**ORIGINAL RESEARCH ARTICLE**

**EFFECTS OF UPRIGHT AND RECUMBENT CYCLING ON EXECUTIVE FUNCTION AND PREFRONTAL CORTEX OXYGENATION IN YOUNG, HEALTHY, MEN**

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**Abstract**

**Background**: The purpose of this study was to assess the acute effects of posture (upright vs. recumbent) during moderate-intensity cycle exercise on executive function and prefrontal cortex oxygenation, in young healthy adults. **Methods:** Seventeen physically active men (24.6 ± 4.3y) completed two 30-minute submaximal, exercise tests (Conditions: upright and recumbent cycle ergometry). Executive function was assessed using the ‘colour’ and ‘word’ Stroop task, pre- (resting) and post-exercise. Regional oxygen saturation (rSO2) to the prefrontal cortex was continuously monitored using near-infrared spectroscopy. **Results:** Significant improvements in executive function (Stroop colour and word tasks) were observed following 30 minutes of exercise, for both upright and recumbent cycling (*P* < .05). However, there were no differences in executive function between cycling Conditions (*P* > .05). A significant increase in rSO2 was recorded immediately post-exercise compared to pre-exercise for both Conditions (*P* < .05), with a trend (*P* = .06) for higher peak rSO2 following recumbent cycling compared to upright cycling (81.9 ± 6.5 cf. 79.7 ± 9.3%, respectively). **Conclusions:** Although submaximal cycling exercise acutely improves cognitive performance and prefrontal oxygenation, changes in cognition are not perceived to be dependent on body posture in young, healthy men.

**Introduction**

A number of randomized control trials have demonstrated that a single bout of aerobic exercise can acutely improve various cognitive domains,[1](#_ENREF_1) including spatial and executive functioning.[2](#_ENREF_2) However, further research is necessary to mechanistically link the beneficial effects of exercise on cognition. Accordingly, it is important to investigate this relationship in young, healthy adults as this may lead to the development of exercise programmes that have important implications for various population groups. This could be evident when trying to optimize academic performance in school children, or in the rehabilitation of certain clinical groups (i.e., patients with Stroke, Parkinson’s disease and vascular dementia).

A number of mechanisms have already been proposed which link acute exercise to cognitive performance, including elevated levels of brain-derived neurotrophic factor[3](#_ENREF_3), [4](#_ENREF_4) and changes in plasma catecholamines.4,[5](#_ENREF_5) These studies have demonstrated either associational3,5 or causational4 links between changes in such physiological markers and corresponding improvements in cognitive performance (i.e., reaction time, executive function [Stroop task]). Cerebral perfusion may also be an important mechanism, as blood flow, especially to the prefrontal frontal cortex, will directly govern oxygen delivery.[6](#_ENREF_6) Research has shown that prefrontal oxygenation is either maintained or increased between moderate and heavy exercise intensities, but may decrease at near extreme exercise intensities.[7-10](#_ENREF_7) However, while these findings suggest that moderate to heavy intensity exercise provides an optimal stimulus for prefrontal oxygenation, very little research has been undertaken to simultaneously investigate cerebral oxygenation and cognitive function responses to acute exercise[11](#_ENREF_11). In a study by Lucas and colleagues,[11](#_ENREF_11) cognitive function was assessed during a low (30% heart rate reserve [HRR]) and moderate (70 % HRR) bout of exercise. In this study, faster response times using the Stroop task were observed during exercise compared to rest, regardless of the exercise intensity. Despite this finding, prefrontal cortical hemodynamic measures (oxyhemoglobin, total haemoglobin) were differentially affected by exercise intensity, participant age and the difficulty of the cognitive task.[11](#_ENREF_11) Therefore, further research in this area is warranted.

While cerebral perfusion has been investigated during upright cycle ergometry,[11](#_ENREF_11), [12](#_ENREF_12) it has not been examined during recumbent cycle exercise. Recumbent exercise has been shown to enhance venous return, increase stroke volume and activate a greater proportion of lower limb musculature than upright cycle exercise. [13-15](#_ENREF_13) Considering that cardiac output has been shown to have a linear relationship with cerebral blood flow,[16](#_ENREF_16) it is plausible that a recumbent body posture during exercise may elicit greater improvements in cognitive function than upright cycle exercise.

The purpose of this study was to assess the acute effects of posture (upright vs. recumbent) during moderate-intensity cycling exercise on: i) executive function, and ii) prefrontal cortex oxygenation, in young, healthy men. It was hypothesised that recumbent exercise would result in better executive function performance and greater prefrontal cortex oxygenation than upright cycle exercise.

