Mini-Review of Studies Testing the Cardiorespiratory Hypothesis with Near-Infrared Spectroscopy (NIRS): Overview and Perspectives

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**Abstract**

The cardiorespiratory hypothesis (CH) is one of the hypotheses used by researchers to explain the relationship between cardiorespiratory fitness and cognitive performance during executive functions. Despite the indubitable beneficial effect of training on brain blood flow and function that may explain the link between physical fitness and cognition and the recognition of the near-infrared spectroscopy (NIRS) as a reliable tool for measuring brain oxygenation, few studies investigated the CH with NIRS. It is still not well understood whether an increase in brain flow by training is translated into an increase in cerebral
oxygenation. Thus, the objective of this mini-review was to summarize main results of studies that investigated the CH using the NIRS and to propose future research directions.

**Keywords**

Near-Infrared Spectroscopy, Cardiorespiratory Fitness, Executive Functions, Hemodynamic Activity, Brain

**Introduction**

A growing body of evidence shows that physical exercise has a beneficial effect on cognition [1-5]. Nevertheless, the effects of physical exercise on cognition are heterogeneous, as they are more pronounced on executive functions [6,7]. Several hypotheses, namely the cardiorespiratory hypothesis (CH), neurogenesis increase hypothesis, synaptic plasticity increase hypothesis, catecholamines increase hypothesis, and cognitive enrichment hypothesis are used to explain these cognitive effects of physical exercise [8,9]. Beyond these hypotheses, many researchers are using the CH to explain their findings regarding the effect of exercise on cognition. The CH suggests that the improvement in cognitive performance observed in subjects following an aerobic program could be due to an increase in cerebral metabolic activity [10]. The increase in metabolic activity induces increased oxygen and glucose transportation to the brain. In other words, the CH stipulates those subjects who have a high cardiorespiratory fitness oxygenate the brain areas involved in cognitive tasks more efficiently, which allows them to better perform tasks (e.g., executive tasks). Thus, to validate this hypothesis, it is necessary to measure cerebral oxygenation. One of the tools able to measure this oxygenation in a non-invasive way is the near-infrared spectroscopy (NIRS). The biological mechanisms (angiogenesis, vascular plasticity, and better vascular health) underlying the CH were presented in a recent review (see Agbangla et al., [11]). Some studies have tested this hypothesis by examining the relationship between cognitive performance, changes in brain blood flow as measured by functional magnetic resonance imaging (fMRI) and
cardiorespiratory fitness (VO$_2$max) following an aerobic program [12,13]. Their results showed that participants not only increase their cerebral blood flow in different arteries (i.e., middle frontal gyrus, superior parietal cortex, and dentate gyrus), but also their VO$_2$max. In addition, it was demonstrated that the enhancement in cerebral blood flow was related to a significant or substantial improvement of cognitive performance (i.e., selective attention task, verbal learning, and memory) and cardiorespiratory fitness. Thus, studies using fMRI provide undeniable evidence of the CH but do not allow us to know whether the increase in brain flow translates into an increase in oxygen, which is essential for brain metabolism [14].

To answer this question, some authors used NIRS as a tool to examine cerebral hemodynamic activity in humans [15-18], which reflects the neurovascular coupling mechanism that induces both an increase in local cerebral blood volume and blood flow [19]. Indeed, the NIRS allows the investigation of hemodynamic changes associated with brain activity evaluated by changes in oxyhemoglobin (O$_2$Hb), deoxyhemoglobin (HHb), and total hemoglobin (HbT) concentration [20]. Hemodynamic parameters provided by NIRS (i.e., O$_2$Hb, HHb, HbT) while can be considered as more specific for cerebral oxygenation compared to the fMRI-BOLD signal, the raw NIRS-signals cannot be taken as measures for hemodynamic parameters such as flow, volume, oxygen extraction function. Hence it is essential to rely on mathematical models to determine these parameters like the ones reported by Kocsis et al. [21] and Mukli et al. [22]. Several reviews have outlined the principles, strengths, limitations, and good practices of the NIRS [23-25]. Despite the physiological and methodological validation of NIRS, a meticulous search of various databases shows that few studies have investigated the CH using the NIRS even though it has been recognized as a reliable tool for measuring brain oxygenation. In this context, the objective of this mini-review was, to summarize the key results of the studies that investigated the CH using the NIRS.
Literature Search

To perform this mini-review, the Google Scholar, Pubmed, PsycINFO, and Web of Science databases were searched (last search on March 2021) using the terms “cardiovascular fitness” OR “cardiorespiratory fitness” OR “aerobic fitness” AND “fNIRS” OR “NIRS” AND “executive functions.” The search strategy retrieved 386 articles on Google Scholar, 68 articles on Pubmed, 1967 articles on PsycINFO, and 18 articles on Web of Science. Following this search, duplicate references were removed. After this identification step, we proceeded to the screening step, which involved sifting through the titles and abstracts to check their relevance. Studies were selected if they were conducted on populations of any age and had cardiorespiratory fitness and/or executive functions and/or hemodynamic activity as parameters of interest. Twenty-five articles were selected, and their full texts were reviewed by authors for inclusion in the mini-systematic review. Only studies that tested the CH were included. Following the expertise of the selected articles, nine articles were considered in the writing of the mini-review (Figure 1).
Participants and Variables of Interest

Participants

Except for the subject in the case study by Cabral et al. [26] who had been addicted to alcohol and cigarettes for 33 years, subjects of the different studies were either young adults between 17 and 25 years or older adults over 60 years. In terms of cardiorespiratory fitness, studies compared subjects who were highly fit or active with their counterparts who had a low fit or were inactive.

