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Article

Functional Brain Responses to Short-Duration Light Physical Activity in Children: Insights from Near-Infrared Spectroscopy

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Abstract: Background/Objectives: The prefrontal cortex (PFC) plays a crucial role in cognitive functions such as attention, working memory and executive functions. Physical activity (PA), even at light-intensity, has been shown to increase PFC activity. However, most studies have focused on moderate- to vigorous-intensity exercises or on adults, while little data is available for children engaging in light-intensity PA (LPA). The aim of this study was to investigate the changes in the hemodynamics of the PFC during short-term, light-intensity exercises in children using functional near-infrared spectroscopy (fNIRS). The secondary aim was to compare the responses between two exercise patterns differing in duration (10 vs. 20 seconds). **Methods:** Thirty-eight healthy children aged 10 to 14 years from private schools in Barcelona participated in this study. Seven light-intensity exercises were performed in randomized order according to two patterns: Pattern 1 (10 seconds per exercise) and Pattern 2 (20 seconds per exercise). Changes in oxygenated hemoglobin (oxy-Hb) were measured by fNIRS in three PFC regions: right (R-PFC), middle (M-PFC) and left (L-PFC). Analysis of covariance (ANCOVA) was used to determine significant differences, with gender, age and resting oxy-Hb Z-scores as covariates. **Results:** Significant increases in oxy-Hb Z-scores were observed in the M-PFC during event A (Upward Stretch) and in all PFC regions during event D (Trunk Twist) in pattern 1. Events related to coordination and balance, such as balancing on one leg, also elicited significant activation of the PFC. However, simpler movements, such as hand washing and elbow circles, showed no significant changes. Comparisons between patterns 1 and 2 showed no significant differences, suggesting that duration alone has no effect on PFC activation. **Conclusions:** Light-intensity coordination and balance exercises stimulate PFC activity, even for short durations. These results emphasize the potential for integrating such exercises in school or rehabilitation settings to promote cognitive and motor development in children.

Keywords: prefrontal cortex activation; functional near-infrared spectroscopy; child cognitive development; motor coordination; light-intensity physical activity

1. Introduction

Physical activity (PA) exerts a significant impact on neural development, especially in the formative years of childhood [1–3]. Engaging in PA activates complex biochemical processes that improve cerebral blood flow [4], stimulate the release of growth factors [5] such as Brain-Derived Neurotrophic Factor (BDNF) [6], [7] and promote the restructuring of neural circuits [8]. These physiological responses are crucial for the development of cognitive functions such as memory [9], [10], attention and executive processing [11], which are largely mediated by the prefrontal cortex (PFC) [12].

The PFC is significantly involved in higher-order cognitive tasks and behavioral regulation, making its development critical for academic performance and adaptive functioning [13,14]. Physical activities, especially low-intensity ones, contribute uniquely to the activation of this brain region [15], [16]. In contrast to vigorous physical activity (VPA), light-intensity physical activity (LPA) does not significantly stress the cardiovascular system [17,18], but is thought to stimulate sufficient

neurophysiological changes that can improve cognitive function [19]. This form of exercise is particularly valuable in educational settings, as it can be seamlessly integrated into daily routines and provides cognitive benefits without the logistical challenges of more intense exercise programs [20,21].

Research has shown that even minimal increases in PA can improve cerebral blood flow and metabolic function in the PFC [22–24], leading to better cognitive performance. However, detailed insights into the specific hemodynamic changes induced by PLA in children's brains is still lacking. Given the potential of these activities to be regularly integrated into the classroom, there is an urgent need to understand their direct impact on children's neurodevelopment.

This study aims to address this gap by using functional near-infrared spectroscopy (fNIRS) to measure the hemodynamic responses of the PFC to short-duration, LPA in a pediatric population. fNIRS is particularly suited to this task because it is non-invasive and provides real-time insights into the changes in cerebral blood flow and oxygenation associated with brain activity. By elucidating how these exercises affect PFC activity, the study aims to underpin the role of LPA in improving cognitive function and potentially shape future educational and developmental strategies to effectively incorporate such exercises. This could not only improve academic performance, but also contribute to children's overall neurological health.

2. Materials and Methods

2.1. Participants

38 children aged 10 to 14 from private schools in Barcelona took part in this study. Of these, 16 participants were selected with the consent of the principals of their respective schools, while the remaining 22 were recruited through an extended snowball sampling method. Written informed consent was obtained from both the children and their parents or guardians, which also covered the use of the participants' images in freely accessible online publications. The study was ethically approved by the Ethics Committee of the University of Zagreb (protocol code: 29; 4 2023). All research procedures were in strict compliance with international ethical standards and guidelines for research involving human subjects, with participant safety and data integrity being paramount throughout the study.