**Methods**

*Participants*

Seventeen (24.6 ± 4.3 y; 1.79 ± 0.05 m; 76.5 ± 8.7 kg) healthy, physically active men volunteered for this study. All participants were asymptomatic of illness and free from injury, as established by the ACSM participant activity readiness questionnaire and risk stratification procedures[17](#_ENREF_17). Participants were currently involved in regular, ‘recreational’ physical activity, undertaking moderate aerobic exercise (> 60-min) three times per week in the months prior to the commencement of the study. All participants provided written informed consent. Ethical approval was granted by the institutional ethics committee.

*Procedures*

All participants completed four exercise tests: two graded exercise tests (GXT) to maximal aerobic capacity and two submaximal bouts at a moderate constant-load exercise intensity, in a controlled, temperate laboratory environment. Tests were performed on either an upright- (1 x GXT, 1 x submaximal bout) or recumbent (1 x GXT, 1 x submaximal bout) cycle ergometer, in a semi-randomised order as it was necessary for submaximal exercise tests to proceed the respective GXTs. There was a 48 to 72 hour recovery period between tests. To reduce the risk of anticipatory effects on physiological parameters, the display screen of the physiological markers (i.e., oxygen uptake [V̇O2], minute ventilation [V̇E], respiratory exchange ratio [RER], heart rate [HR]), along with all cycle ergometer information (i.e., power output), was concealed from the participant during each exercise test.

Prior to- and following the upright and recumbent submaximal exercise tests, participants completed a standard cognitive performance test (Stroop task). Regional oxygen saturation (rSO2) of the prefrontal cortex was continuous and real-time monitored, using near-infrared spectroscopy (NIRS; 5100C INVOS, Coviden, Bloulder, CO, USA), throughout the Stroop tasks and exercise protocols. The continuous wave NIRS device, which collects one measurement every 4 seconds, utilises near-infrared light at wavelengths that are absorbed by haemoglobin.

*Exercise Tests:*

*Upright and recumbent GXT to maximal functional capacity*

The GXTs were continuous and incremental, commencing at a low intensity (60 W and 30 W for the upright and recumbent GXTs, respectively) and progressively increasing by 1 W every 5 seconds until the participant achieved maximal functional capacity. On-line respiratory gas analysis occurred using a breath-by-breath automatic gas exchange system (Sensormedics Corporation, Yorba Linda, CA, USA) following volume and gas calibration. Heart rate was monitored using a wireless chest strap telemetry system (Polar Electro T31, Kempele, Finland). The Borg 6-20 ratings of perceived exertion (RPE) scale[18](#_ENREF_18) was used to quantify the subjective perception of effort every 3-minutes during the GXTs. Participants’ peak oxygen consumption (V̇O2peak) and gaseous exchange threshold (GET) were ascertained for both exercise tests. The GXTs were used to determine the exercise intensities that would be prescribed in both the upright and recumbent submaximal exercise tests.

*Submaximal exercise tests*

The V-slope method[19](#_ENREF_19) was used to analyse the slopes of V̇O2 and carbon dioxide (V̇CO2) volume curves from both the upright and recumbent GXTs to determine each participant’s power output at GET. The GET typically equates to a moderate exercise intensity (45-60% V̇O2max)[20](#_ENREF_20). During the upright and recumbent submaximal exercise tests, participants cycled at a power output equivalent to GET for 30-minutes. Physiological markers were continuously monitored throughout the test.

### *Cognitive assessments*

Executive function was assessed using the Stroop task (Xavier Educational Software Ltd., Bangor, Wales), a classic measure of prefrontal cortex function[21](#_ENREF_21) which has been widely used to assess the effects of acute exercise on cognition[11](#_ENREF_11),[22](#_ENREF_22),[23](#_ENREF_23). Participants were familiarized with the Stroop task on their first laboratory visit, as well as following each GXT. Thereafter, Stroop task performance was assessed at 5-minutes prior to- and 5-minutes following each of the subsequent submaximal exercise tests, in their upright or recumbent position, to assess temporal changes in executive function. A 5-minute follow-up assessment was chosen as past research has shown that positive, moderate effects are observed when cognitive performance is assessed soon after moderate intensity exercise (Chang et al., 2012).