Executive Functions

Executive functions (EFs) are cognitive processes that regulate thought and action in unusual situations [27]. More precisely, there are high-level cognitive processes that, through their influence on lower-level processes, enable individuals to regulate their thoughts and actions during goal-directed behavior [28].
They can be subdivided into core EFs, namely inhibition, updating of working memory, shifting, and higher-order EFs such as reasoning, problem-solving, planning, and dual-task management [29,30]. To measure executive functions, studies that investigated the CH used various executive tasks such as the Stroop task [26,31-34], random number generation [35], n-back [36], the dual-task [37], and the Trail Making Test (TMT) [38]. These executive tasks allowed the researchers to measure, respectively, the interference control, behavioral inhibition, updating of working memory, shifting, and dual-task management. In brief, the studies cited above used more tasks involving core EFs than tasks requiring higher-order EFs. Finally, only two studies considered the complexity of the executive task [35,36]. Indeed, the study by Albinet et al. [35] used the random number generation with two paces that consisted, firstly, of giving a digit every second and a half and, secondly, a digit every second. In a study by Agbangla and colleagues, three levels of complexity of the n-back were proposed to the subjects (i.e., 1, 2, 3-back) [36].

Cardiorespiratory Fitness

Cardiorespiratory fitness is the ability to perform a dynamic activity of moderate to high intensity involving large-muscle groups over a prolonged period [39]. It is highly dependent on the integrity of the cardiovascular, respiratory, and musculoskeletal systems [40]. Cardiorespiratory fitness is measured by several methods. The reference method is the maximal effort test in which the participant is asked to perform a physical effort with an incremental load [40]. The maximal oxygen consumption is then determined by gas analysis. In default of this gold standard test, sub-maximal tests and questionnaires can be used to estimate cardiorespiratory fitness. Most studies that have investigated the CH have used the maximal effort test [26,31,32,34,35,37,38]. However, other studies have used a sub-maximal test [33] or a sub-maximal test and questionnaire [36]. These tests allowed the researchers to measure various cardiorespiratory parameters such as $\text{VO}_{2}\text{max}$,
peak oxygen consumption (VO$_2$peak), peak power output, and relative power output to muscle mass.

**Brain Hemodynamic Activity**

All studies measure hemodynamic activity in the prefrontal cortex (PFC) regions (i.e., left and right dorsolateral, left and right ventrolateral, frontopolar, and anterior prefrontal cortices) using continuous wave NIRS. However, unlike frequency and time domain NIRS, continuous wave NIRS does not allow for absolute measurements of hemodynamic activity [24]. According to these authors, continuous wave NIRS does not fully determine the scattering and absorption coefficients of near-infrared light. To determine hemodynamic activity, the authors mainly used the subtractive method, which involves subtracting the concentration of the hemodynamic index (HHb and/or O$_2$Hb, and/or HbT) during the baseline or compatible condition from the concentration of the hemodynamic index during the experimental or incompatible condition [31-34,36-38]. Apart from this subtractive method, another method, consisting of applying a linear regression on the entire signal window to obtain the slope coefficient of the regression line (slope method), was used in a study by Albinet et al. [35].

