2016

The (possibly negative) effects of physical activity on executive functions: Implications of the changing metabolic costs of brain development

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Background: An area of growth in physical activity research has involved investigating effects of physical activity on children's executive functions. Many of these efforts seek to increase the energy expenditure of young children as a healthy and low-cost way to affect physical, health, and cognitive outcomes. Methods: We review theory and research from neuroscience and evolutionary biology, which suggest that interventions seeking to increase the energy expenditure of young children must also consider the energetic trade-offs that occur to accommodate changing metabolic costs of brain development. Results: According to Life History Theory, and supported by recent evidence, the high relative energy-cost of early brain development requires that other energy-demanding functions of development (ie, physical growth, activity) be curtailed. This is important for interventions seeking to dramatically increase the energy expenditure of young children who have little excess energy available, with potentially negative cognitive consequences. Less energy-demanding physical activities, in contrast, may yield psychosocial and cognitive benefits while not overburdening an underweight child's already scarce energy supply. Conclusions: While further research is required to establish the extent to which increases in energy-demanding physical activities may compromise or displace energy available for brain development, we argue that action cannot await these findings.

Keywords

physical, development, effects, (possibly, executive, functions:, implications, changing, metabolic, costs, brain, negative), activity

Disciplines

Education | Social and Behavioral Sciences

Publication Details

Howard, S. J., Cook, C. J., Said-Mohamed, R., Norris, S. A. & Draper, C. E. (2016). The (possibly negative) effects of physical activity on executive functions: Implications of the changing metabolic costs of brain development. Journal of Physical Activity and Health, 13 (9), 1017-1022.

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Manuscript Type: Review

Keywords: nutrition; neuroscience; psychology; risks of exercise; youth

Abstract Word Count: 200 words

Manuscript Word Count (Text + References): 4,667 words

Date of Revised Manuscript Submission: 1 March 2016

Abstract

Background: An area of growth in physical activity research has involved investigating effects of physical activity on children's executive functions. Many of these efforts seek to increase the energy expenditure of young children as a healthy and low-cost way to affect physical, health, and cognitive outcomes. *Methods*: We review theory and research from neuroscience and evolutionary biology, which suggest that interventions seeking to increase the energy expenditure of young children must also consider the energetic trade-offs that occur to accommodate changing metabolic costs of brain development. *Results:* According to Life History Theory, and supported by recent evidence, the high relative energy-cost of early brain development requires that other energy-demanding functions of development (i.e., physical growth, activity) be curtailed. This is important for interventions seeking to dramatically increase the energy expenditure of young children who have little excess energy available, with potentially negative cognitive consequences. Less energy-demanding physical activities, in contrast, may yield psychosocial and cognitive benefits while not overburdening an underweight child's already scarce energy supply. *Conclusions:* While further research is required to establish the extent to which increases in energy-demanding physical activities may compromise or displace energy available for brain development, we argue that action cannot await these findings.

The (Possibly Negative) Effects of Physical Activity on Executive Functions: Implications of the Changing Metabolic Costs of Brain Development

An area of recent growth in physical activity research has involved investigating the effects of physical activity not just on physical (e.g., motor development) and health outcomes (e.g., body composition), but also cognitive outcomes in children. Particular interest has been directed toward executive functions (EFs), given mounting evidence for their relation to: (i) school readiness, academic learning, and success (e.g., literacy, numeracy, learning more broadly)[1,2]; (ii) social and emotional outcomes (e.g., theory of mind, moral conduct)[3]; and (iii) developmental disorders (e.g., ADHD)[4]. EFs refer to cognitive control processes that allow individuals to activate, maintain, and manipulate information in mind (working memory), resist task-irrelevant impulses and distractions (inhibition), and flexibly shift attention between tasks, rules, or requirements (shifting). EFs thus represent an interesting target for intervention in childhood, given that early EF development appears to set the stage for a broad range of later outcomes.

Whereas recent attempts to support and enhance EFs by development researchers have often involved computerized 'brain training' programs (which now constitutes a more than $1 billion industry)[5], physical activity researchers have sought to evaluate whether, and under what conditions, engaging in physical activity might support the development of EFs. It is postulated that physical activities serve to engage and extend higher-order cognition through their physiological, morphological, and neurochemical effects on the brain.[6] Research in this area has increasingly focused on the early years of life, as intervening in these formative years may generate a more stable and lasting change.[7] If a cause and effect relationship exists, according to this line of reasoning, physical activity may thus represent a healthy and low-cost way to – at least indirectly – affect a range of outcomes that extend beyond those already well established in the physical activity literature (e.g., cardiovascular health and academic achievement).[8-10]

