Original Article

Effect of Physical Exercise on Neurocognitive Performances in University Students

Said Lotfi[1], Soukyana Karyouh[2]

[1]Evaluation of Sport Sciences and Didactic of Physical Activity, Normal Superior School, Hassan II University of Casablanca, BP 50069, Ghandi, Morocco, [2]Evaluation of Sport Sciences and Didactic of Physical Activity, Normal Superior School, Hassan II University of Casablanca, BP 50069, Ghandi, Morocco

ABSTRACT

The aim of our study was to determine the effect of acute exercise on neurocognitive functions. 19 trained athletes, aged 20.68 ± 0.82 years, pursuing a program university sports for 3 years and been have evaluated at rest and after an intense physical exercise on cognitive tests: Working memory tests, processing speed tests, perceptual reasoning tests (Wechsler, Intelligence Scale Wechsler tests for Children, Fourth Edition [WISC-IV], 2003), and Rey complex figure test (RCFT). The results show that exercise increased slightly and significantly the performance specifically at the visuomotor coding-decoding system of 4.57%, perceptual skills of 15.45%, the spatial organization of objects 13.39%, and the visuospatial memory tasks of 15.41% (RCFT). The exercise affects positively but selectively on certain cognitive functions. The extension effects of exercise should not be generalized to all the functions. These findings suggest that physical exercise program should be a support of the cognitive enrichment of students.

Keywords: Physical exercise, cognitive function, working memory, processing speed and perceptual reasoning

INTRODUCTION

The relationship between physical exercise and neurocognitive functions is an issue that generated interest from longstanding researches stating that psychomotor learning brings many positive effects on human intellectual functions (Piaget, 1956). Numerous studies have shown that physical exercise has positive effects on neurocognition in healthy adults (Szuhany et al., 2015; Audiffren et al., 2011; Ratey and Loehr, 2011; Sandroff et al., 2015). A recent systematic review (including experimental, longitudinal, and epidemiological studies) showed that physical activity may protect against cognitive impairment (Coelho et al., 2009; Sofi et al., 2011; Hamer and Chida, 2009; Sandroff et al., 2015).

Access this article online

Website: http://sjsr.se/

ISSN: 2001-9211

The study findings concluded that the neurocognitive improvements affect both children, adolescents, adults, and the elderly either during acute exercises or training sessions of physical activity. In fact, several recent meta-analysis revealed multiple positive associations between physical activity and neurocognition (Etnier et al., 2006; Ratey and Loehr, 2011; Audiffren et al., 2011; Szuhany et al., 2015).

However, physical inactivity is associated not only to deleterious effects on physical health but also to a decrease in cognitive abilities (Lipnicki and Gunga, 2008). Indeed, several studies have shown the positive effects of exercise training, fitness level, lifestyle physical activity (Dunn et al., 1998), and acute exercises (Dietrich and Audiffren, 2011; Sandroff et al., 2015 ; Sandroff, 2015) on cognition abilities.

Address for correspondence:
Said Lotfi, Evaluation of Sport Sciences and Didactic of Physical Activity, Normal Superior School, Hassan II University of Casablanca, BP 50069, Ghandi, Morocco. Phone: +212-667803551, Fax: +212-522985326, E-mail: lotfisaid@gmail.com

A single session of physical activity increases attentional performance (span and capacity) and speed of decision making in children and adolescents (Tomporowski et al., 2011; Gallotta et al., 2012; Budde et al., 2008). Other studies have observed an improvement in cognitive function with increasing reaction time, the magnitude of memory. In experimental studies, it has been observed the positive effects on memory performance after 40 min of playing team sports (Pesce et al., 2009; Budde et al., 2010) and logical memory assessed by the Wechsler Memory Scale (Hill et al., 1993; Tomporowski et al., 2011). Furthermore, the executive functions are varied positively through physical education (Kubesch et al. 2009; Hill et al. 2010; 2011) and even in a month of fasting, the work memory and visual perception increase significantly after exercise (Lotfi et al., 2010). In other studies, it has been concluded that aerobic activity in physical training increases the ability of solving mathematical problems (Gabbard and Barton, 1979; McNaughten and Gabbard, 1993; Lojovich, 2010; Bala, 2014).