**Links between Executive Functions, Cardiorespiratory Fitness, and Cerebral Hemodynamic Activity**

Cross-sectional studies showed that young and old adults with high (46–56 mL$^{-1}$kg$^{-1}$min$^{-1}$ for young and 26–30 mL$^{-1}$kg$^{-1}$min$^{-1}$ for old adults) cardiorespiratory fitness have better executive performance (i.e., updating of working memory, inhibition, shifting, and dual-task ability) compared to their counterparts with low (36–38 mL$^{-1}$kg$^{-1}$ min$^{-1}$ for young and 17–21 mL$^{-1}$kg$^{-1}$ min$^{-1}$ for old adults) cardiorespiratory fitness [31,33-38]. These results have also been confirmed by intervention and case studies, showing that participants who followed an aerobic program or an intermittent high-intensity session improved their
executive performance [26,32] and their cardiorespiratory fitness [26]. Another important finding is that some of the studies included in the review highlighted a link between executive performance and cardiorespiratory fitness or cerebral hemodynamic. Indeed, some of the cross-sectional studies reported that only participants (young and older adults) with high cardiorespiratory fitness significantly increase their cerebral hemodynamic activity during the executive task [31,34]. In addition, other cross-sectional studies reported that participants with high cardiorespiratory fitness who increased their cerebral hemodynamic activity did the best executive performances [36,38]. These results suggest a link between cardiorespiratory fitness, cerebral hemodynamic activity and executive performance. Finally, other authors have observed a correlation between cardiorespiratory fitness and executive performance in older adults [35] and young adults [33]. However, this correlation was mediated by hemodynamic activity only in older adults. These results concur with the results of studies that have tested the CH using fMRI [12,13]. These results suggest that the effect of cardiorespiratory fitness on executive functions is mediated by an increase in hemodynamic activity depending on the age of the participant. The mediating effect of hemodynamic activity on the link between physical exercise and executive performance could be explained by the fact that physical exercise increases cerebral blood flow [41]. Indeed, the increase in cerebral blood flow ensures the supply of the necessary energetic substrates and oxygen to neuronal networks involved in the investigated executive function. However, the increase in cerebral blood flow would be underpinned by several biological mechanisms. On the one hand, we have angiogenesis, enhanced vascular plasticity, and improved vascular health [11]. Regarding angiogenesis, regular exercise induces the release of neurotrophic factors, namely vascular endothelial growth factor and insulin growth factor 1, which are required for angiogenesis [8,42]. As for vascular plasticity, it is underpinned by a better bioavailability of nitric oxide which enhances vasodilatation [43]. Finally, the improvement in vascular health is explained by the beneficial effects of exercise on arterial stiffness and vascular dysfunction [44]. On the other hand, the increase in blood flow
could be explained by the modulation of functional brain networks during the performance of the cognitive task [45,46]. This modulation would result in a redistribution of local support systems (i.e., blood flow, oxygenation, and metabolism). In this context, we can hypothesized that participants with good cardiorespiratory fitness would be the ones with better modulation of functional brain networks most likely due to enhanced neuro-vascular coupling.

**Futures Perspectives of Research**

The summary of studies presented in this mini-review showed that the subjects solicited in the exploration of the CH were generally healthy young (17–25 years) or older (over 60 years). Consequently, consideration of other age groups between 25 and 59 years but also pathological populations is essential for extending the CH to other populations. For example, it would be interesting to explore this hypothesis in patients with cerebrovascular pathologies. A recent meta-analysis showed that a program combining aerobic and resistance exercise (i.e., performed at moderate intensity, three times a week for 20 weeks) had a greater effect on cardiorespiratory fitness, muscle strength, and walking ability in stroke patients [47] than aerobic or resistance training alone. However, this effect of exercise on cardiorespiratory fitness is not related to executive functions, which are dysfunctional in 75% of stroke patients [48]. Hence, future studies may explore the links between executive functions, cardiorespiratory fitness and cerebral oxygenation in stroke patients and even in other populations suffering from other chronic pathologies using a randomized controlled protocol. From this perspective, several interventions can be suggested to participants according to their functional abilities. For example, fit participants may participate in a training program combining endurance and resistance [47] or in a training program combining physical and cognitive exercises [49]. Moreover, the immersive virtual reality could be proposed to participants with low functional capacity preventing them from doing traditional physical exercise [50]. At last, these future studies in patients with stroke or other chronic conditions
should also consider the motivational profile of the patients to adjust the physical activity program. Indeed, patients with high self-efficacy, expectancy and self-determination are those who are more likely to be involved in a physical activity program and to maintain physical activity [51]. However, when dealing with unmotivated patients, the use of a motivational intervention would be appropriate to induce engagement in the physical activity program [52].

Various executive tasks have been used to measure executive performance. Among these tasks, there is the Stroop task, the random number generation test, the n-back test, the Trail Making Test, and the dual-task test. However, the limitation of these tasks is their inability to directly measure an executive function without involving other cognitive processes [29]. Indeed, confirmatory analyses performed on the main components of executive functioning (i.e., inhibition, updating of working memory, and shifting) showed that inhibition had a common factor with the rest of the executive functions [53]. Thus, inhibition would be found in several executive tasks that would require the suppression of responses, distractors, and memory representations [54]. To address this problem of impurity in neuropsychological tasks that measure executive functions, some authors have used multiple tasks to assess an executive function [55,56]. This multi-task method for assessing executive function appears to be adequate in our opinion and should be used in future studies exploring the cardiorespiratory fitness hypothesis to obtain a composite score of executive functioning.

