Shenoy, S., Khandekar, P., & Sathe, A. (2021). High Intensity Intermittent Exercise Plays a Role in Improving Brain Activation During Complex Executive Functional Tasks. *Teorìâ ta Metodika Fizičnogo Vihovannâ, 21*(1), 36-42.
https://doi.org/10.17309/tmfv.2021.1.05
ISSN 1993-7989 (print). ISSN 1993-7997 (online)

ORIGINAL SCIENTIFIC ARTICLE

HIGH INTENSITY INTERMITTENT EXERCISE PLAYS A ROLE IN IMPROVING BRAIN ACTIVATION DURING COMPLEX EXECUTIVE FUNCTIONAL TASKS

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Accepted for Publication: March 20, 2021
Published: March 25, 2021

DOI: 10.17309/tmfv.2021.1.05

Abstract

Several neuroimaging studies have examined the effect of different types and combinations of exercises on activation of brain associated with cognitive testing but none of these studies have examined the role of high intensity intermittent exercise (HIIE) in altering cortical activation from simple to complex cognitive tasks.

The purpose of this study was to find if HIIE has a role in modulating executive functions related to inhibitory control as expressed by changes in prefrontal cortex (PFC) activation.

Materials and methods. 40 healthy adults aged between 18-30 years volunteered for the study. They were randomly divided into HIIE a (n = 20) group and a control (n = 20) group. The HIIE group performed 4*4 min of high intensity exercise on a cycle ergometer with 3 minutes of active recovery at lower intensities between the bouts, whereas the control group performed no exercise. Prefrontal hemodynamics (oxy and deoxy haemoglobin) were assessed using functional near infrared spectroscopy (fNIRS) during the Colour Word Stroop test (CWST) on two sessions: pre-session and post-session (1 week after pre-session).

Results. The results indicate a significant difference in CWST scores which coincided with a significant difference in hemodynamics of PFC between a congruent and a complex incongruent task in the HIIE group. There was a greater activation of the right frontopolar area, the left ventrolateral prefrontal cortex, and the left frontopolar area during the incongruent task in response to acute HIIE.

Conclusion. HIIE plays a role in changing brain activation during more complex interference related tasks.

Keywords: HIIE, fNIRS, prefrontal cortex, Colour Word Stroop test, cognition.

Introduction

A growing body of literature has reported that exercise has an effect on brain activation during cognitive testing (Hyodo et al., 2012; Chang et al., 2012; Bediz et al., 2016). Cognition improvement is related to the type of exercise, improvement is smaller with low to moderate intensity exercise and larger with high intensity exercise (Hashimoto et al., 2017; Tsukumoto et al., 2016, 2017). The colour word Stroop test (CWST) has been widely used to assess changes in cognitive performance as a result of acute (Tsujii et al., 2013; Yanagisawa et al., 2010) as well as long term exercise (Martinsen et al., 2018).

CWST is a robust test which is used to assess executive functions including processing speed, selective attention and the degree of automaticity (Martinsen et al., 2018). It has two types of stimuli: congruent, testing fluency of reading words and incongruent, testing the ability to inhibit the interference (Scarpina & Tagini, 2017). The latter is a more complex task and needs involvement of more neural substrate (Floden et al., 2011). SCWT assesses executive functions that are mediated by changes in the hemodynamics in prefrontal cortex (Moriguchi & Hiraki, 2013). Executive functions involve activation of many brain sites, such as the prefrontal cortex (PFC), anterior cingulate, and parietal cortex (Scarpina & Tagini, 2017). Acute exercise enhances the activity of prefrontal cortex and involves activation in dorsolateral prefrontal cortex and frontopolar area of prefrontal cortex (Byun et al., 2014).