The neurophysiological mechanisms, which are often mentioned in literature as explaining the regular physical activity effect, are related on the one hand at an increasing in regional cerebral blood flow, activating of synaptic plasticity, neurogenesis, and brain catecholamines, and on the other at the effort invested in cognitive tasks. The purpose of this study is to evaluate the effects of intense exercise on neurocognitive functions related with working and visual-spatial memory, processing speed and perceptual reasoning. This work is part of a strategy to improve cognitive and academic performance.

MATERIALS AND METHODS

Participants

About 19 healthy university students were recruited for this study aged 20.68 ± 0.82 years, with a body mass index of 21.27 ± 2.05. All subjects recruited from Physical Education Program at the Hassan II University, Casablanca and pursued 2-4 regular physical training sessions per week during 3 years. All of the subjects were informed of the purpose and procedures of the tests, and informed consent was obtained before the commencement of the study.

Research Design

The subjects were evaluated at rest and 15 min after the exercise test on cognitive tests: Working memory tests, processing speed tests, perceptual reasoning tests (WISC-IV, 2003), and Rey complex figure test (RCFT), whose the psychometric properties are very strong. The peer items of each test are administered at rest and odd items after exercise. The test administration order is reversed in the second phase of the evaluation to preserve the same duration of both sides of physical exercise. Before each passing tests, some repetitions were performed to familiarize them and avoid the effect of learning.

Physical Test

The physical exercise performed is a speed running on foot 250 m realized in the form of timed competition in a circular track 250 m athletics, after warming up for 5 min. This test mobilizes the capacity of the anaerobic system, sufficient to induce a significant cardiovascular activity, and an increasing in blood lactate accumulation.

Working Memory Tests

The memory tests are used to assess the short-term auditory memory, sequencing capabilities, attention, and concentration (Wechsler, 2003). It contains two subtests: The digit span (forward and backward).

The digit span forward (DSF) is formed by eight-digit sequences with progressive difficulties, which are played on one after the other that must be repeated in the same order (each sequence is composed of two different series).

The digit span backward (DSB) is also formed by eight-digit sequence to which the subject restores them in reverse order. The sequences of figures presented at rest and after exercise are different.

The calculated scores are: The total score in memory numbers (MW) is the sum of the marks obtained in the two subtests (Baddeley, 1986): DSF and DSB, each is scored on 16 points. WM (32 points) = DSF (16 points) + DSB (16 points).

The span memory (SM) corresponds to the amplitude of the memory. It is cleared from the number of digits returned correctly in the block the last test in each subtest. The span in memory (SM) is the sum of the marks obtained in SM forward (SMF) noted on 9 points and in the SM backward (SMB), recorded on 8 points.

SM (17 points) = SMF (9 points) + SMB (8 points)

Letter-number sequencing (LNS) assesses mainly short-term auditory memory, the ability to make sequences, attention, and concentration. It requires examinees to recall numbers in ascending order and letters in alphabetical order from a given number and letter sequence. The subject must repeat 10 sequences of numbers in the same order and reverse order then. The evaluator reads a sequence of letters and numbers and the subject must return, starting with the numbers in ascending order, then the letters in alphabetical order.

The scores of WM and LNS subtests are transformed into standard notes, then an index of working memory (WMI) using the scoring tables proposed by Wechsler, 2003 (WISC IV). The WMI assesses the attention, concentration, and working memory. The internal consistency coefficient in these tests is very high (0.92).