The Stroop interference task involves four words (‘blue’, ‘yellow’, ‘green’, ‘red’) being randomly presented, consecutively, on a computer screen. The colour that each word is presented in is either congruent or incongruent with the relevant semantic information (e.g., ‘red’ presented in the colour red or the colour green, respectively). In this study, participants were tasked with identifying both the colour of each word being presented (test A), and the word itself (test B), as quickly as possible, which they responded to by clicking on the respective answer button (blue, yellow, green, red). Each presentation of a word constituted a sequence; each test comprised 32 sequences, and the total time to complete each test was recorded as a measure of performance. The order of the tests (A & B) were randomised.

*NIRS*

The rSO2 of the prefrontal cortex, an indicator of tissue saturation index, was monitored using NIRS. NIRS assessments have been demonstrated to provide a metric of cognitive activation similar to functional magnetic resonance imaging during cognitive performance tasks.[24](#_ENREF_24) NIRS sensors were placed bilaterally over each contralateral frontal lobe, approximately 3 cm from the forehead midline and immediately above the supra-orbital ridge. To measure the absorption spectra of oxyhemoglobin and deoxyhemoglobin, each sensor emits near-infrared light (730 and 810 nm) at source-detector distances of 3 cm and 4 cm. The shorter detector distance signal is subtracted from the longer distance in order to diminish the contribution of the skin and scalp.[25](#_ENREF_25)

*Data Analysis*

Following the presentation of normally-distributed data, a series of paired sample *t*-tests compared peak physiological, physical and perceptual responses from the upright and recumbent GXT. When considering the submaximal exercise tests, two-way repeated measures analysis of variance (ANOVA): Test (upright, recumbent) by Time (pre, post) were used to compare the time to complete both Stroop tasks (colour and word) and the rSO2 between the two modes of exercise. A similar analysis was used to assess the rate of change in rSO2 before, during and following (baseline, 10-min, 20-min, 30-min, post) the submaximal exercise tests. A two-tailed paired samples *t*-test was used to compare the time to steady state during the upright and recumbent exercise tests. For all statistical tests, alpha was set at 0.05 and adjusted accordingly using Bonferroni correction factor to reduce the risk of type I errors. Effect sizes are reported using Cohen’s *d*; in general, <0.20 is considered to be a small effect, >0.20 to <0.50 a moderate effect, and >0.80 a large effect.[26](#_ENREF_26)

**Results**

*Graded Exercise Tests*

Peak values at the termination of the upright and recumbent GXT are reported in Table 1. The upright GXT elicited a significantly higher V̇O2, HR, RPE and power output than the recumbent GXT (all *P* < .05). When expressed as a proportion of the peak values, the power output and V̇O2 calculated at GET proved comparable between the upright GXT (48.3 ± 4.3 and 47.7 ± 7.4%, respectively) and recumbent GXT (48.4 ± 5.2 and 47.5 ± 5.3%, respectively; *P* > .05).

*Executive function (Stroop task); pre- and post-exercise*

Although a non-significant Test (upright, recumbent) by Time (pre, post) interaction was reported for the time to complete the Stroop tests (word and colour) (*P* > .05), a Time main effect was observed (*P* < .001). Significant improvements in the time to complete the Stroop test (word and colour) was observed following both upright and recumbent submaximal exercise (Table 2). There was no Test main effect for Stroop task performance (*P* > .05).

The rSO2 responses during the pre-exercise Stroop task were statistically similar between exercise modes (75.1 ± 9.0 and 76.7 ± 6.7% for upright and recumbent exercise, respectively; *P* > .05). Significantly higher values were reported during the post-exercise Stroop task (81.5 ± 10.6 and 83.8 ± 6.9% for upright and recumbent exercise, respectively), compared to the pre-exercise Stroop task (*P* < .001).

*Regional oxygen saturation (rSO2) during exercise*

There was no Test by Time interaction for rSO2 (*P* > .05) but a significant Time main effect was demonstrated (*P* < .001). Post-hoc analysis revealed a significant increase in rSO2 between baseline and 10-min (*P* < .001; Figure 1). The mean rSO2 was 2.2% higher during recumbent compared to upright exercise (81.9 ± 6.5 cf. 79.7 ± 9.3%, respectively; *P* = 0.06). The time to achieve steady state was similar for upright and recumbent exercise (593 ± 283 cf. 569 ± 219 s, respectively; *P* > .05).