Finally, despite the diversity of the executive functions assessed in the different studies considered in this mini-review, all studies measured hemodynamic activity only in the PFC. Although it is undoubtedly recognized that the PFC is invariably involved in executive functioning [57]. However, other brain areas are activated when performing an executive task. For example, the random number generation task is associated with significant activation of the left dorsolateral PFC, anterior cingulate cortex, superior parietal cortex, inferior frontal cortex, and right and left cerebellar hemispheres [58]. In the Stroop task, the areas
activated include the dorsolateral PFC, the supplementary motor area, the left premotor cortex, the superior temporal gyrus, the left putamen, and the anterior cingulate cortex [59,60]. Regarding N-back, brain imaging studies have shown activation of the right dorsolateral PFC, the anterior cingulate cortex, the posterior parietal cortex, and the inferior frontal gyrus [57]. As for the Trail Making Test, it has been shown that the left dorsolateral PFC, supplementary motor area, cingulate sulcus, intraparietal sulcus are the areas that are activated [61]. Finally, the dual-task comprised a cognitive-motor task soliciting not only the PFC but also the sensorimotor area, the supplementary motor area, and the occipital cortex [62]. When we identified the brain areas that were activated during the executive tasks used in the CH, we found that there were three brain areas that were common to the tasks (i.e., PFC, parietal cortex, cingulate cortex). Therefore, it is essential to extend the measurement of the hemodynamic activity to the parietal and cingulate cortices to explore the connectivity of these areas with the PFC in the context of the CH. It would be judicious to explore the interactions between the various physiological systems (i.e., central nervous, respiratory, cardiovascular systems) involved in the CH and executive performances using the integrative approach [63,64] in future studies. It will be a question, for example, of exploring both the nature and the strength of the interactions that take place between these different physiological systems and the effects of these interactions on executive performances.

**Conclusion**

This mini-review highlights that the majority of studies exploring the cardiorespiratory fitness hypothesis enrolled healthy young and old participants. These studies are CH mostly cross-sectional studies. Therefore, it is suggested that randomized controlled studies conducted in other age groups (e.g., 8–16 or 25–59 years old) or in participant with different pathological concerns (e.g., stroke; cognitive disorders), using a multi-task method may offer a valuable way to measure executive functions and answer to the CH.
References

1. Gomes-Osman J, Cabral DF, Morris TP, McInerney K, Cahalin LP, et al. Exercise for cognitive brain health in aging: a systematic review for an evaluation of dose. Neurology. Clin. Pract. 2018; 8: 257–265.
2. Loprinzi PD, Edwards MK, Crush E, Ikuta T, Del Arco A. Dose-Response Association Between Physical Activity and Cognitive Function in a National Sample of Older Adults. Am. J. Health Promot. 2018; 32: 554–560.
3. Herold F, Müller P, Gronwald T, Müller NG. Dose-Response Matters! - A Perspective on the Exercise Prescription in Exercise-Cognition Research. Front. Psychol. 2019; 10: 2338.
4. Netz Y. Is There a Preferred Mode of Exercise for Cognition Enhancement in Older Age? Front. Med. 2019; 6: 57.
5. Sanders L, Hortobágyi T, La Bastide-van GS, van der Zee EA, van Heuvelen M. Dose-response relationship between exercise and cognitive function in older adults with and without cognitive impairment: a systematic review and meta-analysis. PLoS One. 2019; 14: e0210036.
6. Andrés P, Van der Linden M. Age-related differences in supervisory attentional system functions. J. Gerontol. B Psychol. Sci. Soc. Sci. 2000; 55: 373–380.
7. Fjell AM, McEvoy L, Holland D, Dale AM, Walhovd KB. Alzheimer’s Disease et al. What is normal in normal aging? Effects of aging, amyloid and Alzheimer’s disease on the cerebral cortex and the hippocampus. Prog. Neurobiol. 2014; 117: 20–40.
8. Audiffren M, André N, Albinet CT. Positive effects of chronic physical exercise on cognitive functions in aging people: assessment and prospects. Revue de Neuropsychol. 2011; 3: 207–225.
9. Maillot P, Perrot A. La théorie de l’enrichissement cognitif à travers la stimulation physique: activité physique traditionnelle versus exergames. Neurol. Psychiatrie Gériat. 2012; 12: 217–229.
10. Dustman RE, Ruhling RO, Russell EM, Shearer DE, Bonekat HW, et al. Aerobic exercise training and improved neuropsychological function of older individuals. Neurobiol. Aging. 1984; 5: 35–42.

11. Agbangla NF, Fraser SA, Albinet CT. An Overview of the Cardiorespiratory Hypothesis and Its Potential Contribution to the Care of Neurodegenerative Disease in Africa. Medicina. 2019b; 55: 601.

12. Colcombe SJ, Kramer AF, Erickson KI, Scalf P, McAuley E, et al. Cardiovascular fitness, cortical plasticity, and aging. Proc. Natl. Acad. Sci. U. S. A. 2004; 101: 3316–3321.

13. Pereira AC, Huddleston DE, Brickman AM, Sosunov AA, Hen R, et al. An in vivo correlate of exercise-induced neurogenesis in the adult dentate gyrus. Proc. Natl. Acad. Sci. U. S. A. 2007; 104: 5638–5643.

14. Attwell D, Buchan AM, Charpak S, Lauritzen M, Macvicar BA, et al. Glial and neuronal control of brain blood flow. Nature. 2010; 468: 232–243.