Processing Speed Tests

Coding subtest (CD)

The subject copies symbols matched with numbers and utilizing 9 symbols randomly presented in a limited time. This test evaluates primarily the velocity of information processing, short-term memory, visual discrimination, visual perception, visual-motor coordination, visual scanning and attention, and cognitive flexibility (Wechsler, 2003).

Symbol search subtest (SS) (Wechsler, 2003)

The test takes place in 120 seconds during which the subject observes a series of 60 different items each formed of a series of five symbols and must decide each time, as soon as possible if one of two target symbols is present or not in the series. The test assesses visual perception, i.e. the capacity and processing speed of visual information (Flanagan and Kaufman, 2004; Sternberg, 1995). The internal consistency coefficient in the SS is very high (0.91).

The scores obtained in both tests (CD and SS) are transformed into standard note and a processing speed index (PSI) according to scoring tables proposed by Wechsler, 2003 (WISC IV), The PSI assesses the abilities to focus attention and quickly scan and discriminates between and sequentially order visual information and the graphomotor capacity.

Perceptual Reasoning Tests

Block design subtest (BD)

The subject uses colored cubes to reproduce a construction, in a determined time, from a model presented in different forms. This test evaluates primarily the analytical capacity and synthesis of abstract visual stimuli.

Picture concepts subtest (PC)

The subject observes two or three rows of pictures and selects one picture from each row to form a group with a common characteristic. This test consisting of 28 items, measures the categorization and abstract reasoning.

Matrix reasoning subtest (MR)

The subject views an incomplete matrix or series and selects the response option that completes the matrix or series. This test consisting of 36 items, evaluates primarily the processing of visual information and abstract reasoning. The subject observes an incomplete matrix in series and selects the response option that completes the matrix among five possible answers.

The scores obtained in the three tests (BD, PC, and MR) are transformed into a standard note and a perceptual reasoning index (PRI) according to scoring tables proposed by Wechsler, 2003 (WISC IV). The PRI assesses the perceptual reasoning and organization.

RCFT

The RCFT is developed by André Rey-Osterrieth, in 1941, and standardized by Osterrieth, in 1944, and recalibrated by Mesmin and Walloon, 2011, allows the assessment of executive functions such as visual-spatial abilities and visuoconstructive, non-verbal memory and working memory, attention, and planning. It is a neuropsychological test. The figure is composed of 18 elements organized in 3 parts: Overall shapes (rectangles) and external members (squares, crosses, and triangles) and the internal components to the overall shapes (internal, lines, and circles). It is administered in two phases, reproduction by direct copying of the figure (unaccounted), followed by 2 min of memory reproduction, it indicates what spontaneously remained in memory. It is the latter which is considered in notation according to a rating scheme Boston qualitative scoring system (qualitative rating system Boston).

Data Analysis

The comparison of averages scores at rest and after exercise for each test is analyzed by the non-parametric Wilcoxon t-test valid for dependent samples, with significance threshold set at $P < 0.05$. The data were processed with SPSS (21).

RESULTS

Variation in the parameters of the scores of memory, processing speed, and perceptual reasoning at rest and after exercise are presented in Table 1. It is noticed that compared to the values obtained at rest, there is a significant increase ($P < 0.05$) after exercise at the CD test (4.57%), SS (15.45%), BD (13.39%), and figure Rey (15.41%), whereas the means of the working memory index (WMI) (DSF, DSB, and LNS), PRI (BD, PC, and MR), and PSI (CD and SS), remain stable after exercise.

Results regarding memory span scores at rest and outside of exercise are presented in Figure 1. The average of the scores obtained at the SMF (6.00 ± 1.09 vs. 6.36 ± 1.08) and SMB (5.21 ± 1.43 vs. 5.64 ± 1.55) after exercise were not significantly varied compared with at rest values. While the averages scores of the RCFT increase significantly ($P < 0.008$) of 15.41% after exercise.