2.1.1. Number of Participants and fNIRS Data Analyzed

Of the 38 participants recruited for the study, data from 33 participants were included in the final analysis after excluding those with excessive motion artifacts based on predefined assessment criteria. For Pattern 1 (10 s), 30 participants (81.6% males) provided valid data, while for Pattern 2 (20 s), 31 participants (84.2% males) were eligible for analysis. Table 1 summarizes the demographic characteristics of the participants included in the study.

Table 1. Participant characteristics and data analyzed in Patterns 1 and 2.

	All		Pattern 1		Pattern 2	
	N	%	N	%	N	%
Age, mean ± SD, years	12.3 ± 1.4		12.3 ± 1.3		12.3 ± 1.3	
Gender						
Male	24	63	21	66	22	65
Female	14	37	11	34	12	35
Age Groups						
10–11 years	12	31	9	29	10	30

12 years	15	39	12	38	13	38
13–14 years	11	29	8	25	9	27
Dominant Hand						
Right	35	92	30	91	31	91
Left	3	8	3	9	3	9

SD: Standard deviation. Pattern 1: Exercises performed with a 10-second duration. Pattern 2: Exercises performed with a 20-second duration.

2.2. Procedure

The experimental sessions were conducted in a multipurpose room in a private facility and in a specific area of the collaborating private school in Barcelona. Before starting the experiment, the research team verified the name, age, gender and dominant hand of each participant. Detailed instructions were given for the LPA, emphasizing the importance of moving the head as little as possible, avoiding rapid movements and not holding the breath or straining excessively during the exercises.

To demonstrate the exercises and provide clarity, the researchers performed each movement as it would be performed during the actual experiment. Participants were then asked to rate their perceived exertion for each exercise using the modified Borg scale.

An fNIRS system (model and manufacturer's specifications, similar to the OEG-16H; Spectratech Inc. but localized for the study) was then carefully attached to each participant's head while they were seated. The device was calibrated to ensure accurate measurement of cerebral blood flow. After verifying the accuracy of the device setting, participants performed the prescribed LPA as planned.

2.3. LPA

The study included seven different light intensity exercises, labeled A through G (see Table 2). The selection of these exercises was based on two criteria: (1) the exercises had to be of light intensity and simple enough that they could be comfortably performed by all children, including those with limited motor skills, in everyday situations, such as during short breaks in class or as part of regular class activities; and (2) the exercises required minimal head movement to reduce movement artifacts in the fNIRS data and thus avoid interference related to changes in cerebral blood flow due to head tilt. Consequently, the selected exercises excluded any form of running, jumping or extensive dynamic movements involving significant trunk and head movement in the sagittal or frontal plane.

The exercises selected were primarily gentle static and dynamic stretching exercises that are known to be feasible in typical school settings. As there is evidence that exercises involving fine motor skills and balance can activate the PFC, such movements were also integrated into the training program. All exercises were performed in a seated position, with the exception of a standing balance task to further limit movement noise during fNIRS monitoring.

Table 2. Light-intensity exercise utilized in protocol.

Event ID	Exercise	Description
A	Nick Tilts	Gently tilt your head toward one shoulder and hold for a few seconds, then repeat on the other side.
B	Arm Cross Stretch	Extend one arm straight across your chest. Use the other hand to pull the extended arm closer, stretching the shoulder.
C	Wrist Rolls	Extend your arms out in front of you and gently roll your wrists clockwise and then counterclockwise.
D	Side Bends	Stand with feet shoulder-width apart. Slowly bend to one side, sliding your hand down your leg, then switch to the other side.

E	Heel Digs	Stand upright and dig one heel into the ground, toe pointing upwards. Alternate legs.
F	Torso Twists	Stand with feet planted firmly, twist your torso to one side as far as is comfortable, then switch sides.
G	Marching in Place	Lift your knees high one at a time, as if marching on the spot.
	Ankle Circles	Lift one foot off the ground and rotate the ankle in a circular motion. Rotate a few times in one direction, then switch directions and finally switch feet.

To investigate the effects of exercise duration on cerebral blood flow, two exercise patterns were designed: one with a movement duration of 10 seconds (pattern 1) and another with a movement duration of 20 seconds (pattern 2). While static stretching exercises typically last 15 to 60 seconds per movement, a shorter duration was chosen in our protocol to focus the study on educational application rather than flexibility improvement. To control for possible sequence effects on the response variables, the order of the exercises (A-G) and the two patterns (1 and 2) was randomized for each participant, as shown in Figure 1 and Figure 2.

Instructional videos were produced for each child showing the order of the exercises as they were to be performed. Participants watched these exercises on a monitor at eye level, with a 10-second pause between the first and second movement. After each event, there was a 30-second pause during which participants viewed a calming naturalistic image to facilitate mental recovery. After completing the first exercise pattern, participants rested in a seated position for five minutes before recalibrating the fNIRS device to perform the second pattern.