Previous literature shows that exercise increases neuronal activity (Dalsgaard et al., 2002, Endo et al., 2013; Cooper, 1973), improves cognitive performance (Cooper, 1973; Tsukamoto et al., 2016, 2017; Hashimoto et al.; 2018) and exercise with sufficient intensity and duration prolongs the exercise-induced improvement in executive functions. In particular, high intensity intermittent exercise

(HIIE) facilitates neuronal activation and excitation levels (Hashimoto et al., 2018). HIIE is an exercise regime which includes number of bouts of exercising at high intensities (85-95% of HR max) (Helgerud et al., 2007) interspersed with intervals of exercise at lower intensities (40-50% of HR max) (Kravitz, 2014). HIIE is an exercise regime which motivates young adults for continued engagement in exercise for its behavioural, affective and cognitive outcome (Burn & Niven, 2018). Literature suggests that participation in high intensity exercise is positively associated with existing cognitive health and produces broader benefits on cognition (Tsukumoto et al., 2016). However, studies determining the effect of HIIE on brain areas involved in cognitive tasks are few.

Changes in the brain activation, associated with cognitive improvement have been recently assessed by Functional near infrared spectroscopy (fNIRS). It is an optical, non-invasive method which measures changes in the cortical hemodynamics and is suitable for assessing the effect of acute exercise on changes in brain activation (Yanagisawa et al., 2010). Kujach et al. (2018) examined the effect of short duration transferable high intensity intermittent exercise on CWST associated prefrontal cortex activation and they found increased corticalactivation related to Stroop interference on the left-dorsal-lateral prefrontal cortex (DLPFC) with improved cognitive performance. However they could not explain the difference in the activation during congruent and incongruent task. Brain activation from simple to complex tasks are needed to be evaluated as it may provide valuable information about sports performance enhancement through HIIE during formation of complex game strategies. To our knowledge the studies determining the difference in brain activation during congruent and more challenging incongruent task as an effect of HIIE are less and needed to be studied. Thus the aim of our study was to find if HIIE has a role in modulating executive functions related to inhibitory control as expressed by changes in prefrontal cortex activation.

Materials and methods

Study Setup and Participants

The setup of the study was the Neuro Physiology Lab, MYAS-GNDU Department of Sports Sciences and Medicine, Guru Nanak Dev University, Amritsar, Punjab. Participants were asked to volunteer from various departments of the University. The study was randomized two group pre post design. The procedure of testing protocol was explained to the participants thoroughly and written informed consent was obtained from all participants. 40 healthy adults (24 females and 16 males) aged between 18 to 30 years volunteered for the study. They were randomly divided into HIIE group and control group (Table 1). The study was approved by Institutional Ethical committee of Guru Nanak Dev University, Amritsar, Punjab, India. (No. 158/HG; Dated 01/10/2019)

Study Criteria

Males and females participants between 18-30 years of age were included for the study. All subjects were in intellectual norm measured by measured by Multidimensional Aptitude Battery-II and had IQ between 90-119. Participants were excluded if they answered yes to any of the questions of Physical activity readiness questionnaire (PARQ), had a history of cardio-respiratory or cerebro-vascular disease, had a history of psychiatric or neurological disease, had done strenuous activity or had a history of use of tobacco/nicotine products such as cigarettes or chewing tobacco, had a history of alcohol consumption 24 hours prior to the test, had poor sleep (measured by Pittsburgh Sleep Quality Index) or had consumed 2 or more than 2 cups of caffeine on that day or a large meal for 2 hours before exercise.

Table 1. Descriptive characteristics of participants

Descriptive characteristics of participants	Control group n = 20	HIIE group n = 20	p
Age (years)	24.12 ± 0.64	24.11 ± 1.53	0.981
BMI	23.05 ± 3.59	22.25 ± 2.40	0.458
Resting HR (beats/min)	81.00 ± 2.72	79.22 ± 6.09	0.460
PSQI score	3.12 ± 1.64	4.00 ±1.65	0.293
IPAQ (MET·min/week)	1743.76 ± 1353.81	2559.58 ± 1475.99	0.115
IQ score	92.50 ± 9.47	92.55 ± 13.56	0.992

Values of above variables are presented as mean ± standard deviation. There was no significant difference ($p > 0.05$) found on comparison with independent t-test for the above mentioned variables between control and HIIE group.