DISCUSSION

The aim of our study is to evaluate the effect of physical exercise on cognitive function. For this, we conducted an experimentation on 19 healthy university students athletes, assessing three neurocognitive indexes: The WMI, PRI, and the PSI before and after exercise, referring to the intelligence scale Wechsler (WISC-IV, 2003), and the visual-spatial memory by the RCFT.

The results obtained from this study show that exercise increased slightly and significantly the performance specifically at the visuomotor coding-decoding system of 4.57% (CD), perceptual skills of 15.45% (SS), the spatial organization of objects 13.39% (BD), and the visuospatial memory tasks of 15.41% (RCFT), and no effect recorded in the Wechsler Index Scores of cognitive functioning (WMI, PSI, and PRI). These results partially assume the model that physical exercise has a positive impact on the functions of cognitive skills of the subjects practicing physical activity.

Indeed, several meta-analyses have shown a causal relationship between physical exercise (moderate- to high-intensity exercises) and cognitive performances and that the size of this effect is moderate to large (Audiffren et al., 2011; Colcombe and Kramer, 2003; Angevaren et al., 2008; Smith et al., 2010). Other epidemiological studies have often reported a positive correlation between physical fitness and vitality of neurocognition (Barnes et al., 2003).

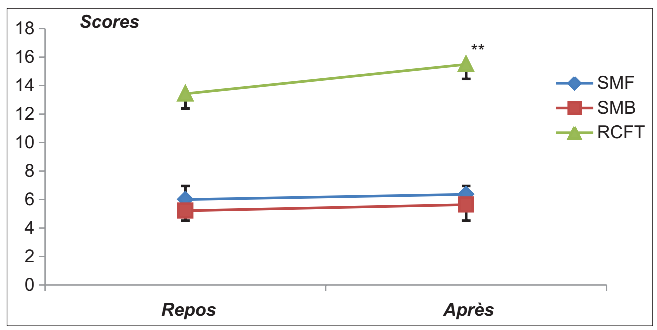

Figure 1: Variation in the span in memory forward, span in memory backward, and Rey complex figure test at rest and after exercise. **significant variation, $P < 0.05$

Table 1: Variation of test scores of memory, processing speed, and perceptual reasoning at rest and after exercise (n=19)

Parameters	Tests	At rest	After exercise	Wilcoxon test	
				Z	P value
Processing speed	Coding test	95.45±13.00	99.82±19.59*	−1.958	0.050
	Symbol search	31.18±5.53	36.00±9.61*	−2.398	0.016
	Processing speed index	113.87±17.67	122.20±18.98	−1.679	0.093
Work memory	Digit span forward	9.93±2.37	10.07±2.31	−0.321	0.748
	Digit span backward	10.60±2.20	10.13±2.13	−1.116	0.264
	Letter-number sequencing	20.73±3.29	20.18±3.16	−0.655	0.512
	Working memory index	100.56±15.03	98.31±16.76	−0.948	0.343
Perceptual reasoning	Picture concepts	11.42±1.00	11.08±1.31	−0.877	0.380
	Matrix reasoning	14.92±1.44	14.33±1.67	−0.873	0.382
	Block design	23.00±3.41	26.08±2.43*	−2.953	0.003
	Perceptual reasoning index	97.71±13.05	102.07±13.36	−1.061	0.289

Data are presented mean±SD. *Significant comparison with P<0.05. SD: Standard deviation

Considering the results of this study, the acute exercise has mobilized the spatial memory ability is the part of memory responsible for recording information about one's environment and its spatial orientation and the processing speed capabilities of information, visual discrimination, visual perception, visual-motor coordination, visual scanning, and discrimination as well as attention and cognitive flexibility, which are evaluated in this study by the CD subtest and SS subtest by Wechsler scale (2003). During practicing physical exercise, the appearing and disappearing of all play objects (the movements of the defenders, attackers, the ball, and the body) require permanently complex perceptual-cognitive skills: Perceiving opportunities into free space, judging distances, actions anticipation, trajectory analyses, and good visual field.