	Exercise A				Exercise B				...	Exercise F				Exercise G			
	1st	Rest	2nd	Rest	1st	Rest	2nd	Rest		1st	Rest	2nd	Rest	1st	Rest	2nd	
Pattern 1	10	10	10	30	10	10	10	30	10	10	10	30	10	10	10		
Pattern 2	20	10	20	30	20	10	20	30	20	10	20	30	20	10	20		

Figure 1. fNIRS Measurement Setup: Randomized Order of Patterns (1 and 2) and Events (A-G).

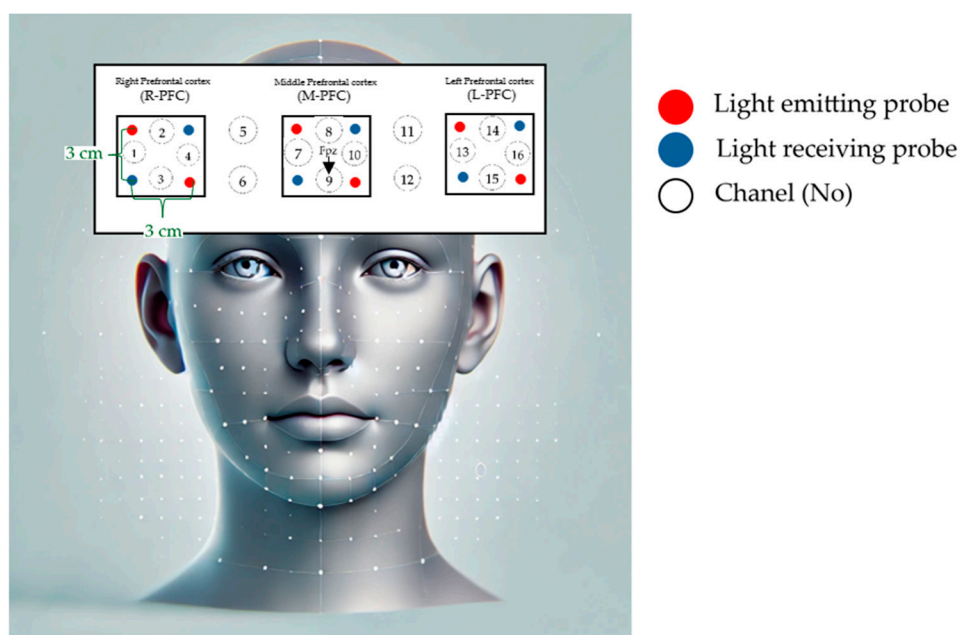


Figure 2. Placement Points and Channel Coordinates of Functional Near-Infrared Spectroscopy Probes.

3. Measures

3.1. fNIRS

Functional Near-Infrared Spectroscopy (fNIRS) is a non-invasive optical imaging technique that tracks the dynamics of cerebral blood flow by emitting near-infrared light through the skull. This light penetrates skin, bone and muscle tissue to a depth of approximately 2 cm and is therefore suitable for monitoring cortical activity, but not deeper brain structures. fNIRS measures variations in the concentrations of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb), providing insight into hemodynamic responses to neural activity. Compared to technologies such as functional magnetic resonance imaging (fMRI), fNIRS offers lower spatial resolution, but has the advantage of being less sensitive to motion artifacts and can record brain activity under more natural conditions without strict postural constraints.

In our study, we used an fNIRS system to monitor hemodynamic changes in the PFC of children during light exercise and at rest. The system was equipped with six transmitters and six receivers distributed over 16 channels to ensure comprehensive coverage of the PFC area. We used near-infrared wavelengths of 770 nm and 840 nm, with a distance of 3 cm between the transmitters and receivers to optimize signal detection. The placement of the sensors was strategically aligned with the Fpz position, according to the international 10–20 system used for EEG recordings. The data acquisition rate was set to 6.10 Hz, which corresponds to 0.08102 seconds per sample. This setup allowed us to closely monitor changes in oxy-Hb, deoxy-Hb, and total hemoglobin levels. Consistent with established research, our study focused on oxy-Hb levels as the primary indicator of regional cerebral blood flow, which is a reliable measure of PFC activity both during exercise and at rest.

3.2. fNIRS Data Processing

The fNIRS data was pre-processed using proprietary software integrated into the fNIRS system. First, all acquired data underwent a hemodynamic separation process to filter out signals associated with increased blood flow in the skin that were not indicative of cerebral activity. This step was crucial to ensure the accuracy of our measurements, which relate exclusively to brain function.