15. Chance B, Zhuang Z, UnAh C, Alter C, Lipton L. Cognition-activated low-frequency modulation of light absorption in human brain. Proc. Natl. Acad. Sci. U. S. A. 1993; 90: 3770–3774.

16. Hoshi Y, Tamura M. Detection of dynamic changes in cerebral oxygenation coupled to neuronal function during mental work in man. Neurosci. Lett. 1993; 150: 5–8.

17. Kato T, Kamei A, Takashima S, Ozaki T. Human visual cortical function during photic stimulation monitoring by means of near-infrared spectroscopy. J. Cereb. Blood Flow Metab. 1993; 13: 516–520.

18. Villringer A, Planck J, Hock C, Schleinkofer L, Dirnagl U. Near infrared spectroscopy [NIRS]: a new tool to study hemodynamic changes during activation of brain function in human adults. Neurosci. Lett. 1993; 154: 101–104.

19. Villringer A, Chance B. Non-invasive optical spectroscopy and imaging of human brain function. Trends Neurosci. 1997; 20: 435–442.

20. Agbangla NF, Audiffren M, Albinet CT. Use of near-infrared spectroscopy in the investigation of brain activation
during cognitive aging: a systematic review of an emerging area of research. Ageing Res. Rev. 2017; 38: 52–66.

21. Kocsis L, Herman P, Eke A. Mathematical model for the estimation of hemodynamic and oxygenation variables by tissue spectroscopy. J. Theor. Biol. 2006; 241: 262–275.

22. Mukli P, Nagy Z, Racz FS, Herman P, Eke A. Impact of Healthy Aging on Multifractal Hemodynamic Fluctuations in the Human Prefrontal Cortex. Front. Physiol. 2018; 9: 1072.

23. Ekkekakis P. Illuminating the black box: investigating prefrontal cortical hemodynamics during exercise with near-infrared spectroscopy. J. Sport Exerc. Psychol. 2009; 31: 505–553.

24. Scholkmann F, Kleiser S, Metz AJ, Zimmermann R, Mata Pavia J, et al. A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. NeuroImage. 2014; 85: 6–27.

25. Yücel MA, Lühmann AV, Scholkmann F, Gervain J, Dan I, et al. Best practices for fNIRS publications. Neurophotonics. 2021; 8: 012101.

26. Cabral DA, da Costa KG, Okano AH, Elsangedy HM, Rachetti VP, et al. Improving cerebral oxygenation, cognition and autonomic nervous system control of a chronic alcohol abuser through a three-month running program. Addict. Behav. Rep. 2017; 6: 83–89.

27. Friedman NP, Miyake A, Corley RP, Young SE, Defries JC, et al. Not all executive functions are related to intelligence. Psychol. Sci. 2006; 17: 172–179.

28. Friedman NP, Miyake A. Unity and diversity of executive functions: individual differences as a window on cognitive structure. Cortex. 2017; 86: 186–204.

29. Miyake A, Friedman NP, Emerson MJ, Witzki AH, Howerton A, et al. The unity and diversity of executive functions and their contributions to complex Frontal Lobe tasks: a latent variable analysis. Cogn. Psychol. 2000; 41: 49–100.

30. Diamond A. Executive functions. Annu. Rev. Psychol. 2013; 64: 135–168.
31. Dupuy O, Gauthier CJ, Fraser SA, Desjardins-Grèpeau L, Desjardins M, et al. Higher levels of cardiovascular fitness are associated with better executive function and prefrontal oxygenation in younger and older women. Front. Hum. Neurosci. 2015; 9: 66.

32. Kujach S, Byun K, Hyodo K, Suwabe K, Fukuie T, et al. A transferable high-intensity intermittent exercise improves executive performance in association with dorsolateral prefrontal activation in young adults. Neuroimage. 2018; 169: 117–125.

33. Ludyga S, Mücke M, Colledge F, Pühse U, Gerber M. A Combined EEG-fNIRS Study Investigating Mechanisms Underlying the Association between Aerobic Fitness and Inhibitory Control in Young Adults. Neuroscience. 2019; 419: 23–33.

34. Goenarjo R, Bosquet L, Berryman N, Metier V, Perrochon A, et al. Cerebral Oxygenation Reserve: the Relationship Between Physical Activity Level and the Cognitive Load During a Stroop Task in Healthy Young Males. Int. J. Environ. Res. Public Health. 2020a; 17: 1406.

35. Albinet CT, Mandrick K, Bernard PL, Perrey S, Blain H. Improved cerebral oxygenation response and executive performance as a function of cardiorespiratory fitness in older women: a fNIRS study. Front. Aging Neurosci. 2014; 6: 272.

36. Agbangla NF, Audiffren M, Pylouster J, Albinet CT. Working Memory, Cognitive Load and Cardiorespiratory Fitness: testing the CRUNCH Model with Near-Infrared Spectroscopy. Brain Sci. 2019a; 9: 38.