Some experimental studies have concluded that an exercise program increases significantly several regional brain volumes (frontal lobes, dorsal anterior cingulate cortex, supplementary motor area, and gyrus) that are implicated in the attentional control and memory processes (West, 1995; Duncan and Owen, 2000; Gunning-Dixon and Raz 2003; Colcombe et al., 2006). Specially, the gyrus plays a critical role in several higher brain functions such as learning, memory, and spatial CD (Jonas and Lisman, 2014). Different neurophysiological mechanisms involving activation process of central nervous system (synapses, motoneuron, and neuron activation [P3 component]) and neurotrophic factors (brain-derived neurotrophic factor, insulin-like growth factor-1, and c-Fos) released during exercise could explain the brain plasticity: Cognitive control and spatial, working memory, processing speed, attention, and executive function (Smith et al., 2010; Voelcker-Rehage and Niemann, 2013; Bherer et al., 2013).

On the other hand, the catecholamines are responsible for many adaptations both at rest and during exercise. Among these, responses are the substrate mobilization and utilization capacity to control blood flow in the working muscles, to control cardiac function and metabolism (Mazzeo, 1991; Savard et al., 1989; Hooker et al., 1990), and increase with the workload (Marshall, 1989), then can be used to estimate the sympathetic nervous system activity (Savard et al, 1987).

On another side, the secretions of a certain group of neurotransmitters, i.e. endorphin and dopamine provide a source of pleasure and facilitate the learning (De Moor et al. 2006). The electric responses (EEG) recorded during the neuromotor process show a three endogenous potential: (1) the P300 (P3) wave occurred especially in the oddball tasks, i.e. detecting the target in a series of different stimuli including many distracters (Van Dinteren et al., 2014; Polich, 2004; 2007), (2) the contingent negative variation is observed in the anticipation tasks and associated with information processing and response preparation (Walter et al., 1964; Ruchkin et al., 1986), and (3) the pre-motor potential or readiness potential is occurred during the motor cortex activity (Kornhuber and Deecke, 1965; Nguyen et al., 2014). Several studies confirmed the cognitive enrichment theory (Hertzog et al., 2009; Hertzog, 2008; Goldberg, 2005) suggesting that all activities related to physical stimulation have a positive impact on the level of neurocognitive efficacy and brain plasticity (Greenwood and Parasuraman, 2010).

Further research should be undertaken to investigate the correlations between academic performance and physical performance, and the effects of sex, age, and the recovery time following the physical training session and also the duration of the positive effects on the brain, examining each time, the cognitive functions, and most sensitive to change.

CONCLUSION

This work was carried out to evaluate the effect of acute physical on the cognitive functions. The main results have shown a significant increase in the visuomotor coding-decoding system, perceptual skills, the spatial organization of objects and the visuospatial memory tasks, and no effect recorded in the Wechsler index scores of cognitive functioning. The exercise affects positively but selectively on certain cognitive functions. The extension effects of exercise should not be generalized to all the functions. These findings suggest that physical exercise program should be a support of the cognitive enrichment of students.

REFERENCES

Angevaren, M., Aufdemkampe, G., Verhaar, H.J., Aleman, A., Vanhees, L. (2008), Physical activity and enhanced fitness to improve cognitive function in older people without known cognitive impairment. Cochrane Database of Systematic Reviews, (2), CD00538.

Audiffren, M., André, N., Albinet, C. (2011), Positive effects of chronic physical exercise on cognitive functions in aging people: Assessment and prospects. Review Neuropsychology, 3(4), 207-225.

Baddeley, A.D. (1986), Working Memory. Oxford, UK: Clarendon Press.

Bala, G. (2014), The effects of acute physical exercise training on mathematical computation in children. Annales Kinesiologiae, 5(1), 15-22.