To further refine the data quality and remove extraneous noise from physiological sources such as heart rhythms and respiratory movements, a dual filtering approach was applied. A high-pass filter with a frequency of 0.01 Hz was used to suppress slow signal shifts, and a low-pass filter with a frequency of 0.3 Hz was applied to exclude high-frequency noise. This band-pass filtering effectively isolated the cerebral blood flow signals of interest.

In the analysis, the waveforms of oxygenated and deoxygenated hemoglobin (oxy-Hb and deoxy-Hb) were closely examined. The classification of the data was based on the phase relationship and stability of these signals:

1. Data where oxy-Hb and deoxy-Hb were in antiphase were considered for further analysis.
2. Data were retained when deoxy-Hb levels were stable and approached zero, indicating minimal extracerebral interference.
3. Simultaneous increases or decreases in oxy-Hb and deoxy-Hb levels were specifically analyzed to assess their coherence.
4. Data were selected if the proportion of deoxy-Hb remained lower than that of oxy-Hb, unless there was significant variation in the deoxy-Hb signal, which led to data exclusion.

After preprocessing, the data was extracted in CSV format and then imported into Microsoft Excel 2019 for detailed analysis. For each channel, the average oxy-Hb values at rest (0-5 seconds before exercise) and during exercise (10 or 20 seconds after the start of exercise) were calculated for

all events and patterns. As each exercise pattern was repeated, the average values of the first and second event were calculated to increase the reliability of the results.

Channels were categorized to reflect specific regions of the PFC:

- Channels 1 to 4 were assigned to the right PFC (R-PFC).
- Channels 7 to 10 corresponded to the middle PFC (M-PFC).
- Channels 13 to 16 represented the left PFC (L-PFC).

Mean oxy-Hb concentrations for each region were calculated both at rest and during exercise, and these values were subsequently converted to Z-scores to standardize results across different sessions and participants. This allowed a comparative analysis of hemodynamic responses under different conditions within the study.

4. Statistical Analysis

The analysis included the examination of differences in oxy-Hb-Z-scores at rest and during exercise in the regions of the PFC (R-PFC, M-PFC and L-PFC) for both exercise patterns (pattern 1 and pattern 2). To assess these differences, an analysis of covariance (ANCOVA) was performed, with age and gender included as covariates to account for potential confounding effects.

To further investigate whether the rate of change in oxy-Hb levels varied between pattern 1 and pattern 2, an additional ANCOVA was performed. In this analysis, baseline oxy-Hb Z values (measured at rest) were included as covariates along with age and gender to ensure a robust comparison between conditions.

A significance threshold of $P < 0.05$ was applied to all statistical tests to determine meaningful differences. Statistical analyses were performed using IBM SPSS Statistics software (version 29.0; IBM Corp., Armonk, NY, USA) to ensure consistency and reliability of data analysis. This approach allowed for a comprehensive assessment of hemodynamic responses to LPA in all regions and patterns of the PFC.

5. Results

Ratings of Perceived Exertion (RPE)

Perceived exertion for each exercise category was rated using the Borg scale, ranging from 6 ("no exertion") to 20 ("maximum exertion"). All reported RPE scores fell below "11," which categorised the exercises as light-intensity. The mean RPE score for the group was 7.5 ± 1.6 , with most participants describing the exercises as "very light" (score 9) or "extremely light" (score 7) according to the Borg scale descriptors. These results confirm that all exercises performed in this study met the criteria for LPA.

Hemodynamic changes in the PFC

Comparison between rest and LPA (pattern 1)

In the 10-second movement pattern, certain regions of the PFC showed significant changes in oxygenated hemoglobin (oxy-Hb) Z-scores during exercise compared to rest. For event A, the M-PFC showed a significant increase ($F [1, 64] = 4.60; P = 0.039$). For event B, no significant differences were observed in any of the PFC regions.

For event C, significant increases were observed in both the M-PFC ($F [1, 64] = 3.87; P = 0.042$) and the L-PFC ($F [1, 64] = 5.21; P = 0.019$). Similarly, an increase in M-PFC ($F [1, 64] = 4.90; P = 0.033$) and L-PFC ($F [1, 64] = 5.87; P = 0.017$) was observed for event D.

In event E, a significant increase in oxy-Hb-Z-scores were identified only in the L-PFC ($F [1, 64] = 3.87; P = 0.049$). Events F and G showed significant increases in all PFC regions. For event F, significant changes were observed in the R-PFC ($F [1, 64] = 4.98; P = 0.028$), M-PFC ($F [1, 64] = 6.73; P = 0.012$) and L-PFC ($F [1, 64] = 8.53; P = 0.005$).

