A Narrative Review of Physical Activity, Nutrition, and Obesity to Cognition and Scholastic Performance across the Human Lifespan[1–3]

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ABSTRACT

We reviewed studies that examine the relationship of energy consumption, storage, and expenditure to cognition and scholastic performance. Specifically, the literature base on nutrient intake, body mass, and physical activity is described relative to cognitive development and academic achievement. The review of literature regarding the overconsumption of energy and excess body mass suggests poorer academic achievement during development and greater decay of brain structure and function accompanied by increased cognitive aging during older adulthood. The review of literature regarding energy expenditure through the adoption of increased physical activity participation suggests increased cognitive health and function. Although this area of study is in its infancy, the preliminary data are promising and matched with the declining physical health of industrialized nations; this area of science could provide insight aimed at improving brain health and cognitive function across the human lifespan. *Adv. Nutr. 2: 201S–206S, 2011.*

Introduction

Since the early 1970s, BMI has been on the rise in children and adolescents across every demographic in the United States (1). According to the NHANES (2), the percentage of overweight and obese elementary age children has risen from 6.5 to 17% between 1971–1974 and 2003–2004. Further, the percentage of obese teens has also risen from 5 to 17.6% during the same timeframe (2). This increasing public health concern transcends all socioeconomic levels (1); however, certain minority groups have demonstrated greater risk for becoming overweight or obese (3). At issue, almost one-third of children and adolescents in the US were overweight or obese in 2004 (3).

Compounding this public health issue, physical activity trends have indicated that children are less active, less fit, and less healthy than previous generations (4). Thus, the combination of an increase in body mass and a decrease in physical activity suggests that an energy (i.e. caloric) imbalance may be at the center of the obesity epidemic facing the youth of industrialized nations (5). Associated with this imbalance are several physical health issues such as type 2 diabetes, colon cancer, and metabolic syndrome (6). However, recent data also indicate that mental health issues may further be tied to poor health status (7). Accordingly, the trends toward increased energy consumption and body mass along with decreased physical activity behaviors may have implications for cognitive health and scholastic performance.

Trends in body mass, energy consumption, and physical activity

An in-depth review of physical health trends is beyond the scope of this article. However, a brief review of the current state of research on body mass, energy consumption,

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and physical activity behavior is provided in this section to set a proper background prior to describing the body of work relating these factors to cognitive health. It has become a national priority to determine what factors are contributing to the rise in obesity as well as to decrease the number of overweight and obese children in the United States. In response, there is an increasing body of literature focused on the nutritional patterns of children. For example, Vadiveloo et al. (8) followed 35 boys and girls between grades 3 and 5 (mean age = 9.5 y) and reported on their food intake and physical activity patterns over the course of 1 y. Their results support extensive national surveys conducted in the US (9) and found that the weekly diet consumed by children was comparable to the recommendations set forth by the Dietary Guidelines for Americans (10) with respect to total daily energy intake and the percent of energy derived from each of the macronutrients (e.g. carbohydrate, protein, fat). Additionally, Vadiveloo et al. (8) observed that the children's energy consumption was within the recommended range for their age group. However, inspection of the specific energy composition indicated that children were consuming well below the recommended standards for daily servings of fruits, vegetables, and fiber and above the recommended standards for saturated fat and sodium. Given that the children also fell short of the recommended guidelines for physical activity (measured by step counts), these comprehensive data shed light on the development of overweight and obesity risk factors.

In support of this notion, only 34.7% of high school students in 2007 performed the recommended amount of moderate to vigorous physical activity (11). Current guidelines indicate that children should engage in 60 min or more of daily physical activity, and the majority of the time should be spent performing moderate to vigorous intensity aerobic activities (12,13). Unfortunately, as exemplified above, the vast majority of youth do not achieve these physical activity recommendations. Increased competition for leisure time stems from the use of sedentary materials (e.g. computers, television, video games), which may be of further detriment to physical health, as the average 8- to 18-y-old in the US spends over 5 h/d in front of a screen (14). These trends remain as children progress through school; the average high school student accumulating over 3 h of screen time daily (14). Other data indicates that these behaviors continue throughout life, with adults performing less physical activity (6) and more screen time as a function of leisure time activities learned during childhood (15,16). The implications of these behaviors in adults are higher BMI, lower aerobic fitness, and other ill health outcomes (i.e. increased smoking, raised serum cholesterol) (16).