Barnes, D.E., Yaffe, K., Satariano, W.A., Tager, L.B. (2003), A longitudinal study of cardiorespiratory fitness and cognitive function in healthy older adults. Journal of the American Geriatrics Society, 51(4), 459-465.

Bherer, L., Erickson, KI., Liu-Ambrose, T. (2013), A review of the effects of physical activity and exercise on cognitive and brain functions in older adults. Journal of Aging Research, 2013, 657508.

Budde, H., Voelcker-Rehage, C., Pietrassyk-Kendziorra, S, Ribeiro P., Tidow, G. (2008), Acute coordinative exercise improves attentional performance in adolescents. Neuroscience Letters, 441, 219-223.

Budde, H., Voelcker-Rehage, C., Pietrassyk-Kendziorra, S., Machado, S., Ribeiro, P., Arafat, A.M. (2010), Steroid hormones in the saliva of adolescents after different exercise intensities and their influence on working memory in a school setting. Psychoneuroendocrinology, 35, 382-391.

Coelho, F.G., Santos-Galduroz, R.F., Gobbi, S., Stella, F. (2009), Systematized physical activity and cognitive performance in elderly with Alzheimer's dementia: A systematic review. Revista Brasileira de Psiquiatria, 31(2), 163-170.

Colcombe, S., Kramer, AF. (2003), Fitness effects on the cognitive function of older adults: A meta-analytic study. Psychological Science, 14, 125-130.

Colcombe, S.J., Erickson, K.I., Scalf, P.E., Kim, J.S., Prakash, R., McAuley, E., Elavsky, S., Marquez, DX., Hu, L., Kramer, AF. (2006), Aerobic exercise training increases brain volume in aging humans. Journals of Gerontology. Series A: Biological Sciences, 61, 1166-1170.

De Moor, M.H.M., Beem, A.L., Stubbe, J.H., Boomsma, D.I., De Geus, E.J. (2006), Regular exercise, anxiety, depression and personality: A population-based study. Preventive Medicine, 42(4), 273-279.

Dietrich, A., Audiffren, M. (2011), The reticular-activating hypofrontality (RAH) model of acute exercise. Neuroscience and Biobehavioral Reviews, 35, 1305-1325.

Duncan, J., Owen A.M. (2000), Common regions of the human frontal lobe recruited by diverse cognitive demands. Trends Neurosciences, 23, 475-483.

Dunn, A.L., Andersen, R.E., Jakicic, J.M. (1998), Lifestyle physical activity interventions. History, short - And long-term effects, and recommendations. American Journal of Preventive Medicine, 15(4), 398-412.

Etnier, J.L., Nowell, P.M., Landers, D.M., Sibley, B.A. (2006), A meta-regression to examine the relationship between aerobic fitness and cognitive performance. Brain Research Reviews, 52(1), 119-130.

Flanagan, D.P., Kaufman, A.S. (2004), Essentials of WISC-IV Assessment. Hoboken, NJ: John Wiley & Sons.

Gabbard, C., Barton, J. (1979), Effects of physical-activity on mathematical computation among young-children. Journal of Psychology, 103, 287-288.

Gallotta, M.C., Guidetti, L., Franciosi, E., Emerenziani, G.P., Bonavolonta, V., Baldari, C. (2012), Effects of varying type of exertion on children's attention capacity. Medicine and Science in Sports and Exercise, 44(3), 550-555.

Goldberg, E. (2006), The Wisdom Paradox: How Your Mind Can Grow Stronger as Your Brain Grows Older. New York: Gotham Books.

Greenwood, P.M., Parasuraman, R. (2010), Neuronal and cognitive plasticity: A neurocognitive framework for ameliorating cognitive aging. Frontiers in Aging Neuroscience, 2, 150.

Gunning-Dixon, F.M., Raz, N. (2003), Neuroanatomical correlates of selected executive functions in middle-aged and older adults: A prospective MRI study. Neuropsychologia, 41, 1929-1941.