In event G, increases in oxy-Hb Z-scores were observed in R-PFC ($F [1, 64] = 8.23; P = 0.008$), M-PFC ($F [1, 64] = 10.80; P = 0.002$) and L-PFC ($F [1, 64] = 14.55; P < 0.001$) during exercise compared to rest (Table 3).

Table 3. Changes in oxy-Hb Z-scores observed during rest and LPA (Pattern 1).

Event (ID-Seconds)	Regio	Oxy-Hb (mM · mm)				Oxy-Hb (Z-score)				F	P	η^2
		Rest		Exercise		Rest		Exercise				
		Mea	SD	Mea	SD	Mea	SD	Mea	SD			
n	n	n	n	n	n	n	n					
A-10 Upward Stretch	R-	0,05	0,1	0,09	0,1	-0,10	0,0	0,65	0,1	1,3	0,430	0,0
	PFC		1		2		8		0	5		1
	M-	-0,03	0,1	0,06	0,1	-0,27	0,0	0,68	0,1	4,6	0.039	0,0
	PFC		0		4		9		1	0	*	7
B-10 Shoulder Stretch	L-PFC	0,02	0,1	0,08	0,1	-0,15	0,1	0,80	0,1	1,2	0,276	0,0
			5		6		3		4	2		3
	R-	0,01	0,0	0,02	0,1	-0,07	0,0	0,50	0,0	1,0	0,362	0,0
	PFC		9		0		7		8	8		0
C-10 Elbow Circles	M-	0,00	0,0	0,12	0,1	-0,12	0,1	0,85	0,1	2,0	0,092	0,0
	PFC		8		5		0		2	3		4
	L-PFC	0,01	0,1	0,10	0,1	-0,10	0,0	0,89	0,1	1,4	0,249	0,0
			1		2		9		1	0		2
D-10 Trunk Twist	R-	-0,02	0,1	0,08	0,1	-0,16	0,1	0,85	0,1	1,8	0,085	0,0
	PFC		2		4		1		2	8		5
	M-	-0,05	0,1	0,10	0,1	-0,50	0,1	0,69	0,1	3,8	0.042	0,0
	PFC		4		6		3		4	7	*	8
E-10 Washing Hands	L-PFC	-0,03	0,1	0,11	0,1	-0,42	0,1	0,87	0,1	5,2	0.019	0,0
			3		5		2		3	1	*	9
	R-	0,00	0,1	0,07	0,1	-0,10	0,0	0,62	0,1	1,3	0,440	0,0
	PFC		0		2		8		0	5		1
F-10 Thumb & Pinky	M-	-0,03	0,1	0,08	0,1	-0,27	0,0	0,80	0,1	4,9	0.033	0,0
	PFC		1		4		9		1	0	*	7
	L-PFC	-0,04	0,1	0,09	0,1	-0,29	0,1	0,84	0,1	5,8	0.017	0,1
			2		5		2		3	7	*	0
G-10 Hand Washing	R-	0,03	0,1	0,06	0,1	-0,10	0,0	0,63	0,1	1,2	0,402	0,0
	PFC		0		2		8		0	7		1
	M-	0,02	0,0	0,11	0,1	-0,22	0,0	0,48	0,1	2,7	0,068	0,0
	PFC		9		4		9		2	8		5
H-10 Hand Washing	L-PFC	0,00	0,0	0,09	0,1	-0,34	0,0	0,89	0,1	3,8	0.049	0,0
			8		1		7		0	7	*	6
	R-	-0,01	0,1	0,07	0,1	-0,20	0,1	0,72	0,1	1,7	0,285	0,0
	PFC		1		3		0		1	0		2
I-10 Hand Washing	M-	-0,03	0,1	0,10	0,1	-0,29	0,1	0,72	0,1	4,9	0.028	0,0
	PFC		2		4		1		3	8	*	8

	L-PFC	-0,02	0,1	0,12	0,1	-0,34	0,1	0,89	0,1	6,7	0.012	0,1
			3		5		2		3	3	*	2
G-10 Single Leg Balance	R-PFC	-0,04	0,1	0,09	0,1	-0,28	0,0	0,90	0,1	6,1	0.017	0,1
	M-PFC		0		2		8		0	0	*	1
	M-PFC	-0,08	0,0	0,15	0,1	-0,38	0,0	0,96	0,0	8,2	0.008	0,1
	L-PFC		9		2		7		9	3	*	4
	L-PFC	-0,06	0,1	0,13	0,1	-0,42	0,1	0,78	0,1	9,4	0.004	0,1
			1		3		0		1	5	*	6

Gender and age were included as covariates. R-PFC: right prefrontal cortex, M-PFC: middle prefrontal cortex, L-PFC: left prefrontal cortex, SD: standard deviation, oxy-Hb: oxygenated hemoglobin. *Indicates a statistically significant difference between rest and exercise Z-scores ($P < .05$).