Cognition and health behaviors

Given the recent trends outlined above, youth in industrialized nations are at risk for decreased physical health. Of further concern is a growing body of literature demonstrating deficits in brain health and cognition as a result of lifestyle choices and behaviors (7). Recent findings using a variety of experimental techniques have indicated that cognitive performance declines with decreases in physical activity and aerobic fitness and increases in body mass and energy consumption (5,7). Several recent studies have demonstrated that these factors influence cognition not only on a rudimentary level but also at the level of scholastic performance (17,18). The remainder of this article focuses on the relationship of these factors to cognitive health in youth (although relevant adult data will be discussed to provide support), with an emphasis on scholastic achievement and performance.

Nutrition and cognition

Nutrition can substantially influence both the development and health of brain structure and function. Providing the proper building blocks for the brain to create and maintain connections is critical for improved cognition and academic performance. It is thought that this process begins during gestation, because supplementing undernourished pregnant mothers, lactating mothers, and children with both energy and protein during the first few years of development had a marked, positive impact on measures of language, memory, and perception (19). Freeman et al. (19) collected data from over 1000 3- and 4-year-old children residing in 4 rural Guatemalan villages and examined the relation between nutritional status (measured via height and head circumference) and cognitive performance. All volunteers from the villages had the opportunity to consume a supplement twice per day. In 2 of the villages, mothers who were pregnant and/or lactating and their children were offered a supplement containing 11 g of protein and 163 kilo-calories. Volunteers in the other 2 villages were supplemented with a sugar drink that contained 59 kilo-calories. Regardless of the beverage supplement, all participants were also offered a vitamin and mineral supplement. Freeman et al. (19) measured language, memory, and perception and found associations between increased protein-energy consumption and improved cognitive performance, providing support for the importance of nutrition to cognition. Interestingly, the data also indicated that cognitive performance was higher for those children whose mother consumed the protein-energy supplement during pregnancy and lactation, indicating that pre- and postpartum nutrition is influential in cognitive development (19).

Even short term fasting during preadolescence (i.e. skipping breakfast) has been related to transient decreases in late morning cognitive performance on measures of IQ, the Matching Familiar Figure Test, and the Hagen Central Incidental Test, indicating that early morning fasting is associated with a decreased ability to problem solve (20). Alternatively, consuming a balanced meal has been related to marked, positive changes in disposition, attentiveness, and motivation among individuals 19–33 y of age (21). In addition, families who indicated that they "sometimes or often did not get enough food to eat" had elementary school children who were more apt to struggle with academics compared with their peers (22). When researchers adjusted for socioeconomic and other factors, food insufficiency was associated with significantly lower standardized mathematics scores, and students were 1.44 times more likely to repeat a grade relative to those children who reported receiving enough food to eat (22).

Overweight, obesity, and cognitive performance

Others have demonstrated that overnutrition, more specifically an overconsumption of energy, is maladaptive for brain health and function (23,24). Specifically, a link between an excess of body fat and decrements in cognitive performance have also been investigated (25). This relationship becomes an ever-growing concern as the percentage of overweight and obese children of elementary school age continues to rise, indicating the immediate need to understand the effects of increased weight on scholastic performance. Although the body of research is currently limited, available results have identified an inverse relationship between obesity and cognition in children. Campos et al. (26) examined intelligence (i.e. Wechsler Intelligence Scale for Children) in 65 obese adolescents relative to healthy weight individuals within the same community (age range 8–14 y). They found that obese children performed worse on the Wechsler Intelligence Scale for Children than their healthy weight counterparts. Despite these findings, it was noted that causality could not be determined, because the cross-sectional nature of the study left open the possibility that other intervening variables may have been related to the observed pattern of results (26).