Exercise protocol

HIIE protocol was of 4 bouts of 4 minutes (4×4) at 90-95% HRmax with 3min active recovery at 70% HRmax (Helgerud et al., 2007). HRmax (beats/min) was calculated by the formula: (Fox et al., 2013; McArdle., 2010 p. 473)

$$HRmax = 206.9 - 0.67 \cdot age\ (y)$$

Before training, 3 minutes of warm up was done and training was followed by 2 minutes of cool down at the pedalling frequency and intensity according to participant preference between 8-12 grading of 20 pointed Borg's Rating of Perceived Exertion (RPE) scale. Participants cycled on Lode Corival BV Groningen, The Netherlands against a work load of 100-150 W and between 15-18 Borg's RPE during each high intensity bout and with no work load, average 89 RPM and 8-12 Borg's RPE during recovery period. Heart rate was monitored using Polar heart rate Monitor (Polar Vantage V Pro Multisports Watch). Borg's RPE grading was noted after one minute of start of each high intensity bout and after the end of each high intensity bout session. All training sessions were conducted in neurophysiology lab of MYAS-GNDU department of Sports Sciences and Medicine, Guru Nanak Dev University, Amritsar, Punjab, India.

Cognitive testing

Cognitive functions were tested by Stroop Colour and Word test. There was a gap of at least one week between pre and post session in order to dilute the effect of learning of the cognitive test.

Colour and Word Stroop test

Colour-word Stroop test was used to assess executive functions. It is a paper pencil based test which has 4 pages of 5 by 20 matrixes of colour- word items (total 100 items). First and second page included congruent stimuli, whereas third and fourth page included incongruent stimuli. Subjects were instructed to read the words across the column on each page. On the first page participants were instructed to read the words written with black inc above downwards. On the second page participants were instructed to read the colours by which 'XXXX' are printed. The third page had 5 columns of colour names (red, green, and blue), which were printed in different colours. For this participants were instructed to name the ink of each word, ignoring the word that was spelled out. For example, if the printed word "red" appeared in blue colour font, the word should be read "blue". For the fourth page participants were instructed to name the ink by which the words were printed, ignoring the word which is written but to read the word which is highlighted with the box, ignoring its colour. The time taken and errors during reading the 100 items were noted. Stroop testing was done on following sessions: Pre HIIE and Post 10-15 min of HIIE. These raw scores were converted into the variables of time interference score, Average reaction time score and error interference scores using following formulae:

Stroop interference score = CWS - [(CS+WS)/2]

Where, CWS – Colour word score, CS – Colour score and WS – Word Score

Average reaction time = Summation of total time taken to complete individual sheets/400

Error Interference score = CWE - [(WE + CE)/2]

Where, CWE – Colour word error, CE – Colour error and WE – Word error

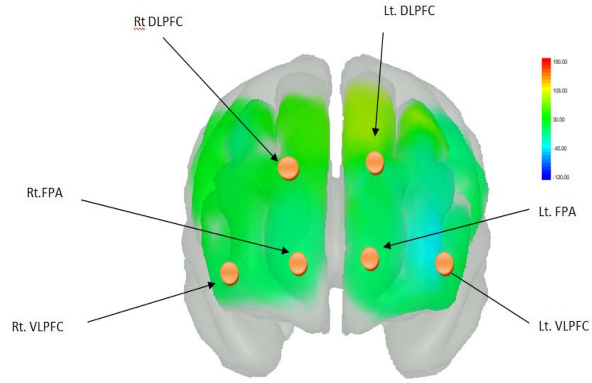

Fig. 1. Region of interest in right and left Prefrontal cortex shown by 3D cortical mesh view. (Rt. - right, Lt.-left)

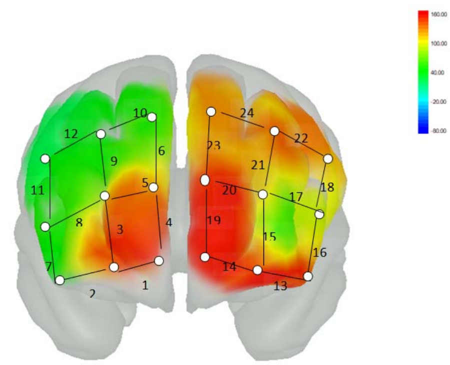

Fig. 2. Schematic representation of arrangement of 24 channels of fNIRS on prefrontal cortex shown on cortical 3D Mesh view. Optodes were arranged according to topographic probe layout map along with the standard EEG 10/20 coordinate system