Comparison Between Rest and LPA (Pattern 2)

During the 20-second movement pattern (pattern 2), significant increases in oxygenated hemoglobin (oxy-Hb) Z-scores were observed in several regions of the PFC for certain events. For event A, the R-PFC showed a significant increase during exercise compared to rest ($F [1, 64] = 7.12$; $P = 0.011$). No significant changes were observed in the M-PFC and L-PFC during this event.

For event B, a significant increase in M-PFC was observed ($F [1, 64] = 3.95$; $P = 0.049$). However, no significant differences in R-PFC or L-PFC were observed.

Event C showed significant increases in both the M-PFC ($F [1, 64] = 5.42$; $P = 0.026$) and the R-PFC ($F [1, 64] = 4.28$; $P = 0.041$). No significant differences were observed in the L-PFC during this event.

For event D, all three PFC regions showed significant increases in oxy-Hb Z-scores. In particular, the R-PFC ($F [1, 64] = 18.31$; $P < 0.001$), the M-PFC ($F [1, 64] = 22.10$; $P < 0.001$) and the L-PFC ($F [1, 64] = 26.87$; $P < 0.001$) showed significant changes.

For event E, the R-PFC ($F [1, 64] = 7.21$; $P = 0.012$), the M-PFC ($F [1, 64] = 13.47$; $P < 0.001$) and the L-PFC ($F [1, 64] = 5.19$; $P = 0.029$) all showed a significant increase during exercise.

For event F, the R-PFC ($F [1, 64] = 11.65$; $P = 0.001$), the M-PFC ($F [1, 64] = 4.71$; $P = 0.032$) and the L-PFC ($F [1, 64] = 9.88$; $P = 0.003$) showed significant increases in oxy-Hb Z-scores during exercise compared to rest.

Similarly, event G showed significant increases in all three PFC regions. Significant changes were observed in the R-PFC ($F [1, 64] = 16.20$; $P < 0.001$), M-PFC ($F [1, 64] = 19.10$; $P < 0.001$) and L-PFC ($F [1, 64] = 22.71$; $P < 0.001$) (Table 4).

Table 4. Changes in oxy-Hb Z-scores observed during rest and LPA (Pattern 2).

Event (ID-Seconds)	Regio	Oxy-Hb (mM mm)				Oxy-Hb (Z-score)				F	P	η^2
		Rest		Exercise		Rest		Exercise				
		Mea	SD	Mea	SD	Mea	SD	Mea	SD			
n	n	n	n	n	n	n	n					
A-20 Upward Stretch	R-PFC	-0,05	0,2	0,10	0,3	-0,32	0,9	0,28	0,9	7,12	0.011*	0,1
	M-PFC		2		0		0		2			0
	M-PFC	0,02	0,2	0,12	0,2	-0,22	0,7	0,64	1,1	3,32	0.068	0,0
	L-PFC		5		8		8		5			5
	L-PFC	-0,03	0,2	0,14	0,2	-0,14	0,8	0,71	1,1	2,10	0.125	0,0
	PFC		3		7		0		0			3
B-20 Shoulder Stretch	R-PFC	0,00	0,1	0,08	0,1	-0,08	0,6	0,62	1,0	1,82	0.220	0,0
	PFC		4		8		8		1			2

