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Original Research Article

Exercise-Induced Cognitive Enhancement and Prefrontal Cortex Activation

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Abstract:

Background: Physical exercise has been shown to positively influence brain function by enhancing neurovascular coupling and neuroplasticity. Emerging evidence highlights the role of the prefrontal cortex (PFC) in mediating exercise-induced cognitive enhancement, particularly in domains such as working memory, attention, and executive function. Non-invasive imaging techniques, such as functional near-infrared spectroscopy (fNIRS), allow objective assessment of PFC activation during exercise and provide in-sights into its neural correlates.

Aim: To assess the effect of moderate-intensity aerobic exercise on prefrontal cortex activation and cognitive performance in healthy young adults.

Methods: This prospective observational study was conducted at Bhagwan Mahavir Institute of Medical Sciences, Pawapuri, Nalanda, Bihar over 11 months. A total of 90 participants aged 18–40 years were included. Participants underwent standardized aerobic exercise (20 minutes of moderate-intensity cycling). Prefrontal cortex activation was measured using fNIRS, while cognitive performance was assessed using the Digit Span Test, Stroop Test, and Trail-Making Test. Data were collected at baseline, immediately After-exercise, and 30 minutes After-exercise. Statistical analysis was performed using SPSS version 23.0, with repeated-measures ANOVA and Pearson correlation applied.

Results: Mean prefrontal HbO_2 concentration significantly increased from 1.82 ± 0.45 μM (baseline) to 3.12 ± 0.62 μM immediately post-exercise ($p < 0.001$). Cognitive performance improved significantly across all domains: Digit Span scores increased from 8.2 ± 1.6 to 10.5 ± 1.8, Stroop accuracy improved from 68.4% to 77.2%, and Trail-Making completion time reduced from 46.8 ± 7.9 to 39.2 ± 7.1 seconds (all $p < 0.001$). Improvements persisted at 30 minutes post-exercise though slightly attenuated. A positive correlation ($r = 0.62$, $p < 0.001$) was observed between PFC activation and cognitive gains.

Conclusion: Moderate-intensity aerobic exercise significantly enhances prefrontal cortex activation and improves cognitive functions in young adults. The findings support the neurophysiological basis of exercise-induced cognitive enhancement, highlighting PFC activation as a potential biomarker for brain health.

Recommendations: Routine incorporation of moderate-intensity exercise into daily activities should be encouraged to promote cognitive health. Future studies should include larger samples, diverse populations, and longitudinal designs to examine sustained effects and potential clinical applications in populations with cognitive decline.

Keywords: Prefrontal cortex, Cognitive enhancement, Exercise, fNIRS, Neuroplasticity.

Introduction

Physical activity has long been recognized for its beneficial effects on brain health, with mounting evidence attributing improvements in cognitive function to exercise-induced neurophysiological changes. A comprehensive review involving over 258,000 participants across 133 systematic reviews concluded that various forms of physical exercise—particularly moderate-intensity activity—significantly enhance memory, executive function, and general cognition across all age groups. Notably, exergames and mind–body exercises like yoga and Tai Chi stood out for their effectiveness in promoting (PFC) health [1].

Beyond behavioral outcomes, neuroimaging studies reveal structural and functional brain changes associated with exercise. Aerobic exercise stimulates neuroplasticity by elevating neurotrophic factors such as BDNF, IGF-1, and VEGF, leading to increased grey matter volume in critical regions including the PFC and hippocampus [2]. These neural adaptations underpin improvements in executive control, working memory, and processing speed—a finding corroborated by longitudinal evidence showing that sustained moderate exercise boosts cognitive faculties and brain structure [2].

Technological advancements such as (fNIRS) have shed light on the PFC's role during acute and chronic exercise interventions. A randomized controlled study in older adults demonstrated that mild cycling over three months improved executive function and enhanced neural efficiency in the PFC, as indicated by reduced Stroop interference reaction times [3]. Complementing this, a 2024 systematic review of fNIRS literature confirmed that exercise induces measurable hemodynamic activation in the PFC, although many studies remain cross-sectional, underscoring the need for more causal investigations [4].

Meta-analytic work using fMRI further illuminate's specific neural correlates of exercise-induced cognitive gains. One 2025 synthesis of 52 studies reported a moderate effect size (Hedges' g = 0.271) for cognitive improvements, with consistent activity increases observed primarily in the bilateral precuneus—regions that integrate attentional and default-mode networks [5]. Another meta-analysis examining inhibitory control found enhanced activation in regions across the frontal lobe, including superior frontal gyrus, following exercise intervention [6].

Acute exercise effects also persist beyond the activity period. Improved PFC-dependent cognition—like executive control—has been observed to last up to two hours' post-exercise, possibly due to transient increases in neurotransmitters and neurotrophins that follow physical activity [7].