Evaluation of brain hemodynamics

A continuous wave functional near infrared spectroscopy (fNIRS) System Brite Artinis 24, Netherlands, was used to assess oxy and deoxy haemoglobin concentration of prefrontal cortex during colour-word Stroop test. Hemodynamic changes were recorded as oxy haemoglobin (oxy-Hb) and deoxyhemoglobin (deoxy-Hb) in µ mol, measured during congnitive testing, before and after HIIE with participants in sitting position. In order to establish a baseline (Fox et. al 2013) 10 s of fNIRS data was also be collected immediately prior to starting of cognitive tests and also before HIIE session. For baseline data acquisition participants were asked to sit quietly and relax.

The fNIRS data was collected using a 24 channel BriteArtinisfNIRS system configured into 3×3 optodes patterns on each lateral side of prefrontal cortex. The optodes were placed on head according to topographic probe layout map along with the standard EEG 10/20 coordinate system 24 channel grids were placed to cover following Regions of Interest (ROI) for each hemisphere: the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC) and fronto-polar area (FPA) over prefrontal cortex (figure 1). Participants' heads were individually fitted with a retaining cap (which was selected by measuring the circumference of each participant's head) and contained all of the source and detector fibers (yellow: emitter and blue: detector). This arrangement gave a total of 24 (12 on each side) measurement channels, with an overall emitter-detector separation of ~3 cm (Kalia et al., 2018) (figure 2). A differential path length factor was calculated on the basis of the exact age of the participant. There was a delay of at least 10 minutes after the HIIE cessation before taking the post Hemodynamic data to ensure fading of physiological noises. The Oxy-HB and DeOxy-Hb data was collected separately for congruent and incongruent task.

The area over the scalp was identified as 6 region of interests (ROI) for analysis with an area for the right DLPFC which included channel number 5, 6, 9, 10, 11 and 12, a second one over the right VLPFC which included channel number 2, 3, 7 and 8, a third area over the right FPA which included channel number 1 and 4, a fourth area over the left DLPFC which included channel number 18, 20, 21, 22, 23 and 24, a fifth area over the left VLPFC which included channel number 13, 15, 16 and 17 and finally a sixth area over the left FPA which included channel number 14 and 19 over the prefrontal cortex.

For fNIRS data, the pre-processing was conducted using the open-source software HOMER2 implemented in MATLAB. All recorded signals were first converted to optical density for processing in the HOMER2 software. Channels with low amplitude were excluded from group processing. Signals were then processed by the principal component

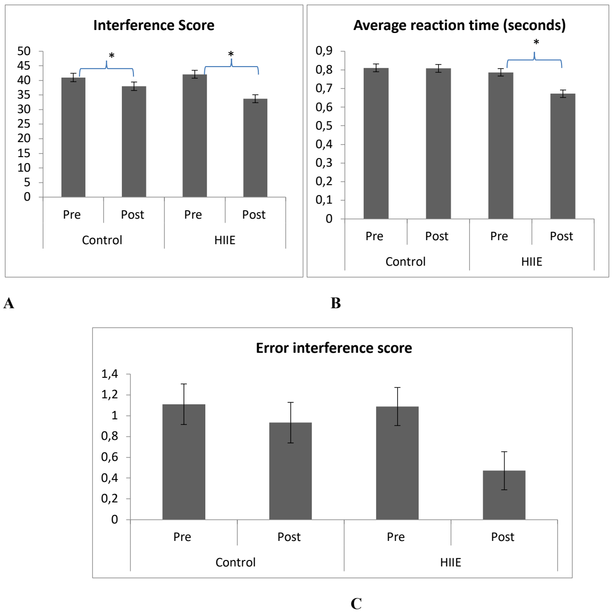

Fig. 3. Graphical Representation of the results showing changes in the cognitive score of Colour word Stroop test in pre and post session of control and HIIE group. The bars shows mean values of (A). Interference score, (B). Average reaction time score and (C). Error interference score. The error bars show standard error values