**Discussion**

The present study demonstrates that an acute bout of moderate intensity exercise, on either an upright or recumbent cycle ergometer, elicits improvements in executive function in a population of young, healthy men. The changes in executive function following moderate intensity exercise are in accordance with previous research.[1](#_ENREF_1), [27-29](#_ENREF_27) In the current study, 30 minutes of submaximal exercise generated a 4-6 % and 5-7 % improvement in Stroop task performance (for word and colour tasks, respectively), for both the recumbent and upright cycle exercise. The improvements in cognitive performance may therefore, at least in part, be associated with the observed exercise-induced increase in cerebral oxygen delivery. Previous research has shown that exercise intensities up to and including ~60 % V̇O2peak may produce elevations in cerebral blood flow.[16](#_ENREF_16) Indeed, in this study whereby participants exercised at a moderate exercise intensity (~48 % of V̇O2peak), a 5-6 % increase in rSO2 was observed. An exercise-induced increase in cerebral perfusion is related to an increase in brain neuronal activation and metabolism,[11](#_ENREF_11),[30](#_ENREF_30),[31](#_ENREF_31) of which neurovascular coupling has been identified as an important mechanism for adequate oxygen delivery.[32](#_ENREF_32)

Regional oxygenation saturation increased and Stroop task performance improved between the pre- and post-exercise assessment. Nevertheless, it must be recognised that the timing of the assessment (e.g., 5-minutes post-exercise rather than immediately following the submaximal exercise session) may have moderated the magnitude of the observed findings. For example, differences in systemic haemodynamics, localised sympathetic effects and feedforward signalling from the motor cortex may influence Stroop task performance if the cognitive assessment is administered during exercise, immediately after exercise (< 1-min post exercise cessation) or following a delay (> 1 min post exercise cessation). Chang and colleagues’ meta-analysis (2012)[1](#_ENREF_1) suggests that the greatest positive effect on cognition occurs 11-20 min after exercise cessation, with effects subsiding following a longer delay (>20 min). Yet, despite being informative, these aforementioned findings must be viewed cautiously as meta-analytical techniques can mask some effects of moderator variables on key outcomes. More recently, research has shown that improvements in cognition can be maintained for a period of 30 minutes post-exercise, regardless of the exercise intensity employed (moderate vs. vigorous).[33](#_ENREF_33) Future research is therefore needed to identify whether the observed improvements in cognitive performance following recumbent or upright exercise can be maintained for a longer period of time. This may have practical implications, particularly if implementing exercise to improve the cognitive performance of certain clinical populations (patients with stroke and Parkinson’s disease), as it may demonstrate a window of opportunity following participation in an acute bout of exercise for presenting such patient groups with tasks that challenge executive function. In this regard, the data from this current study will aid in calculating appropriate sample sizes for future research in this area.

Although recumbent cycle exercise elicited a higher (~2.2%) prefrontal cortex oxygen saturation than upright cycle exercise, it was only approaching statistical significance. This is contrary to our hypothesis which postulated that greater prefrontal cortex oxygenation would be observed during recumbent compared to upright cycle exercise. This study recruited a homogenous cohort of young, physically fit men, who were accustomed to moderate intensity aerobic exercise and who did not exhibit any obvious signs of impaired cognition prior to commencing exercise. Previous research has shown that regular exercise training, as undertaken by the sample in this study, may improve the acute exercise-induced changes in cerebral oxygenation and the velocity of blood flow through the middle cerebral artery,[34](#_ENREF_34) and the cerebrovascular reactivity to CO2.[35-37](#_ENREF_35) In the present study, it is plausible that the subtle increases in prefrontal cortex oxygenation during recumbent exercise were insufficient for eliciting improvements in executive function, at least with regards to the task employed in this study (e.g., Stroop task). As a result, similar improvements in executive function were observed between the exercise modes.

The observed ~2 % difference in prefrontal cortex oxygenation between recumbent and upright cycling could be of practical significance for certain low-fit and/or patient groups with known cognitive impairments. It is plausible that patient groups, such as those diagnosed with stroke or Parkinson’s disease, may be more responsive to subtle oxygenation changes than the young, fit and healthy cohort used in the current study. This may be of particular interest when considering that recumbent cycling exercise has been shown to be a safer alternative to upright cycling, and may provide practical advantages for muscle and aerobic training in patients with impaired physical function.[38](#_ENREF_38), [39](#_ENREF_39)