Further, Datar et al. (27) examined the relationship between weight and test score performance in mathematics and reading from the Early Childhood Longitudinal Study consisting of ≥11,000 nationally representative kindergarteners in the US. They found that overweight children had lower test scores relative to children of normal weight. However, when the data were adjusted for socioeconomic status, physical activity, television viewing, and other social variables, the relationship diminished, with the exception of the association between boys' overweight status and mathematics (27). The authors concluded that being overweight is not causally related to lower test scores but rather may serve as marker for poorer scholastic performance. Given that overweight status is more easily identifiable than other related factors (such as socioeconomic status or home environment), it may help identify those at risk for poorer scholastic performance (27). Similar findings supporting those of Datar et al. (27) were noted by Judge and Jahns (28), who found that the relationship between overweight status and poorer performance on mathematics and reading achievement was modified by demographic factors in a nationally representative sample of almost 14,000 3rd grade children from the Early Childhood Longitudinal Study.

In a follow-up study, Datar and Sturm (29) examined the prospective relationship between weight status at the time of entry into kindergarten and weight status or change in weight status at the conclusion of the 3rd grade on academic test performance in ~7000 children. Their findings indicated that girls of normal weight at kindergarten who were classified as overweight in 3rd grade demonstrated significant decrements in test performance, whereas no such relationship was observed for boys (29). However, overweight boys were observed to have more absences from school (29). In addition, more social-behavioral issues were noted for overweight girls, indicating that change in overweight status during early school years is a significant risk factor for academic performance and behavior in girls but not in boys (29). Other research indicates that as adolescents mature into teens, problems with academic performance may persist. Obese teenage girls are 50% more likely to repeat a grade than their healthy weight counterparts and obese boys drop out of school more than twice as often as their healthy weight peers (30). Additionally, Sargent and Blanchfower (31) found that teen obesity is associated with a significantly lower education level (along with lower income) continuing into adulthood.

Overweight and obesity have also been linked to cognitive dysfunction across adulthood (32). Sabia et al. (33) examined the relation of BMI at age 25 y with cognitive health across the adult lifespan to better determine the extent to which cognition in late midlife (i.e. mean age = 61 y) is affected by obesity during earlier adulthood. Their results indicated that long-term underweight or overweight status was associated with lower scores on the Mini-Mental State Examination, tests of memory, and executive control function later in life (33). Further, a large increase in BMI from early to late midlife was associated with poorer performance on tests of executive control function (33).

Cournot et al. (34) also employed a prospective design over a 5-y period to assess the relation of BMI to cognitive function and decline in healthy 32- to 62-y-old men and women in the workforce. Along with BMI, cognitive tests of attention, learning, and memory were conducted and the results indicated that higher BMI was associated with poorer cognitive performance after adjusting for demographic and psychosocial variables (i.e. age, sex, education, health status). Additionally, higher BMI at baseline was predictive of greater cognitive decline during the 5-y follow-up (34), indicating that BMI is independently associated with cognitive function during adulthood.

Jeong et al. (32) investigated the relation between obesity and cognitive dysfunction in 467 South Korean elderly adults (>65 y) through the measurement of waist circumference and BMI and the Korean Mini-Mental State Examination, which is a cognitive screening tool for dementia. Their results indicated that poorer performance on the examination was negatively associated with overweight status (BMI = 23–25 kg/m^2) obesity (BMI > 25 kg/m^2) (32). Accordingly, their findings indicate that overweight and obesity are related to cognitive dysfunction, as assessed via screening measures for dementia, among older adults.

Recent neuroimaging data corroborate these earlier behavioral findings (32–34) and suggest that overweight and obesity effects on cognitive dysfunction may result from changes in brain structure. Raji et al. (35) used tensor based morphometry within a functional MRI environment to assess gray and white matter volume atrophy in 94 elderly adults (mean age of 77 y) who remained cognitively healthy 5 y after the images of their brain were taken. Results indicated that BMI, plasma insulin taken after a fast, and type 2 diabetes were strongly associated with atrophy of the frontal, temporal, and subcortical regions of the brain. After controlling for the other factors, BMI remained negatively correlated with atrophy in those brain regions. Further, BMI > 30 was associated with atrophy in the frontal lobes, the anterior cingulate gyrus, hippocampus, and thalamus relative to individuals with normal BMI (i.e. 18.5–25), and overweight (BMI 25–30) and obese individuals (BMI > 30) exhibited overall reduced brain volume relative to normal weight individuals (35). Accordingly, these data indicate the overweight and obesity may be associated with marked decreases in brain volume and provide a greater understanding of the underlying causes of obesity related changes in cognitive dysfunction. Given that several of the brain regions demonstrating decreases in brain volume are associated with attention, memory, and the control of cognition (17,36,37), obesity related deficits in cognitive and scholastic performance mediated by these brain regions might be expected.