analysis method to remove systematic artifacts according to methods described in previous literature (Tak & Ye, 2014). The motion artifact threshold of more than 15 standard deviations from the mean were identified and replaced with spline interpolation based on preceding and subsequent segment of the signals. Wavelet filtering was used to remove motion induced sharp spikes as suggested by previous literature (Jahani et al., 2018) such as wavelet filtering, are excellent in removing motion-induced sharp spikes, the baseline shifts in the signal remain after this type of filtering. Methods, such as spline interpolation, on the other hand, can properly correct baseline shifts; however, they leave residual high-frequency spikes. We propose a hybrid method that takes advantage of different correction algorithms. This method first identifies the baseline shifts and corrects them using a spline interpolation method or targeted principal component analysis. The remaining spikes, on the other hand, are corrected by smoothing methods: Savitzky-Golay (SG. After this processing, the signals were then band pass filtered with frequencies between 0.02 to 0.5 Hz to remove baseline drift and physiological noises. Finally, these filtered signals were converted to oxy and deoxy haemoglobin concentration (μ Mol.) data using modified Beer-Lambert law (Cope & Delpy, 1988). Block averaging method was used to infer changes in hemodynamic response across the participants.

Statistical analysis

Cognitive data of colour word Stroop test was analysed for normality distribution using Shapiro-Wilk test. The data was normally distributed hence two way ANOVA was done to find interaction of stroop interference score; average reaction time and error interference score for group (control/ HIIE) and sessions (Pre/post).

Thepre-processed data obtained from fNIRS was subjected to Shapiro-Wilk test in order to determine the normality distribution of the data. The data was normally distributed and oxy and deoxy haemoglobin concentration data associated with cognitive task was subjected to three way ANOVA test with group (control/HIIE), sessions (pre/post) and condition (congruent/Incongruent) as factors to examine the interaction between.

Results

Cognitive results

Two way ANOVA (figure 3) results showed a significant difference between pre and post scores of Stroop interference scores, shown by a significant interaction of group*session ($F_{1,\,39} = 7.35$, $p = 0.008$, partial $\eta^2 = 0.76$) for interference score between the subjects. Average reaction time scores showed a significant difference between the scores shown by a significant effect of group ($F_{1,\,39} = 20.85$, $p < 0.001$, partial $\eta^2 = 0.588$), and a significant interaction of group*session

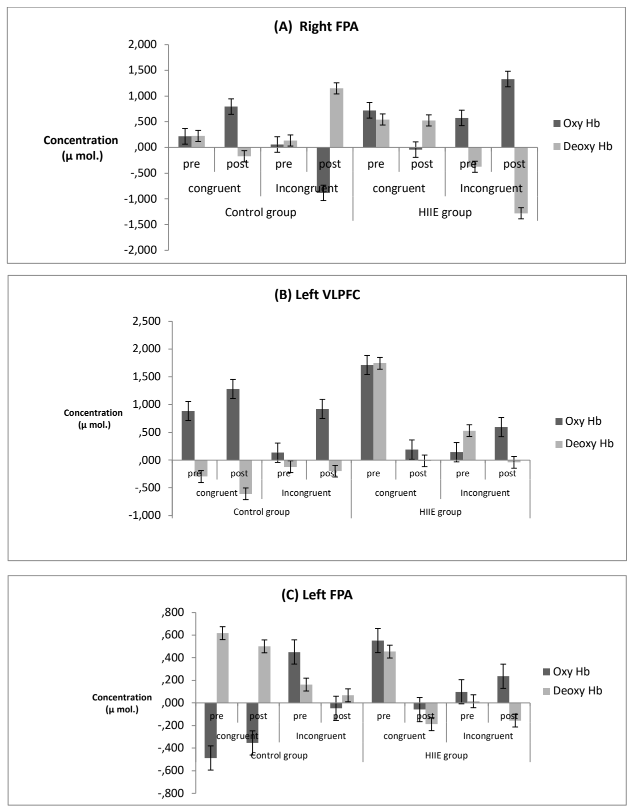

Fig. 4. Graphical Representation of the results showing the comparison of oxy and deoxy haemoglobin concentration during congruent and incongruent conditions of pre and post sessions of control and HIIE group. The hemodynamic variables (oxy and deoxy haemoglobin concentration) were compared using three way ANOVA. We found a significant interaction of group (control/ HIIE), session (pre/ post) and condition (congruent/ incongruent) in the three areas of pre frontal cortex which are shown in the above figure. (A) showing changes in the hemodynamic variables of right FPA. (B) showing changes in the hemodynamic variables of left VLPFC. (C) showing changes in the hemodynamic variables of left FPA