Hamer, M., Chida, Y. (2009), Physical activity and risk of neurodegenerative disease: A systematic review of prospective evidence. Psychological Medicine, 39, 3-11.

Hertzog, C. (2009), Use it or lose it: An old hypothesis, new evidence, and an ongoingcontroversy. Cognition in Aging: Methodologies and Applications. Washington, DC: American Psychological Association.

Hertzog, C., Kramer, A.F., Wilson, R.S., Lindenberger, U. (2008), Enrichment effects on adult cognitive development: Can the functional capacity of older adults be preserved and enhanced? Psychological Science in the Public Interest, 9, 1-65.

Hill, L., Williams, J.H., Aucott. L., Milne, J., Thomson, J., Greig, J., Munro, V., Mon-Williams, M. (2010), Exercising attention within the classroom. Developmental Medicine and Child Neurology, 52, 929-934.

Hill, L.J.B., Williams, J.H.G., Aucott, L., Thomson, J., Mon-Williams, M. (2011), How does exercise benefit performance on cognitive tests in primary-school pupils? Developmental Medicine and Child Neurology, 53, 630-635.

Hooker, S.P., Wells, C.L., Manore, M.M., Philip, S.A., Martin, N. (1990), Differences in epinephrine and substrate responses between arm and leg exercise. Medicine and Science in Sports and Exercise, 22, 779-784.

Jonas, P., Lisman, J. (2014), Structure, function, and plasticity of hippocampal dentate gyrus microcircuits. Front Neural Circuits. DOI: 10.3389/fncir.2014.00107.

Kornhuber, H.H., Deecke, L. (1965), Hirnpotentialänderungen bei Willkürbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. Pflugers Archiv, 284, 1-17.

Kubesch, S., Walk, L., Spitzer, M., Kammer, T., Lainburg, A., Heim, R., Katrin, H. (2009), A 30-minute physical education program improves students executive attention. Mind, Brain, and Education, 3, 235-242.

Lipnicki, D.M., Gunga, H.C. (2008), Physical inactivity and cognitive functioning: Results from bed rest studies. European Journal of Applied Physiology, 105(1), 27-35.

Lojovich, J.M. (2010), The relationship between aerobic exercise and cognition: Is movement medicinal? Journal of Head Trauma Rehabilitation, 25(3), 184-192.

Lotfi, S., Madani, M., Tazi, A., Boumahmaza, M., Talbi, M. (2010), Variation of cognitive functions and glycemia during physical exercise in Ramadan fasting. Revue Neurologique, 166(9), 721-726.

Mazzeo, R.S. (1991), Catecholamine responses to acute and chronic exercise. Medicine and Science in Sports and Exercise, 23, 839-845.

McNaughten, D., Gabbard, C. (1993), Physical exertion and immediate mental performance of 6^{th}-grade children. Perceptual and Motor Skills, 77, 1155-1159.

Mesmin, C., Walloon, P. (2011), Figure complexe de Rey A et B: Guide d'utilisation et d'interprétation. Paris: ECPA.

Nguyen, V.T., Breakspear, M., Cunnington, R. (2014), Reciprocal interactions of the SMA and cingulate cortex sustain pre-movement activity for voluntary actions. Journal of Neuroscience, 34, 16397-16407.

Osterrieth, P.A. (1944), Le test de copie d'une figure complexe: Contribution à l'étude de la perception et de la mémoire. Archives de Psychologie, 30, 286-356.

Pesce, C., Crova, C., Cereatti, L., Casella, R., Bellucci, M. (2009), Physical activity and mental performance in preadolescents: Effects of acute exercise on free-recall memory. Mental Health and Physical Activity, 2, 16-22.

Piaget, J., Inhelder, B. (1956), The Child's Conception of Space. London: Routledge.

Polich, J. (2004), Clinical application of the P300 event-related brain potential. Physical Medicine and Rehabilitation Clinics of North America, 15, 133-161.

