordance with most studies on older adults (Pelicioni et al., 2019; Stuart et al., 2018; Udina et al., 2020). The cause of this increase of PFC activation is the significant implication of attentional resources during DT walking (Holtzer et al., 2011).

We found no difference in  $\Delta$ HbO<sub>2</sub> or  $\Delta$ HbR during DT walking between the groups. This could indicate that the level of physical activity had no effect on PFC activity during DT walking in this sample of older adults. The amount of physical activity over the previous year was much higher ( $10.4 \pm 5.8$  hr/week) in the group of active older adults than in the group of inactive older adults ( $1.8 \pm 0.4$  hr/week), which led us to think that this level of physical activity was sufficient to have induced prophylactic health effects. Our two groups of older adults were also different in their spontaneous walking speed on the floor and on the treadmill, indicating a higher gait capacity in the active group compared with the inactive one. As it was shown that older adults whose PS is slower are less physically active (Egerton et al., 2017), this difference in the gait capacity of our two groups of participants could actually be linked to the physical activity of the two groups. The distance at 6MWT was not significantly higher in active older adults than in inactive older adults, indicating that the inactive and active older adults in this study had a similar functional capacity.

The unchanged PFC activation between the groups during DT walking should be interpreted according to the cognitive and motor load of the task. Cognitive performance, evaluated by the number of digits spoken during the task and by the adjacency score, was not significantly different between both groups. The fact that the older adults generated more numbers during DT walking than in the static cognitive task (RNG) could be due not only to a habituation effect (as DT walking always occurred after the static cognitive task) but also to the “facilitator” effect of the gait on cognitive

performance (Schaefer et al., 2010) and, more precisely, on the executive functions (Tomporowski & Audiffren, 2014). Regarding gait parameters, there was no significant difference between the groups in gait performance evaluated with stride length and cadence variability. This result is not in accordance with previous studies showing that physical activity impacts gait variability in older adults (Ciprandi et al., 2017; Egerton et al., 2017; Wang et al., 2015). It should be noted that gait variability was significantly lower at the PS than at the imposed speed only in active older adults. However, as explained earlier for ST walking, this is likely due to the velocity of the PS condition that was higher than the imposed speed for active older adults but not for inactive older adults. Therefore, the similar cognitive and motor performance in inactive and active older adults suggests that cognitive and motor load during DT walking were not different between both groups. The similar perceived difficulty of the task in inactive and active older adults is in accordance with that. It can be considered that the similar load of the task represented similar stimulation in both inactive and active older adults, inducing a similar perception of the difficulty of DT walking. In response to this similar stimulation, the PFC in inactive and active older adults was activated to a similar degree. We can hypothesize that cognitive and motor stimulation was not great enough to induce hyperactivation of the PFC and/or a decrease in cognitive and motor performance in the inactive older adults. Further studies should certainly focus on a higher walking speed and a more challenging cognitive task for DT walking.

### Limitations

To evaluate the participants' level of physical activity, we used a self-administered questionnaire, whereas direct measurement of daily physical activity would have been preferable to establish inactive and active groups. The lack of test–retest for the 6MWT could partially explain why the distance obtained at 6MWT was not significantly higher in the active group than in the inactive one. The cognitive task used in the present study did not assess overall cognitive performance of executive functions that may be associated with PFC activity in older people. The cognitive task used here involves inhibition and working memory, and it is possible that physical activity would have a different effect on other executive functions in older adults. In addition, our equipment did not allow us to explore several cortical areas simultaneously. Therefore, we were unable to assess cortical activity in another area (Menant et al., 2020). Finally, considering the reliability of the fNIRS, it is obvious that a block design study would be preferable to explore the hemodynamic change in PFC during the tasks. However, this type of block design is difficult for our study wherein the walking task lasted 2 min.

### Conclusion

Our findings suggest that the level of physical activity in older adults does not alter PFC activation during treadmill walking in ST and DT conditions. This unchanged activation with physical activity was likely the consequence of a similar motor and cognitive load in both inactive and active older adults.

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