($F_{1, 39}$ = 10.791, p = 0.001, partial η^2 = 0.107). Error interference scores showed a significant main effect of session ($F_{1, 39}$ = 4.558, p = 0.035, partial η^2 = 0.048) and showed no interaction of group with session.

Changes in cortical activation between congruent and incongruent task

Three way ANOVA (figure 4) indicated a significant interaction of group (control/HIIE), session (pre/post) and condition (congruent/ incongruent) of only three (out of 6) areas of PFC; right FPA($F_{oxy\,(1,\,152)}$ = 31.45, p = 0.0001, $F_{deoxy\,(1,\,152)}$ = 39.39, p = 0.0001), left VLPFC ($F_{oxy\,(1,\,152)}$ = 101.11, p = 0.0001, $F_{deoxy\,(1,\,152)}$ = 131.01, p = 0.0001) and left FPA ($F_{oxy\,(1,\,152)}$ = 56.34, p = 0.0001, $F_{deoxy\,(1,\,152)}$ = 58.14, p = 0.0001). The results demonstrated a greater activation (increased oxy haemoglobin and decreased deoxy haemoglobin concentration) in incongruent condition in response to HIIE. There was a decreased activation (decreased oxy haemoglobin and increased deoxy haemoglobin concentration) during congruent condition as compared to control group.

Discussion

The current study was aimed to explain the role of HIIE in enhancing brain activation during a more complex Stroop interference task. The focus of the study was to find the differences in brain activation during congruent and incongruent task during CWST as a result of HIIE. The result of the study indicate that there is a significant increase in brain activation, shown by increase in Oxy-Hb and decrease in DeOxy-Hb in right frontopolar area (FPA), left ventrolateral prefrontal cortex (VLPFC) and left frontopolar area (FPA).

The HIIE group showed improved executive function performance with decreased interference and decreased reaction time after the HIIE intervention reflecting a greater speed of processing with improved accuracy in response. These results are consistent with the findings of previous studies (Yanagisawa et al., 2010; Kujach et al., 2018; Hyodo et al., 2012; Tsukamoto et al., 2016) which explained a greater improvement in Stroop incongruent performance as a result of exercise intervention in young adults. These behavioural results coincided with increased activation of PFC areas in our study.

The increased activation is demonstrated in the current study by increased Oxy-Hb and decreased DeOxy-Hb in the region of interest. The information regarding both Oxy-HB and DeOxy-Hb is imperative as Oxy-Hb gives the information about delivery of oxygen in the particular area and DeOxy-Hb provides information about oxygen utilization by the neural tissue during activity (Lambrick et al., 2016; Herold et al., 2018). Moreover changes in DeOxy-Hb is considered a more sensitive indicator of overall neural process since unlike Oxy-Hb it is less affected by extra-cerebral processes (Seidel et al., 2019) like heart beat and increase in scalp blood flow. Thus both Oxy-Hb and DeOxy-Hb variables of the hemodynamics were included for the evaluation of cortical activation.

The fundamental mechanism of the acute exercise effect has been explained by a sudden increase of neural substances such as lactate, cortisol, neurotrophins, neurotransmitters, and neuromodulators (Basso & Suzuki, 2017), as well as increases in regional cerebral blood flow (CBF) following acute exercise (Bae & Maasaki, 2019; Querido & Sheel, 2007; Pontifex et al., 2009b). Exercise interventions with various modulations such as low intensity exercise (Byun et al., 2014), moderate intensity exercises (Hyodo et al., 2012), resistance exercises (Herold et al., 2019)physical capabilities (e.g., muscular strength and transferable high intensity intermittent exercise (Kujach et al., 2018) have been used previously to examine the effect of acute exercise interventions on the hemodynamic functions of the cortical areas related to CWST performance. All these studies have found an increase in the activation in areas of PFC associated with an improved CWST performance, specific to the type of exercise intervention used.