Future research investigating temporal associations between exercise-induced changes in prefrontal cortex oxygenation and cerebral perfusion should ensure the exercise perturbation is of a sufficient duration. A novel finding of the current study pertained to the time necessary to reach peak cerebral oxygenation. For example, Lucas and colleagues[11](#_ENREF_11) recently investigated the effect of age on exercise-induced (upright cycling) alterations in cognitive function (Stroop task). Two exercise intensities were prescribed, 30% and 70% of heart rate range, with each intensity lasting 8 minutes and the higher intensity immediately following the lower intensity. The authors reported that the higher exercise intensity elicited greater improvements in cognitive function. For the current study, it took participants, on average, 9.5 minutes (range: 1.8 - 21.7 minutes) to achieve steady-state oxygen saturation during both upright and recumbent cycle exercise. Based on our study findings, it may be postulated that the study by Lucas et al.,[11](#_ENREF_11) may have underestimated the magnitude of change in cognitive performance elicited by exercise, and/or potentially may have come to an erroneous conclusion with regards to the importance of exercise intensity.

It is pertinent to recognise that there are potential limitations to this study. Firstly, it would have been useful to report other haemodynamic indices during the upright and recumbent exercise (i.e., oxy-, deoxy- and total haemoglobin). The NIRS device employed in this study was only able to provide a measure of rSO2, which limits the depth of interpretation that can be formed when assessing the relationship between acute exercise and executive function in a young, healthy population. Secondly, for gas exchange to be efficient there must be a close match, or coupling, between ventilation of the lung alveoli and the perfusion of the pulmonary capillaries. As gravity causes regional variations in both blood and air flow in the lungs, further research is needed to assess the effect of posture (upright vs. recumbent) on ventilation-perfusion coupling (e.g., PETCO2) and the effect this may have on cerebral blood flow.

In conclusion, the present study has demonstrated that 30-minutes of moderate intensity upright or recumbent cycle exercise significantly enhances executive function and prefrontal cortex oxygenation in young, physically fit males. Further research is warranted to investigate the clinical utility of recumbent exercise for patients with known cognitive impairments.

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**Conflicts of interest:** None to declare

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**Figure Legend:**

**Figure 1:** Mean (± SD) oxygen saturation (*rS*O2) before (baseline), during (10, 20, 30-min) and after (post) exercise for seated and recumbent exercise

**Table 1** Mean (± SD) values reported at the termination of the upright seated and recumbent GXT. Oxygen uptake and power output data at GET are also reported.

|  |  |  |
| --- | --- | --- |
|  | **Seated GXT**  **(mean ± SD)** | **Recumbent GXT**  **(mean ± SD)** |
| **V̇O2peak (L·min-1)** | 3.70 ± 0.71\* | 3.41 ± 0.51 |
| **V̇O2peak (mL·kg-1·min-1)** | 49.1 ± 5.3\* | 45.1 ± 5.4 |
| **HRpeak (b·min-1)** | 186 ± 15\* | 168 ± 20 |
| **V̇Epeak (L·min-1)** | 135 ± 35 | 117 ± 26 |
| **RER** | 1.16 ± 0.04 | 1.13 ± 0.05 |
| **RPE** | 19.5 ± 0.7\* | 19.1 ± 0.8 |
| **Peak power output (W)** | 263 ± 40\* | 237 ± 31 |
| **Duration (min)** | 16.91 ± 3.33\* | 17.25 ± 2.58 |
| **Power output @ GET (W)** | 129 ± 25\* | 115 ± 23 |
| **V̇O2 @ GET (L·min-1)** | 1.81 ± 0.50 | 1.63 ± 0.36 |
| **V̇O2 @ GET (mL·kg-1·min-1)** | 23.5 ± 4.8 | 21.5 ± 4.1 |

*Abbreviations:* HR, heart rate; GET, Gaseous exchange threshold; RER, Respiratory exchange ratio; RPE, Ratings of perceived exertion; V̇O2, oxygen uptake

\*Significant difference between seated and recumbent GXT (*P* < .05)

**Table 2** Mean (± SD) time to complete the Stroop task (word, colour) before and after the upright seated and recumbent submaximal exercise test

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Stroop Response Time: Seated (s)** | |  | **Stroop Response Time: Recumbent (s)** | | | | |
|  | **Pre** | **Post** | ***d*** | **Pre** | **Post** | ***d*** | |
| **Stroop Word** | 53.4 ± 3.5 | 50.8 ± 4.0\* | 0.69 | 53.0 ± 4.6 | 51.3 ± 5.6\* | | 0.51 | |
| **Stroop Colour** | 60.4 ± 5.6 | 57.7 ± 4.9\* | 0.51 | 60.6 ± 8.6 | 57.3 ± 9.6\* | | 0.36 | |

\*Significant change in Stroop from pre- to post (*P* < .05)