Collectively, this evidence underscores that exercise promotes both acute and long-term enhancements in cognitive performance, closely linked to PFC activation and neuroplastic adaptation. It establishes a clear rationale for studying the neural mechanisms—particularly PFC activation via fNIRS—underlying exercise-induced cognitive improvements in healthy individuals.

Methodology

Study Design: This research was conducted as a prospective observational study.

Study Setting: The study was carried out at Bhagwan Mahavir Institute of Medical Sciences, Pawapuri, Nalanda, Bihar, which is a tertiary care teaching hospital equipped with the necessary facilities for clinical research, including neurocognitive assessment tools and exercise monitoring equipment.

Study Duration: The total duration of the study was 11 months, during which participants were recruited, assessed, and followed for the outcomes of interest.

Participants: A total of 90 participants were enrolled in the study. Participants were adults aged between 18 and 40 years, selected from the general outpatient population as well as volunteers from the hospital staff and students. Written informed consent was obtained from all participants prior to enrolment.

Inclusion Criteria

- Adults of aged 18 between 40 years
- Both male and female participants
- Individuals with no prior neurological or psychiatric disorders
- Participants willing to undergo exercise sessions and cognitive testing
- Those who provided informed consent

Exclusion Criteria

- Individuals with history of epilepsy, head trauma, or psychiatric illness
- Participants with cardiovascular or musculoskeletal conditions limiting exercise tolerance
- Current use of psychotropic or cognition-enhancing medications
- Substance abuse (alcohol, drugs, or smoking)
- Participants unwilling to comply with the study procedure

Bias: To minimize bias, random selection of participants was undertaken within the eligible pool. Observer bias was reduced by ensuring that the neurocognitive testing and data recording were carried out by blinded assessors who were not informed of the study hypothesis. Performance bias was controlled by standardizing the exercise protocol for all participants.

Data Collection: Baseline demographic data, clinical history, and physical examination findings were recorded. Prefrontal cortex activation was assessed using non-invasive neuroimaging tools such as functional near-infrared spectroscopy (fNIRS). Cognitive performance was evaluated with validated neuropsychological tests including working memory, attention span, and executive function tasks. Data were collected at baseline, immediately post-exercise, and at 30 minutes' post-exercise.

Procedure: Participants were subjected to a standardized aerobic exercise protocol consisting of moderate-intensity cycling on an ergometer for 20 minutes. Prefrontal cortex activity was recorded before, during, and after exercise. Cognitive assessments were conducted pre-exercise, immediately after exercise, and during the recovery period. All measurements were carried out in a controlled laboratory environment under supervision.

Statistical Analysis: All data were entered into SPSS version 23.0 for statistical analysis. Continuous variables were expressed as mean ± standard deviation (SD), while categorical variables were presented as frequencies and percentages. Paired t-tests and repeated-measures ANOVA were applied to compare pre- and post-exercise prefrontal activation and cognitive test scores. A p-value of <0.05 was considered statistically significant.

Results

A total of 90 participants were included in the study. The mean age of participants was 27.4 ± 5.8 years, with 52 (57.8%) males and 38 (42.2%) females. The majority of participants (61.1%) were students, followed by healthcare staff (25.6%) and others (13.3%). Baseline characteristics such as (BMI), resting heart rate, and baseline cognitive test scores were comparable between male and female participants.

Table 1: Baseline Characteristics of Participants (n=90)

Variable	Total (n=90)	Male (n=52)	Female (n=38)	p-value
Age (years), mean ± SD	27.4 ± 5.8	27.8 ± 5.6	26.9 ± 6.1	0.48
BMI (kg/m²), mean ± SD	23.1 ± 2.7	23.4 ± 2.9	22.7 ± 2.5	0.29
Resting Heart Rate (bpm)	76.5 ± 7.2	77.1 ± 6.9	75.7 ± 7.6	0.41
Baseline Cognitive Score (%)	68.4 ± 8.9	67.8 ± 9.1	69.3 ± 8.7	0.52

There was no statistically significant difference in baseline demographic and clinical variables between male and female participants, ensuring comparability.

Prefrontal Cortex Activation: (fNIRS) revealed a significant increase in prefrontal cortex oxygenated hemoglobin (HbO_2) concentration during and immediately after exercise compared to baseline. Mean activation increased from 1.82 ± 0.45 µM at baseline to 3.12 ± 0.62 µM post-exercise ($p < 0.001$).

Table 2: PCA (HbO_2 concentration in µM, n=90)

Time Point	Mean ± SD	p-value (vs. Baseline)
Baseline	1.82 ± 0.45	—
During Exercise (10 min)	2.74 ± 0.57	<0.001
Post-exercise (Immediate)	3.12 ± 0.62	<0.001
Post-exercise (30 min)	2.21 ± 0.49	0.004

There was a sharp increase in prefrontal cortex activation during and immediately after exercise, followed by a partial decline at 30 minutes but still significantly higher than baseline.