	M-	0,04	0,1	0,15	0,2	-0,16	0,8	0,82	0,9	3,95	0,049*	0,0
	PFC		6		0		0		8			6
	L-	-0,01	0,1	0,09	0,1	-0,12	0,7	0,68	1,0	2,37	0,099	0,0
	PFC		5		9		3		3			4
C-20 Elbow Circles	R-	0,02	0,1	0,11	0,2	-0,18	0,7	0,71	1,1	4,28	0,041*	0,0
	PFC		3		4		2		5			7
	M-	-0,03	0,1	0,14	0,2	-0,25	0,6	0,89	1,1	5,42	0,026*	0,0
	PFC		7		5		5		0			9
	L-	-0,02	0,1	0,12	0,2	-0,15	0,6	0,74	1,0	3,10	0,073	0,0
	PFC		4		3		8		7			5
D-20 Trunk Twist	R-	-0,06	0,1	0,15	0,2	-0,38	0,7	0,85	1,1	18,3	<	0,2
	PFC		2		0		0		0	1	0,001*	1
	M-	-0,08	0,1	0,19	0,2	-0,40	0,7	0,92	1,1	22,1	<	0,2
	PFC		8		7		4		2	0	0,001*	4
	L-	-0,09	0,1	0,20	0,2	-0,45	0,7	1,01	1,1	26,8	<	0,2
	PFC		6		6		8		5	7	0,001*	8
E-20 Washing Hands	R-	-0,04	0,1	0,09	0,1	-0,30	0,6	0,64	0,9	7,21	0,012*	0,1
	PFC		3		8		8		8			1
	M-	-0,05	0,1	0,13	0,2	-0,36	0,6	0,81	0,9	13,4	<	0,1
	PFC		5		2		2		3	7	0,001*	5
	L-	-0,03	0,1	0,10	0,1	-0,34	0,5	0,74	0,8	5,19	0,029*	0,0
	PFC		2		8		9		5			7
F-20 Thumb & Pinky	R-	-0,02	0,1	0,07	0,1	-0,20	0,6	0,72	0,9	11,6	0,001*	0,1
	PFC		3		6		4		0	5		4
	M-	0,01	0,1	0,09	0,1	-0,15	0,7	0,81	0,9	4,71	0,032*	0,0
	PFC		4		8		0		2			8
	L-	-0,03	0,1	0,11	0,2	-0,31	0,7	0,85	1,0	9,88	0,003*	0,1
	PFC		5		0		8		3			2
G-20 Single Leg Balance	R-	-0,05	0,1	0,14	0,1	-0,41	0,7	0,88	1,0	16,2	<	0,1
	PFC		2		8		0		8	0	0,001*	9
	M-	-0,07	0,1	0,18	0,2	-0,37	0,7	0,95	1,1	19,1	<	0,2
	PFC		6		2		2		0	0	0,001*	3
	L-	-0,08	0,1	0,15	0,2	-0,45	0,8	0,87	1,0	22,7	<	0,2
	PFC		7		1		0		2	1	0,001*	6

Covariates included gender and age. *Indicates a significant difference between mean Z-scores at rest and during exercise ($P < .05$). R-PFC: right prefrontal cortex, M-PFC: middle prefrontal cortex, L-PFC: left prefrontal cortex, SD: standard deviation, oxy-Hb: oxygenated hemoglobin.

Comparison Between Pattern 1 and Pattern 2

The comparison of the oxy-Hb-Z-scores between Pattern 1 and Pattern 2 showed no significant differences in any of the regions of the PFC for most events. Slight differences were observed in the mean oxy-Hb-Z-scores, but none of the changes reached statistical significance ($P > 0.05$). This consistency between patterns suggests a similar hemodynamic response in the R-PFC, M-PFC, and L-PFC during LPA (Table 5).

Table 5. Differences in oxy-Hb Z-score changes between Pattern 1 and Pattern 2.

Event (ID, Name)	Region	Pattern 1		Pattern 2		F	P
		Mean	SD	Mean	SD		
A Upward Stretch	R-PFC	0,20	1,32	0,62	1,30	0,78	0.381
	M-PFC	0,48	1,29	0,41	1,48	0,12	0.731
	L-PFC	0,28	1,64	0,31	0,84	0,15	0.699
B Shoulder Stretch	R-PFC	0,07	1,40	0,16	1,10	0,18	0.672
	M-PFC	0,12	1,28	0,34	1,53	0,09	0.762
	L-PFC	0,22	1,30	0,36	1,48	0,27	0.601
C Elbow Circles	R-PFC	0,31	0,97	0,12	1,40	0,30	0.587
	M-PFC	0,98	1,02	1,07	1,36	0,42	0.519
	L-PFC	0,82	1,16	1,03	1,50	0,53	0.469
D Trunk Twist	R-PFC	0,18	1,50	0,62	1,38	0,51	0.479
	M-PFC	0,52	1,69	0,86	1,32	0,36	0.549
	L-PFC	0,55	1,28	0,94	1,18	0,66	0.422
E Washing Hands	R-PFC	0,22	1,46	0,60	1,38	0,33	0.564
	M-PFC	0,45	1,52	0,72	1,24	0,20	0.656
	L-PFC	0,66	1,32	0,78	1,40	0,18	0.678
F Thumb & Pinky	R-PFC	0,56	1,65	0,73	1,25	0,08	0.778
	M-PFC	0,92	1,14	0,88	1,06	0,14	0.707
	L-PFC	0,75	1,20	0,90	1,14	0,11	0.741
G Single Leg Balance	R-PFC	0,72	1,29	0,88	1,19	0,19	0.662
	M-PFC	0,82	1,42	1,10	1,32	0,24	0.626
	L-PFC	0,85	1,25	1,12	1,30	0,17	0.681

Covariates included gender, age, and oxy-Hb Z-scores at rest. R-PFC: right prefrontal cortex, M-PFC: middle prefrontal cortex, L-PFC: left prefrontal cortex, SD: standard deviation, oxy-Hb: oxygenated hemoglobin.