Research in this area, however, has found at best mixed results. Some studies have shown a modest improvement in EFs after either acute aerobic exercise[11] or chronic aerobic exercise.[12] Yet two separate meta-analyses have indicated little to no effect of aerobic activity on subsequent executive functioning.[13,14] There has been a similar lack of consistent success with resistance training interventions.[15] Despite these findings, promising results have been shown with martial arts,[16] yoga,[17] and some other sports,[18] which have yielded moderate effects on EFs and/or EF-related abilities. On this basis, it has been suggested that *what* is done during physical activity (i.e., physical activity that provides opportunity to engage and challenge EFs) may be the most important factor contributing to group-level effects of physical activity on EFs.[6,19] In fact, Best states in his critical review, "cognitively-engaging exercise appears to have a stronger effect than non-engaging exercise on children's executive function" (p. 331).[6] He further asserts that efforts to understand the link between physical activity and cognition are worthwhile, given the importance of physical activity for the developing mind.

What may be overlooked in this emerging line of research, however, are the individual or sub-group level effects of physical activity on EFs and cognitive development more broadly. On the one hand, there are known health benefits of physical activity (e.g., obesity prevention, gross motor competence, positive psychosocial and health outcomes).[20-23] Also well established are the negative consequences of unhealthy weight status[24,25] and sedentary behaviour in childhood (e.g., overweight, unfavourable psychosocial health and cognitive outcomes).[26-29] Yet insights from neuroscience (PET and MRI data)[30] and evolutionary biology (Life History Theory applied to humans)[31] suggest the need to consider the impact of the metabolic costs of physical activity in terms of energy expenditure across different stages of life and individuals' metabolic conditions.

The Changing Metabolic Costs of Brain Development

Life History Theory (LHT), which is derived from evolutionary biology and ecology,[31] seeks to explain the processes, timing, and evolutionary forces that shape the timing and form of life events (e.g., early development, maturation, fertility, mortality).[32] More specifically, LHT proposes that survival requires the 'capture' of resources (e.g., energy) from the environment and subsequent 'allocation' of resources (e.g., energy, time) to activities that are essential to maximize fitness (i.e., reproduction and survival). Given that resources available to an individual are finite (often termed an 'energy budget' in the case of energy resources),[32] allocation of energy thus must involve trade-offs with other energy-expending pursuits. This notion of functional trade-offs to accommodate our finite energy budget is supported by evidence that energy expenditure scales closely to body mass,[33] which suggests a ceiling on the typical energy expenditure for a given body size. While evidence shows humans to have a low energy budget relative to their body mass index, compared to other placental animals, it is notable that this overall energy budget appears to be largely unaffected by physical activity levels or energy input[34] (and instead may relate to increased investment in brain structures).

LHT further posits that the allocation of energy and time changes with life history stages (in infancy more energy is allocated to physical and brain growth, whereas in adolescence the energy is more often allocated to reproduction) and circumstances (i.e., ecological factors, health, and social context).[35,36] In humans, LHT suggests that resources can be allocated to three fundamental functions: maintenance, growth, and reproduction.[36] According to the principle of allocation, trade-offs are expected between these functions such that greater resource allocation to one function depletes the resources available for another function.

Particularly relevant to infant, child, and adolescent development are the energetic trade-offs that must occur to ensure physical growth, brain development, the learning of complex cultural practices, and mastery of energy acquisition skills. While it is clear that the pre-adult life-stage is unusually long by primate standards,[37] such that a sizeable proportion of pre-adult growth does not occur until adolescence,[38] less clear are the evolutionary reasons for such a protracted developmental phase.[30] From a life history theory perspective, it has been suggested that the high relative energy-cost of brain development requires that other energy-demanding functions of development be curtailed.[32,39,40]

In line with this assertion, research by Kuzawa et al. suggests that, in early childhood, a down-regulation in energy devoted to physical growth (e.g., body weight) coincides with an increase in the energy demands for brain development.[30] Specifically, using pooled PET and MRI data the researchers found an average pattern that, beginning at around 6 months of age, steady increases in brain glucose demands were accompanied by proportional decreases in body-weight growth. In contrast to previous suggestions of peak brain energy costs at birth,[41] Kuzawa and colleagues found that the glucose demands of the brain peaked at around 4.3 years of age – accounting for approximately 65% of resting metabolic rates and 43% of daily energy requirements – which co-occurred with a low point in body-growth energy demands. After this age, gradual physical growth (i.e., height, weight) was accompanied by decreases in brain energy demands, as both converged toward adult levels.[30]

In light of these findings, Kuzawa et al. propose that, in humans, physical growth and activity may be attenuated in the early years to increase the energy available for brain development.[30] For typically developing children, Kuzawa et al.'s assertion receives support from studies on primates and other non-human animals showing investment in locomotor play carried "sizeable costs" to physical growth[42,43], as well as longitudinal human research suggesting physical activity levels may decrease across the preschool years[44] as children approach the peak in brain glucose demands. Reasons for this physical activity decline are likely complex and multi-factorial, however, as illustrated by evidence of a continued decline in physical activity after brain energy demands begin to decrease.[45] Nevertheless, this decrease in physical activity levels coinciding with increasing brain glucose demands suggests a potential compensatory relationship. If true, attenuation of physical-activity-based energy expenditure in the early years may be especially pronounced in children who are already energy-deficient.