Cognitive Performance: Cognitive performance significantly improved after exercise, as measured by working memory (digit span test), attention (Stroop test), and executive function (trail-making test).

Table 3: Cognitive Performance Before and After Exercise (n=90)

Cognitive Test	Baseline (Mean ± SD)	Immediate post-exercise	30 Min Post-exercise	p-value (RM-ANOVA)
Digit Span (score out of 15)	8.2 ± 1.6	10.5 ± 1.8	9.7 ± 1.7	<0.001
Stroop Accuracy (%)	68.4 ± 8.9	77.2 ± 9.1	73.5 ± 8.6	<0.001
Trail-Making Test (seconds)	46.8 ± 7.9	39.2 ± 7.1	42.7 ± 7.6	<0.001

Significant improvements in working memory, attention, and executive function were observed immediately after exercise. Although the effects slightly declined at 30 minutes, cognitive performance remained better than baseline ($p < 0.001$).

Correlation Between Prefrontal Activation and Cognitive Enhancement: Pearson correlation analysis demonstrated a positive correlation between increased HbO_2 concentration in the prefrontal cortex and cognitive performance improvement ($r = 0.62$, $p < 0.001$). Participants with higher neural activation showed greater enhancement in attention and working memory scores.

Summary of Results

- Of the 90 participants, both males and females showed comparable baseline characteristics.

- Prefrontal cortex activation increased significantly during and after exercise, peaking immediately post-exercise.
- Cognitive functions (working memory, attention, and executive function) improved significantly post-exercise.
- A strong positive correlation was found between prefrontal cortex activation and cognitive performance, suggesting exercise-induced neurocognitive benefits.

Discussion

In this study involving 90 participants, baseline demographic and clinical characteristics such as age, BMI, resting heart rate, and cognitive scores were comparable between males and females, indicating a well-balanced study population. This ensured that observed changes in cognitive performance and prefrontal cortex activation could be attributed primarily to the exercise intervention rather than baseline differences.

The results demonstrated a significant enhancement in PCA following exercise. Oxygenated hemoglobin concentration (HbO_2), measured via fNIRS, showed a substantial increase during exercise and peaked immediately post-exercise. Although activation declined at 30 minutes' post-exercise, it remained significantly above baseline levels, suggesting a transient but measurable neurophysiological effect of physical activity on prefrontal cortex function. This pattern is consistent with prior evidence indicating increased cerebral perfusion and oxygenation during aerobic exercise.

Cognitive performance, measured through working memory (digit span), attention (Stroop test), and executive function (trail-making test), also improved significantly after exercise. The most pronounced improvements were observed immediately post-exercise, with working memory and attention scores increasing by nearly 20–25%, and executive function tasks showing faster completion times. While there was a partial decline in performance at the 30-minute mark, the scores remained superior to baseline, indicating a short-term but persisting cognitive benefit induced by exercise.

Importantly, correlation analysis revealed a strong positive association between prefrontal cortex activation and cognitive improvement. Participants with higher HbO_2 levels demonstrated greater gains in attention and working memory, suggesting that the neural activation of the prefrontal cortex may serve as a physiological basis for the cognitive enhancements observed. This reinforces the hypothesis that exercise-induced neurovascular changes directly facilitate cognitive gains.

Recent research highlights a strong link between exercise and enhanced cognitive performance through increased prefrontal cortex activation. Mekari et al. found that acute aerobic exercise significantly improved working memory performance in older adults, with corresponding increases in prefrontal cortex oxygenation, suggesting that exercise-induced neurovascular responses play a role in executive functioning [8]. Similarly, Hyodo et al. reported that moderate-intensity exercise enhances cognitive flexibility by boosting prefrontal activation, further supporting the role of aerobic activity in modulating executive control processes [9].

In addition to aerobic exercise, even short bouts of physical activity have been shown to improve cognitive function. Alghadir et al. demonstrated that brief exercise sessions improved inhibitory control and were accompanied by increased dorsolateral prefrontal cortex activation, indicating that benefits extend even to low-dose interventions [10]. Complementing this, Krafft et al. studied children and found that regular aerobic exercise improved attention and executive functions, with functional near-infrared spectroscopy confirming enhanced prefrontal activity [11].

Furthermore, Ludyga et al. examined the effects of exercise intensity and showed that high-intensity interval training (HIIT) not only improved executive functions but also increased prefrontal cortical activity, suggesting that both moderate and high-intensity modalities are effective in promoting cognitive enhancement [12]. In summary, exercise across different intensities and durations consistently enhances executive functions—such as working memory, cognitive flexibility, and inhibitory control—primarily through increased prefrontal cortex activation.

Conclusion

The findings indicate that moderate-intensity aerobic exercise significantly enhances prefrontal cortex activation and improves cognitive functions in healthy young adults. The results support the role of physical activity as a non-pharmacological intervention for boosting cognition, with potential implications in academic, occupational, and clinical settings.

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