37. Goenarjo R, Dupuy O, Fraser S, Perrochon A, Berryman N, et al. Cardiorespiratory fitness, blood pressure, and cerebral oxygenation during a dual-task in healthy young males. Behav. Brain Res. 2020b; 380: 112422.

38. Mekari S, Dupuy O, Martins R, Evans K, Kimmerly DS, et al. The effects of cardiorespiratory fitness on executive function and prefrontal oxygenation in older adults. Geroscience. 2019; 41: 681–690.
39. American College of Sports Medicine [ACSM]. ACSM’s Guidelines for Exercise Testing and Prescription, 7th edn. Philadelphia: Lippincott Williams & Wilkins. 2006.
40. Hayes SM, Hayes JP, Cadden M, Verfaellie M. A review of cardiorespiratory fitness-related neuroplasticity in the aging brain. Front. Aging Neurosci. 2013; 5: 31.
41. Zimmerman B, Sutton BP, Low KA, Fletcher MA, Tan CH, et al. Cardiorespiratory fitness mediates the effects of aging on cerebral blood flow. Front. Aging Neurosci. 2014; 6: 59.
42. Lopez-Lopez C, LeRoith D, Torres-Aleman I. Insulin-like growth factor I is required for vessel remodeling in the adult brain. Proc. Natl. Acad. Sci. U. S. A. 2004; 101: 9833–9838.
43. Tanaka H, Dinenno FA, Monahan KD, Clevenger CM, DeSouza CA, et al. Aging, habitual exercise, and dynamic arterial compliance. Circulation. 2000; 102: 1270–1275.
44. Albinet C, Fezzani K, Thon BV. Vieillissement, activité physique et cognition. Mov. Sport Sci. 2008; 63: 9–36.
45. Racz FS, Mukli P, Nagy Z, Eke A. Increased prefrontal cortex connectivity during cognitive challenge assessed by fNIRS imaging. Biomed. Opt. Express. 2017; 8: 3842–3855.
46. Kaposzta Z, Stylianou O, Mukli P, Eke A, Racz FS. Decreased connection density and modularity of functional brain networks during n-back working memory paradigm. Brain Behav. 2021; 11: e01932.
47. Lee J, Stone AJ. Combined Aerobic and Resistance Training for Cardiorespiratory Fitness, Muscle Strength, and Walking Capacity after Stroke: a Systematic Review and Meta-Analysis. J. Stroke Cerebrovasc. Dis. 2020; 29: 104498.
48. Povroznik JM, Ozga JE, Vonder Haar C, Engler-Chiurazzi EB. Executive [dys]function after stroke: special considerations for behavioral pharmacology. Behav. Pharmacol. 2018; 29: 638–653.
49. Ji Z, Feng T, Mei L, Li A, Zhang C. Influence of acute combined physical and cognitive exercise on cognitive function: an NIRS study. PeerJ. 2019; 7: e7418.
50. Burin D, Liu Y, Yamaya N, Kawashima R. Virtual training leads to physical, cognitive and neural benefits in healthy adults. NeuroImage. 2020; 222: 117297.
51. Sweet SN, Tulloch H, Fortier MS, Pipe AL, Reid RD. Patterns of motivation and ongoing exercise activity in cardiac rehabilitation settings: a 24-month exploration from the TEACH Study. Ann. Behav. Med. 2011; 42: 55–63.
52. Schertz A, Herbeck Belnap B, Chavanon ML, Edelmann F, Wachter R, et al. Motivational interviewing can support physical activity in elderly patients with diastolic heart failure: results from a pilot study. ESC Heart Fail. 2019; 6: 658–666.
53. Miyake A, Friedman NP. The nature and organization of individual differences in executive functions: four general conclusions. Curr. Dir. Psychol. Sci. 2012; 21: 8–14.
54. Zacks RT, Hasher L. Directed ignoring: inhibitory regulation of working memory. In: D Dagenbach, TH Carr, editors. Inhibitory Processes in Attention, Memory, and Language. San Diego: Academic Press. 1994; 241–264.
55. Albinet CT, Boucard G, Bouquet CA, Audiffren M. Processing speed and executive functions in cognitive aging: how to disentangle their mutual relationship? Brain Cogn. 2012; 79: 1–11.
56. Boucard GK, Albinet CT, Bugaiska A, Bouquet CA, Clarys D, et al. Impact of physical activity on executive functions in aging: a selective effect on inhibition among old adults. J. Sport Exerc. Psychol. 2012; 34: 808–827.
57. Collette F, Hogge M, Salmon E, Van der Linden M. Exploration of the neural substrates of executive functioning by functional neuroimaging. Neuroscience. 2006; 139: 209–221.
58. Jahanshahi M, Dirnberger G, Fuller R, Frith CD. The role of the dorsolateral prefrontal cortex in random number generation: a study with positron emission tomography. Neuroimage. 2000; 12: 713–725.
59. Pardo JV, Pardo PJ, Janer KW, Raichle ME. The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. Proc. Natl. Acad. Sci. U S. A. 1990; 87: 256–259.
60. Banich MT. Executive function. The search for an integrated account. Curr. Dir. in Psychol. Sci. 2009; 18: 89–94.
61. Moll J, de Oliveira-Souza R, Moll FT, Bramati IE, Andreiuolo PA. The cerebral correlates of set-shifting: an fMRI study of the trail making test. Arq. Neuropsiquiatr. 2002; 60: 900–905.