Our study was the first to examine the difference in the activation during congruent and incongruent CWST task in response to HIIE and we found a significant increase in the activation during the incongruent task indicating the facilitation effect of HIIE on executive function. Our results showed a decreased activation during the easier task whereas increased the activation during a complex task in response to HIIE.Further work is required to understand the changes in brain activation while performing simple to complex cognitive tasks in the population of different age groups and various sports disciplines.

Conclusions

We conclude that introduction of HIIE intervention causes greater activation of prefrontal cortex areas involved in maintenance of executive functions. We found evidences of increased cortical hemodynamics in the area of right FPA, left VLPFC and left FPA during incongruent CWST in response to HIIE session. Thus it is suggested that the HIIE protocol plays a role in increasing activity of prefrontal cortex while performing more complex executive functional tasks and hence recommended to improve the cognitive performance.

Acknowledgement

The authors would like to thank the participants who agreed to be a part of the study. The study was supported by grant received from Ministry of Youth Affairs and Sports, Government of India. Equipments, tests and Research Fellows were all funded by this grant. We are grateful to Mr. Abhishek Sathe for his help with data analytics.

Conflict of Interest

The authors declare no conflict of interest.

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ВПЛИВ ПЕРЕРИВЧАСТИХ ВПРАВ ВИСОКОЇ ІНТЕНСИВНОСТІ НА ПОЛІПШЕННЯ АКТИВАЦІЇ МОЗКУ У ВИКОНАННІ СКЛАДНИХ ФУНКЦІОНАЛЬНИХ ЗАВДАНЬ

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 7 с., 1 рис., 4 табл., 33 джерел.

Кілька досліджень нейровізуалізації вивчали вплив різних типів та комбінації вправ на активацію мозку, пов’язані з когнітивним тестуванням, але жодне з цих досліджень не вивчало роль високоінтенсивних інтермітуючих вправ (HIIE) у зміні активації кори від простих до складних когнітивних завдань.

Метою цього дослідження було з'ясувати, чи відіграє роль HIIE в модуляції виконавчих функцій, пов'язаних з інгібуючим контролем, що виражається змінами в активації префронтальної кори (PFC).

Матеріали і методи. У дослідженні взяли участь 40 здорових дорослих людей віком від 18 до 30 років. Вони були випадковим чином розділені на групу HIIE (n = 20) та контрольну (n = 20) групу. Група HIIE виконувала 4 * 4 хв вправ високої інтенсивності на велоергометрі з 3 хвилинами активного відновлення, тоді як контрольна група не виконувала вправ. Префронтальну гемодинаміку (окси- та дезоксигемоглобін) оцінювали за допомогою функціональної ближньої інфрачервоної спектроскопії (fNIRS) під час кольорового тесту Stroop (CWST) на двох сеансах: перед сеансом та після сеансу (через 1 тиждень після сеансу).

Результати. Результати вказують на значну різницю в показниках CWST, яка співпала зі значною різницею в гемодинаміці PFC між конгруентними та складними невідповідними завданнями у групі HIIE. Під час інконгруентного завдання у відповідь на гострий HIIE спостерігалася більша активація правої лобово-полярної області, лівої вентролатеральної префронтальної кори та лівої лобово-полярної області.

Висновки. HIIE відіграє роль у зміні активації мозку під час більш складного завдання, пов’язаного з втручаннями.

Ключові слова: HIIE, fNIRS, префронтальна кора, кольоровий тест Stroop, пізнання.

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Cite this article as: Shenoy, S., Khandekar, P., & Sathe, A. (2021). High Intensity Intermittent Exercise Plays a Role in Improving Brain Activation During Complex Executive Functional Tasks. *Teoriâ ta Metodika Fìzičnogo Vihovannâ, 21*(1), 36-42. https://doi.org/10.17309/tmfv.2021.1.05

Received: 25.12.2020. Accepted: 20.03.2021. Published: 25.03.2021