Physical activity, cognition, and scholastic performance

Despite the growing literature base demonstrating potential overweight and obesity related deficits in cognition, an also large and growing literature has expounded on the beneficial relation of physical activity and aerobic fitness to cognitive health and scholastic performance (38). Briefly, a consensus on the relation of fitness to scholastic performance has not been reached, because the available data indicate either a positive relationship or no relationship of fitness to cognition. Regardless, the data suggest that time spent engaged in physical activities is beneficial, because it does not detract from scholastic performance and in fact can improve overall health and function (17,18,38,39).

One of the most high-profile studies to date, conducted by the California Department of Education (CDE) (40), examined the relationship of physical fitness to academic performance in a sample of ~885,000 students in 5th, 7th, and 9th grades through the comparison of a field test of physical fitness known as the Fitnessgram [i.e. PACER shuttle run (aerobic capacity), push-ups and sit-ups (muscle strength), sit and reach (muscle flexibility), and BMI (body composition)] and performance on the Standardized Achievement Test (39,40). The findings revealed a positive relationship between fitness and SAT performance such that students who had higher scores on the Fitnessgram (i.e. achieved the necessary criteria to be classified in the Healthy Fitness Zone on a minimum of one-half of the subtest of the Fitnessgram) also had higher scores on the mathematics and reading portions of the SAT (40). Further examinations revealed females exhibited higher academic achievement than males, especially at higher fitness levels (40), suggesting that physical activity participation may be more beneficial for girls, as those who were more vigorously engaged performed better in school (41).

Castelli et al. (42) extended the findings of the CDE (40) through the examination of younger children (i.e. 3rd and 5th grade students) and of the differential contributions of the various subcomponents of the Fitnessgram. Specifically, Castelli et al. (42) parsed the individual contributions of aerobic capacity (i.e. the PACER test), muscle strength (i.e. push-ups, sit-ups), flexibility (i.e. sit and reach), and body composition (BMI) on mathematics and reading performance from the Illinois Standardized Achievement Test in a sample of 259 students. After controlling for the various demographic factors (e.g. age, sex, socioeconomic status) that were previously demonstrated to influence either fitness or scholastic performance, the results corroborated the findings of the CDE (40), because a general relationship between fitness and achievement test performance was observed. However, when the individual components of the Fitnessgram were examined, it was determined that only aerobic capacity (i.e. the PACER test) was significantly related to achievement test performance (42). Muscle strength and flexibility were unrelated, and a negative relation of BMI to test performance was observed, indicating that increased BMI was associated with poorer performance on the standardized test. Corroborating evidence has emerged recently from Chomitz et al. (43) in a larger sample of 4th to 8th grade students indicating that the likelihood of passing both mathematics and English achievement tests increases with the number of fitness tests passed during physical education class, and the odds of passing the mathematics achievement tests were inversely related with increased weight status.

Other researchers have further characterized the influence of physical activity intensity on scholastic performance. For example, Coe et al. (44) examined physical education enrollment and self-reported moderate and vigorous physical activity (MVPA) outside school on performance in core academic courses and the Terra Nova Standardized Achievement test in 214 6th-grade students. Findings indicated that scholastic performance was unaffected by whether the participants were enrolled in physical education classes. However, it was determined that physical education classes only averaged 19 min of MVPA. When time spent engaged in MVPA outside of school was considered, a significant relation to scholastic performance emerged, with more time engaged in MVPA relating to better grades (44).

Several other studies are consonant with the findings reported above. Ahamed et al. (45) demonstrated that prolonged (i.e. 16 mo) school based physical activity interventions may be beneficial toward improving scholastic performance. Others have reported that single, short bouts of physical activity (46) or coordinative exercise (47) are beneficial toward improving attention to academic instruction and on cognitive tasks immediately following the short duration intervention. Lastly, potential mechanisms underlying these apparent acute effects of physical activity on attention have emerged, as recent data indicate short term exercise-induced alterations in the neuroelectric system support changes in the cognitive control of attention and relate to task performance (48).