6. Discussion

This study investigated the hemodynamic responses in the PFC during short-term, light-intensity exercises using functional near-infrared spectroscopy (fNIRS). The results revealed several significant findings that shed light on how specific movements and exercise patterns affect oxygenated hemoglobin (oxy-Hb) levels in different regions of the PFC. At the same time, there were some unexpected findings that lead to further research into the relationship between light exercise and brain activity.

One of the most notable findings was the significant increase in oxy-Hb-Z-scores in the middle PFC (M-PFC) during event A (upward stretch) in pattern 1, which is consistent with previous studies [25–28] indicating that the M-PFC is particularly sensitive to even subtle motor demands, especially when associated with cognitive processes related to the maintenance of postural control. Similar activation of the M-PFC during simple aerobic exercises was reported [29,30], suggesting that even light-intensity tasks can activate this region, possibly due to its role in the integration of motor and executive functions. Although the upward stretch was simple, it may have required sufficient coordination to stimulate activity in the PFC. Another important finding was the significant increase in oxy-Hb-Z-scores across all three PFC regions – right (R-PFC), middle (M-PFC) and left (L-PFC) – during event D (Trunk Twist) in pattern 1. This finding supports the hypothesis that exercises requiring both motor coordination and bilateral movements activate broader PFC regions. Similar conclusions [31,32] emphasized that tasks involving cross-body movements activate broader cortical

networks due to the integration of motor and cognitive functions. Trunk twist probably required not only physical coordination but also spatial awareness and balance, activating a broader range of PFC networks. In contrast, some events, such as event C (elbow circles) and event E (washing hands), showed no significant differences in oxy-Hb-Z-scores between rest and exercise conditions. This was unexpected as previous literature [33,34] that indicates that even light-intensity activities typically lead to measurable activation of the PFC. One plausible explanation is that these movements were too simple and repetitive to require substantial activation of the PFC. Exercises with minimal cognitive or motor complexity may not activate the PFC to the same extent as more demanding tasks. Furthermore, these non-significant results may reflect individual variability in neuronal responses to light-intensity activity, as shown in previous studies. The comparison between patterns 1 and 2 across multiple events also revealed no significant differences in oxy-Hb-Z scores, suggesting that doubling the exercise duration (from 10 to 20 seconds) did not induce significant changes in PFC activation. This result is consistent with previous studies [35–37], who observed that the intensity and complexity of a task plays a more important role in triggering PFC activation than its duration. The lack of significant differences suggests that the short duration used in this study may have limited the ability to detect robust effects, especially for movements that inherently require less cognitive involvement. The results of this study emphasize the nuanced relationship between exercise type, complexity and duration in influencing PFC activation. For example, the results show that tasks requiring coordination, balance or bilateral movements, such as trunk twists and single-leg balance exercises, consistently elicit higher activation in the PFC regions. This is consistent with the concept of dual-tasking, in which simultaneous physical and cognitive demands lead to increased cortical activation [38–40]. In contrast, simple and repetitive movements, even when performed for longer durations, appear to have limited effects on PFC activation, highlighting the importance of task complexity in exercise interventions to promote brain activity. Comparisons with previous studies show both similarities and discrepancies. The significant increases in oxy-Hb-Z-scores observed during certain events, particularly those related to coordination and balance, were confirmed with previous studies [29,38,41–43], who showed that PA, even at light intensity, can induce significant changes in PFC activity under certain conditions. However, the non-significant findings in some events are in contrast to some previous studies [44–47], who reported consistent PFC activation during light-intensity exercises. These differences could be due to variations in the types of exercises studied, participant characteristics or measurement methods. In addition, the limited duration of exercises in this study may have contributed to the lack of consistent results, that emphasise the importance of sufficient exercise duration for the demonstration of reliable neural effects [48–51]. Despite their contributions, this study has several limitations. The short duration of exercises may have limited the ability to observe robust changes in oxy-Hb-Z Z-scores, particularly for events that inherently require minimal cognitive or motor involvement. Future studies should extend the duration of the exercises or include more complex tasks to better understand the relationship between light activity and PFC activation. Furthermore, while the sample size is sufficient to detect significant trends, the generalizability of the results is limited. Expanding the participant pool to include individuals of different ages, fitness levels, and cognitive abilities could provide a more comprehensive understanding of how light-intensity exercise affects PFC activity. Finally, the lack of a control condition, such as a baseline without training, limits the ability to isolate the specific effects of training from other potentially confounding factors, such as participant engagement or external stimuli.

7. Conclusions

In conclusion, this study demonstrates that light-intensity exercises can induce significant hemodynamic changes in the PFC, especially during tasks requiring coordination, balance or bilateral movements. However, the lack of consistent activation across events emphasises the critical role of task complexity and duration in PFC activation. These findings contribute to the growing body of

evidence for the role of PA in promoting brain health and provide valuable insights for the design of PA interventions in educational and clinical settings.

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