Polich, J. (2007), Updating P300: An integrative theory of P3a and P3b. Clinical Neurophysiology, 118, 2128-2148.

Ratey, J.J., Loehr, J.E. (2011), The positive impact of physical activity on cognition during adulthood: A review of underlying mechanisms, evidence and recommendations. Reviews in the Neurosciences, 22(2), 171-185.

Rey, A. (1941), L'examen psychologique dans les cas d'encéphalopathie traumatique. Archives de Psychologie, 28, 286-340.

Ruchkin, D.S., Sutton, S., Mahaffey, D., Glaser, J. (1986), Terminal CNV in the absence of motor response. Electroencephalography and Clinical Neurophysiology, 63(5), 445-463.

Sandroff, B.M. (2015), Exercise and cognition in multiple sclerosis: The importance of acute exercise for developing better interventions. Neuroscience Biobehavioral Reviews, 59, 173-183.

Sandroff, B.M., Hillman, C.H., Benedict, R.H., Motl, R.W. (2015), Acute effects of walking, cycling, and yoga exercise on cognition in persons with relapsing-remitting multiple sclerosis without impaired cognitive processing speed. Journal of Clinical and Experimental Neuropsychology, 37(2), 209-219.

Savard, G., Strange, S., Kiens, B., Richter, E.A., Christensen, N.J., Saltin, B. (1987), Noradrenaline spillover during exercise in active versus resting skeletal muscle in man. Acta Physiologica Scandinavica, 131, 507-515.

Savard, G.K., Richter, E.A., Strange, S., Kiens, B., Christensen, N.J., Saltin, B. (1989), Norepinephrine spillover from skeletal muscle during exercise in humans: Role of muscle mass. American Journal of Physiology, 257, H812-H818.

Smith, P.J., Blumenthal, J.A., Hoffman, B.M., Cooper, H., Strauman, T.A., Welsh-Bohmer, K., Browndyke, J.N., Sherwood, A. (2010), Aerobic exercise and neurocognitive performance: A meta-analytic review of randomized controlled trials. Psychosomatic Medicine, 72, 239-252.

Sofi, F., Valecchi, D., Bacci, D., Abbate, R., Gensini, G.F., Casini, A., Macchi, C. (2011), Physical activity and risk of cognitive decline: A meta-analysis of prospective studies. Journal of Internal Medicine, 269, 107-117.

Sternberg, R.J. (1995), In Search of the Human Mind. Orlando, USA: Harcourt Brace College.

Szuhany, K.L., Bugatti, M., Otto, M.W. (2015), A meta-analytic review of the effects of exercise on brain-derived neurotrophic factor. Journal of Psychiatric Research, 60, 56-64.

Tomporowski, P.D., Lambourne, K., Okumura, M.S. (2011), Physical activity interventions and children's mental function: An introduction and overview. Preventive Medicine 2011;52 Suppl 1:S3-9. DOI: 10.1016/j.ypmed.2011.01.028.

Van Dinteren, R., Arns M., Jongsma, M.L.A., Kessels, R.P.C. (2014), P300 development across the lifespan: A systematic review and meta-analysis. PLoS One, 9(2), e87347.

Voelcker-Rehage, C., Niemann, C. (2013), Structural and functional brain changes related to different types of physical activity across the life span. Neuroscience Biobehavioral Reviews, 37, 2268-2295.

Walter, W.G., Cooper, R., Aldridge, V.J., McCallum, W.C., Winter, A.L. (1964), Contingent negative variation: An electric sign of sensorimotor association and expectancy in the human brain. Nature, 203(4943), 380-384.

Wechsler, D. (2003), Wechsler Intelligence Scale for Children. 4th ed. New York: The Psychological Corporation.

West, R. (1995), An application of prefrontal cortex function theory to cognitive aging. Psychological Bulletin, 120, 272-292.