Summary and future directions

The study of the effects of nutrition, obesity, and physical activity on brain health, cognition, and academic performance is in its infancy. Several encouraging findings outlined above have generated interest in this area of study, but continued exploration is necessary. Relative to energy consumption, many questions regarding the energy profile (i.e. protein, fat, and carbohydrate composition) and the short and long term effects of specific nutritional patterns are of great interest. The effects of under- and overconsumption of high-energy, low-nutrient density foods relative to cognition are also of great interest from a brain maturation perspective. The discovery of how energy consumption influences cognition may inform immediate and prolonged cognitive health and function. The association of obesity with cognitive health and learning has also demonstrated a number of interesting findings, but clear relationships have not been established. This area is an especially challenging direction to study in human models given that obesity is linked to a number of other psychosocial, demographic, and health factors. Nevertheless, future efforts are needed to better characterize the synergistic relationship among nutrition, obesity, and cognition.

Although the study of physical activity and fitness to cognition and scholastic performance is more established in the literature, researchers in this area also need to better characterize the relationship between physical and cognitive health. Future efforts need to use more rigorous experimental designs to causally link physical activity to changes in cognition during development. Currently, all work has been cross-sectional in nature. Finally, researchers must begin to consider the mediating role that each of these factors (i.e. nutrition, body mass, and physical activity) has on one another. That is, a few reports (27,42) have begun to recognize, e.g., that physical activity and body mass may differentially influence cognition within the same sample. However, future efforts should be directed toward the examination of energy consumption, storage, and expenditure to more completely determine the role of lifestyle and physical health factors on cognitive health and function.

Conclusion

In conclusion, researchers have begun to understand the relation of energy balance to brain health, cognition, and scholastic performance. The under- and overconsumption of energy and excess body mass have been linked to deficits in academic achievement in school age children as well as greater decay of brain structure and function during aging. However, physical activity and fitness, associated with an increase in energy expenditure, demonstrated a beneficial relation to cognitive and brain health and better performance on measures of scholastic performance in children. Accordingly, the literature reviewed in this article as a whole indicates that energy balance may be important for enhancing not only physical health but also the requisite cognitive health necessary to meet scholastic challenges and maintain optimal cognitive function throughout the human lifespan.

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T.B and C.H analyzed the data; C.H. wrote the paper. Both authors had primary responsibility for final content. Both authors read and approved the final manuscript.

Literature Cited

1. Ludwig DS. Childhood obesity: the shape of things to come. N Engl J Med. 2007;357:2325–7.
2. CDC. National Center for Health Statistics. Prevalence of overweight among children and adolescents: United States, 2003–2004 [cited 2011 Feb 8]. Available from: http://www.cdc.gov/nchs/data/hestat/overweight/overweight_child_03.htm.
3. Ogden CL, Carroll MD, Curtin LR, McDowell MA, Tabak CJ, Flegal KM. Prevalence of overweight and obesity in the United States, 1999–2004. JAMA. 2006;295:1549–55.
4. Department of Health and Human Services and Department of Education. Promoting better health for young people through physical activity and sports. A Report to the President from the Secretary of Health and Human Services and the Secretary of Education. Silver Spring (MD): CDC; 2000.
5. Vaynman S, Gomez-Pinilla F. Revenge of the "sit": how lifestyle impacts neuronal and cognitive health through molecular systems that interface energy metabolism with neuronal plasticity. J Neurosci Res. 2006;84: 699–715.
6. Health and Human Services. Healthy people 2010. 2nd ed. With understanding and improving health and objectives for improving health. U.S. Department of Health and Human Services. Physical Activity and Health: A Report of the Surgeon General. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, 1996.
7. Hillman CH, Erickson KI, Kramer AF. Be smart, exercise your heart: exercise effects on brain and cognition. Nat Rev Neurosci. 2008;9: 58–65.
8. Vadiveloo M, Zhu L, Quatromoni PA. Diet and physical activity patterns of school-aged children. J Am Diet Assoc. 2009;109:145–51.
9. Interagency Board for Nutrition Monitoring and Related Research. Third report on nutrition monitoring in the United States: executive summary. U.S. Department of Health and Human Services. Physical Activity and Health: A Report of the Surgeon General. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, 1996.
10. Department of Health and Human Services and USDA. Dietary guidelines for Americans. 2005 [cited 2011 Feb 8]. Available from: http://www.health.gov/dietaryguidelines/dga2005/document/default.htm. Accessed February 8, 2011.
11. CDC. Morbidity and mortality weekly report: youth risk behavior surveillance United States, 2007 [cited 2011 Feb 8]. Available from: http://www.cdc.gov/mmwr/preview/mmwrhtml/ss5704a1.htm. Accessed February 8, 2011.
12. United States Department of Health and Human Services. 2008 physical activity guidelines for Americans. 2008 [cited 2011 Feb 8]. Available from: http://www.health.gov/paguidelines/guidelines/default.aspx. Accessed February 8, 2011.
13. Strong WB, Malina RM, Blimkie CJR, Daniels SR, Dishman RK, Gutin B, Hergenroeder AC, Must A, Nixon PA, et al. Evidence based physical activity for school-age youth. J Pediatr. 2005;146:732–7.
14. Roberts DF, Foehr UG, Rideout VJ. Generation M: media in the lives of 8–18 year olds. Menlo Park (CA): Kaiser Family Foundation; 2005.