62. Van Impe A, Coxon JP, Goble DJ, Wenderoth N, Swinnen SP. Age-related changes in brain activation underlying single- and dual-task performance: visuomotor drawing and mental arithmetic. Neuropsychologia. 2011; 49: 2400–2409.

63. Bashan A, Bartsch RP, Kantelhardt JW, Havlin S, Ivanov P. Network physiology reveals relations between network topology and physiological function. Nat. Commun. 2012; 3: 702.

64. Mukli P, Nagy Z, Racz FS, Portoro I, Hartmann A, et al. Two-Tiered Response of Cardiorespiratory-Cerebrovascular Network to Orthostatic Challenge. Front. Physiol. 2021; 12: 622569.
Table 1: Studies exploring the cardiorespiratory hypothesis using the NIRS.

| References      | Characteristics of study | Type of intervention | Outcomes                                                                                                                                 |
|-----------------|---------------------------|----------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Agbangla et al. [11] | Subjects: 19 younger (19.7±1 years) 37 older adults (68.95±4.74); Design study: cross sectional study; Task: n-back (0,1,2,3-back); Executive function: working memory updating; Instruments: OxyMon MkIII; Artinis Medical Systems BV, Zetten, Netherlands); Cerebral area investigated: prefrontal regions (left and right dorsolateral and left and right ventrolateral); Measure of Aerobic fitness: maximal multistage 20-m shuttle run test (Young) and NASA/JSC physical activity scale (Older adults) - VO$_2$max was estimated. | No intervention | - Chronological age had deleterious effects on both cognitive performance and prefrontal cortex activation under a higher cognitive load. - In older adults, higher levels of cardiorespiratory fitness were related bilateral & prefrontal cortex activation that allowed them to sustain better cognitive performances, especially under the highest cognitive load. |
| Albinet et al. [35] | Subjects: older with high-fit (67.32±4.48) and older with low-fit (68.88±3.87); Design study: cross sectional study; Task: Random Number Generation (RNG); Executive function: inhibition; Instruments: NIRO- | No intervention | - Strong activation of the DLPFC during RNG 1 s and 1.5 s compared to the count condition. - DLPFC activation increased as a function of pace (difficulty) during the RNG task. |
200, Hamamatsu Photonics K.K., Japan; Cerebral area investigated: left and right dorsolateral prefrontal (DLPFC); Measure of Aerobic fitness: maximal graded exercise test - VO\textsubscript{2}max was determined.

- Low fit older women showed significantly less DLPFC activation in the right hemisphere compared to their left hemisphere and compared to the high fit older women during the RNG task.
- Increases in [O\textsubscript{2}Hb] in the right DLPFC were found to mediate the relationship between VO\textsubscript{2}max level and executive performance during the RNG task at 1.5 s.