15. Gentile D. Pathological video-game use among youth ages 8 to 18. Psychol Sci. 2009;20:594–602.
16. Hancox RJ, Milne BJ, Poulton R. Association between child and adolescent television viewing and adult health: a longitudinal birth cohort study. Lancet. 2004;364:257–62.
17. Donnelly JE, Greene JL, Gibson CA, Smith BK, Washburn RA, Sullivan DK, DuBose K, Mayo MS, Schmelzle KH, et al. Physical activity across the curriculum (PAAC): a randomized controlled trial to promote physical activity and diminish overweight and obesity in elementary school children. Prev Med. 2009;49:336–41.
18. Tomporowski PD, Davis CL, Miller PH, Naglieri JA. Exercise and children's intelligence, cognition, and academic achievement. Educ Psychol Rev. 2008;20:111–31.
19. Freeman HE, Klein RE, Kagan J, Yarbrough C. Relations between nutrition and cognition in rural Guatemala. Am J Public Health. 1977;67:233–9.
20. Pollitt E, Lewis NL, Garza C, Shulman RJ. Fasting and cognitive function. J Psychiat Res. 1982–1983;17:169–74.
21. Craig A, Richardson E. Effects of experimental and habitual lunch-size on performance, arousal, hunger and mood. Int Arch Occup Environ Health. 1989;61:313–9.
22. Alaimo K, Olson CM, Frongillo EA Jr. Food insufficiency and American school-aged children's cognitive, academic, and psychosocial development. Pediatrics. 2001;108:44–53.
23. Vaynman S, Ying Z, Wu A, Gomez-Pinilla F. Coupling energy metabolism with a mechanism to support brain-derived neurotrophic factor-mediated synaptic plasticity. Neuroscience. 2006;139:1221–34.
24. Wu A, Ying Z, Gomez-Pinilla F. The interplay between oxidative stress and brain-derived neurotrophic factor modulates the outcome of a saturated fat diet on synaptic plasticity and cognition. Eur J Neurosci. 2004;19:1699–707.
25. Taras H, Potts-Datema W. Obesity and student performance at school. J Sch Health. 2005;75:291–5.
26. Campos ALR, Sigulem DM, Moraes DEB, Escrivao AMS, Fisberg M. [Intelligent quotient of obese children and adolescents by the Weschler scale]. Rev Saude Publica. 1996;30:85–90.
27. Datar A, Sturm R, Magnabosco JL. Childhood overweight and academic performance: national study of kindergartners and first-graders. Obes Res. 2004;12:58–68.
28. Judge S, Jahns L. Association of overweight with academic performance and social and behavioral problems: an update from the early childhood longitudinal study: research article. J Sch Health. 2007;77:672–8.
29. Datar A, Sturm R. Childhood overweight and elementary school outcomes. Int J Obes (Lond). 2006;30:1449–60.
30. Falkner NH, Neumark-Sztainer D, Story M, Jeffery RW, Beuhring T, Resnick MD. Social, educational, and psychological correlates of weight status in adolescents. Obes Res. 2001;9:32–42.
31. Sargent JD, Blanchflower DG. Obesity and stature in adolescence and earnings in young adulthood: analysis of a British birth cohort. Arch Pediatr Adolesc Med. 1994;148:681–7.
32. Jeong S-K, Nam H-S, Son M-H, Son E-J, Cho K-H. Interactive effect of obesity indexes on cognition. Dement Geriatr Cogn Disord. 2005;19:91–6.
33. Sabia S, Kivimaki M, Shipley MJ, Marmot MG, Singh-Manoux A. Body mass index over the adult life course and cognition in late midlife: The Whitehall II Cohort Study. Am J Clin Nutr. 2009;89:601–7.
34. Cournot M, Marquie JC, Ansiau D, Martinaud C, Fonds H, Ferrieres J, Ruidavets JB. Relation between body mass index and cognitive function in healthy middle-aged men and women. Neurology. 2006;67:1208–14.
35. Raji CA, Ho AJ, Parikshak NN, Becker JT, Lopez OL, Kuller LH, Hua X, Leow AD, Toga AW, et al. Brain structure and obesity. Hum Brain Mapp. 2010;31:353–64.
36. Colcombe SJ, Kramer AF, Erickson KI, Scalf P, McAuley E, Cohen NJ, Webb A, Jerome GJ, Marquez DX, et al. Cardiovascular fitness, cortical plasticity, and aging. Proc Natl Acad Sci USA. 2004;101:3316–21.
37. Erickson KI, Prakash RS, Voss MW, Chaddock L, Hu L, Morris KS, White SM, Wojcicki TR, McAuley E, et al. Aerobic fitness is associated with hippocampal volume in elderly humans. Hippocampus. 2009;19:1030–9.
38. Castelli DM, Hillman CH. Physical activity, cognition, and school performance: from neurons to neighborhoods. In: Meyer A, Gullotta T, editors. Physical activity as intervention: application to depression, obesity, drug use, and beyond, 2011 In press.
39. Trudeau F, Shephard RJ. Physical education, school physical activity, school sports and academic performance. Int J Behav Nutr Phys Act. 2008;5:10.
40. Grissom JB. Physical fitness and academic achievement. J Exerc Physiol. 2005;8:11–25.
41. Carlson SA, Fulton JE, Lee SM, Maynard LM, Brown DR, Khol HW III, Dietz WH. Physical education and academic achievement in elementary school: data from the early childhood longitudinal study. Am J Public Health. 2008;98:721–7.
42. Castelli DM, Hillman CH, Buck SM, Erwin HE. Physical fitness and academic achievement in 3rd and 5th grade students. J Sport Exerc Psychol. 2007;29:239–52.
43. Chomitz VR, Slinging MM, McGowan RJ, Mitchell SE, Dawson GF, Hacker KA. Is there a relationship between physical fitness and academic achievement? Positive results from public school children in the Northeastern United States. J Sch Health. 2009;79:30–7.
44. Coe DP, Pivarnik JM, Womack CJ, Reeves MJ, Malina RM. Effect of physical education and activity levels on academic achievement in children. Med Sci Sports Exerc. 2006;38:1515–9.
45. Ahamed Y, MacDonald H, Reed K, Naylor P-J, Lui-Ambrose T, McKay H. School-based physical activity does not compromise children's academic performance. Med Sci Sports Exerc. 2007;39:371–6.
46. Mahar MT, Murphy SK, Rowe DA, Golden J, Shields AT, Raedeke TD. Effects of a classroom-based program on physical activity and on-task behavior. Med Sci Sports Exerc. 2006;38:2086–94.
47. Budde H, Voelcker-Rehage C, Pietraßyk-Kendziorra S, Ribeiro P, Tidow G. Acute coordinative exercise improves attentional performance in adolescents. Neurosci Lett. 2008;441:219–23.
48. Hillman CH, Pontifex MB, Thermanson JR. Acute aerobic exercise effects on event-related brain potentials. In: McMorris T, Tomporowski PD, Audiffren M, editors. Exercise and cognition. Indianapolis: Wiley Publications; 2009. p.163–80.