| Cabral et al. [26] |
|-------------------|
| **Subjects:** male patient (mean age of 46) who has been alcohol and cigarette dependent for about 33 years; **Design study:** case report; **Task:** Stroop test; **Executive function:** interference control; **Instruments:** Imagent, ISS, Champaign, IL, USA; Cerebral area investigated: prefrontal cortex; Measure of Aerobic fitness: incremental protocol test - VO\textsubscript{2}max, ventilatory threshold and respiration compensation point were determined. |
| Training program consisted of three weekly sessions during 90 days. Gradual aerobic training: during first week, the patient was instructed to run 3 and 6 min and the distance was recorded. Running time was increased between 3 and 5 min every week to reach 40 to 50 min. |
| - At the end of training, the following parameters were improved: Time running (6 to 45 min); distance covered (765 to 8700 m); VO\textsubscript{2}max (24.2 to 30.1 mL\textpercm\textpermin); [O\textsubscript{2}Hb](24.2 to 30.1 mL\textpercm\textpermin). - Cognitive performance was improved (correct answers and reaction time) after 90 days. - Prefrontal cortex oxygenation was increased after 90 days - Cognitive performance improvement seemed to be matched with |
| Study                  | Subjects: 22 younger (24.6±3.6 years) and 36 older (62.9±5.4 years) women; Design study: cross sectional study; Task: trail making test, Modified Stroop task with two conditions (naming and execution condition); Executive function: cognitive flexibility and Interference control; Instruments: CW6, TechEn Inc., Milford, MA; Cerebral area investigated: prefrontal regions (left and right dorsolateral and left and right ventrolateral); Measure of Aerobic fitness: maximal continuous graded exercise test - VO$_{2}$max was determined. | No intervention | Increased cerebral oxygenation. |
|-----------------------|---------------------------------------------------------------------------------------------------------------|----------------|--------------------------------------------------------------------------------|
| Dupuy et al. [31]     | No intervention                                                                                               | High fit women obtained better scores on the executive condition of the computerized Stroop task, than lower fit women. Only high fit women demonstrated a significant increase of [O$_2$Hb] in the right inferior frontal gyrus (ventrolateral). | No intervention |
| Goenarjo et al. [37]  | No intervention                                                                                               | Low-fit were significantly less accurate in dual-task condition, as compared to single-task condition, but there was no difference between conditions in high- | No intervention |
| Subjects: active younger (21.8±2.0 years) and inactive younger (23.3±2.5 years); Design study: cross sectional study; Task: Stroop task (naming, inhibition and switching trials); Executive function: inhibition and cognitive flexibility; Instruments: Portalite - Artinis Medical Systems, Elst, Netherlands; Cerebral area investigated: left and right dorsolateral and anterior prefrontal cortex; Measure of Aerobic fitness: maximal continuous graded exercise test - VO\textsubscript{2}peak was determined. | Goenarjo et al. [34] | No intervention | - No significant correlation was found between VO\textsubscript{2}peak and dual-task cognitive performance.  
- No significant correlation was found between VO\textsubscript{2}peak and Δ\textsubscript{O}\textsubscript{2}Hb.  
- Significant correlation was found between VO\textsubscript{2}peak and ΔHHb on left and right prefrontal cortex.  
- Active younger were faster than inactive younger in switching condition but not in naming and inhibition conditions.  
- Active younger had a greater Δ\textsubscript{O}\textsubscript{2}Hb than inactive younger in the switching condition.  
- Between inhibition and switching condition, active younger showed greater Δ\textsubscript{O}\textsubscript{2}Hb in the right and left prefrontal cortex compared with inactive younger.  
- Between naming and inhibition conditions, active younger showed greater ΔHHb in the right prefrontal cortex compared with inactive
| Study | Subjects | Design | Task | Executive function | Instruments | Cerebral area investigated | Measure of Aerobic fitness | Outcome |
|-------|----------|--------|------|---------------------|-------------|----------------------------|---------------------------|---------|
| Kujach et al. [32] | Subjects: 25 sedentary young (21.0±1.6 years); Design study: interventional study; Task: color-word matching Stroop; Executive function: interference control; Instruments: ETG-7000, Hitachi Medical Corporation, Japan; Cerebral area investigated: left and right dorsolateral, ventrolateral and frontopolar cortex; Measure of Aerobic fitness: maximal oxygen consumption test - maximal aerobic power was determinated. | Modified Gibala’s group’s High-Intensity Intermittent Exercise: Eight repetitions of 30 s of ergometer exercise at 60% of maximal aerobic power at 100 rpm and 30 s resting after two minutes of warm-up (50 Watts) at 60 rpm. | - Acute high-intensity intermittent exercise improved interference control. - Hemodynamic activity of left-dorsolateral & prefrontal cortex correlated with interference control during acute high-intensity intermittent exercise in subjects with good cardiorespiratory fitness (40.5 mL·kg⁻¹·min⁻¹). |
| Ludyga et al. [33] | Subjects: 20 High-fit (17.2±1.0 years) and 20 Low-fit (17.0±1.1 years); Design study: cross sectional study; Task: modified Stroop color-word test; Executive function: Interference control (inhibition); Instruments: NIRSport, NIRx Medical Technologies, Berlin, Germany; Cerebral No intervention | - Lower interference control in high-fit compared low-fit. - Inverse relation between aerobic fitness and behavioural performance. - Hemodynamic activity of prefrontal cortex did not explain the relation of aerobic fitness with behavioural performance. |
area investigated: left and right dorsolateral prefrontal cortex; Measure of Aerobic fitness: PWC170 cycle test - relative power output was determinated.  

Mekari et al. [38]  

Subjects: 66 (44 females) older adults (68±6.3 years); Design study: cross sectional study; Task: Trail Making Test; Executive function: cognitive flexibility; Instruments: Portalite, Artinis Medical Systems, Netherlands; Cerebral area investigated: Left prefrontal cortex; Measure of Aerobic fitness: maximal continuous graded exercise test - peak power output was used as a marker of cardiorespiratory fitness.  

No intervention  

- Increased cardiorespiratory fitness was associated with better performance during Trail Making Test B.  
- Cerebral oxygenation in higher fit older adults mediated the relationship with improved executive functioning.  
- Particularly, in older adults with higher cardiorespiratory fitness, cerebral oxygenation was related to executive functioning.  

ΔHHb: Changes in deoxyhemoglobin concentration; ΔO₂Hb: Changes in oxyhemoglobin concentration; [HHb]: oxyhemoglobin concentration; [O₂Hb]: deoxyhemoglobin concentration