Evidence suggesting a more pronounced decline in physical activity levels amongst malnourished children is mixed, however, and is exacerbated by the different aspects of malnourishment that have been used to characterize children in these studies (e.g. underweight, stunting, wasting). Furthermore, some studies have compared undernourished and adequately nourished children in terms of physical activity *abilities*, such as gross motor skills and fitness, and have often found more similarities than differences. For instance, a study in India with children (5-10 years old) with chronic protein energy malnutrition found that malnourished and adequately nourished children were comparable in their motor speed and coordination.[46] Similarly, a South African study showed similarities in fitness between undernourished and adequately nourished children (7-14 years), with undernourished children actually performing better on some of the parameters, including a 1600m run.[47]

In contrast, studies that have found associations between malnutrition and free-living physical activity *levels* have more commonly found that underweight children are less likely to engage in physical activity[48] and that stunted children have lower levels of physical activity and activity-based energy expenditure.[49,50] Although studies have not always found this decrement in physical activity levels in undernourished and stunted children,[51-53] these contradictory findings could be a product of differing home contexts (e.g., differences in free living or habitual physical activity, such as household chores or activities). While this issue is currently speculative and undoubtedly requires further study, such as whether, how and under what conditions the patterns identified by Kuzawa et al.[30] might result in individual-level trends, it can be argued that action cannot await these findings. That is, if at least some of this decrement in early childhood physical activity is due to the brain's increased energy requirements, this suggests that interventions seeking to dramatically increase the energy expenditure of young children who have little excess energy available (e.g., underweight or undernourished children) could have negative, rather than positive, cognitive consequences.

Physical Activity and Malnutrition

Undernutrition includes underweight (weight-for-age < -2SD), stunting (height-for-age < -2SD), wasting (weight-for-height < -2SD), and thinness (BMI-for-age < -2SD).[54] Global prevalence of underweight and stunting in young children has decreased since 1990 (from 25% and 40% to 16% and 26%, respectively, in 2011).[55] Yet these statistics highlight that undernourished children should also be considered when planning early physical activity interventions, particularly in developing nations (where 17.4% of young children are estimated as underweight), and to a lesser extent in developed nations (in which 2.4% of young children are estimated to be underweight).[55] That is, if the functional energetic trade-off hypothesis is accurate, there may be potential cognitive repercussions of interventions that aim to significantly increase energy expenditure in children with already low 'energy budgets' (underweight, undernourished), which may divert energy away from brain development functions. This would be particularly problematic given that many of these energy-deficient children are found in disadvantaged circumstances, with already impaired cognitive development (including EFs) as a result of chronic nutrition deficits in early life.[46,56,57]

This hypothesis does not suggest that physical activity should be curtailed in the early years or that efforts to increase physical activity in this age group are not worthwhile. Rather, the logical extension of these ideas would suggest that these efforts should carefully consider the unique (and possibly different) needs of the children being targeted. To illustrate, low- and middle-income countries including South Africa,[58] India,[59] and Brazil[60] face a double burden of over- and under-nutrition. These burdens can occur within the same community, as both under- and over-nutrition are associated with social and economic inequalities.[58,61] In settings such as these, it is therefore essential to promote physical activity as a means of preventing and/or managing overweight and obesity in early childhood and later life. At the same time, it is also important to understand the potential physiological consequences of promoting dramatic energy expenditure increases with early childhood populations in which under-nutrition is more prevalent.

Thus far most early childhood physical activity interventions have not differentiated their approach based on weight status. Instead, studies have tended to introduce a general increase in children's energy expenditure and examine its associated group-level physical benefits.[62-68] Further, in such studies participants' weight status (underweight, normal weight, overweight, obese) is rarely reported, thus making it difficult to estimate the impacts of the intervention on underweight and undernourished children. Instead, participants' body composition is more commonly measured as just one component of an outcome measure such as body mass index (BMI),[64,69,70] weight-for-height z-score,[64] or is used as a variable to evaluate initial group equivalence.[62,63,71] The one identified study reporting weight status of the preschool children involved in a physical activity intervention included the expected proportion of children classified as underweight (2.2%).[72] It therefore can be expected that other studies may have also included children that have differing 'energy budgets' from their normal and overweight peers, yet the intervention has uniformly sought to increase their energy expenditure through physical activity.

This appears to be an under-investigated issue, however, with no literature found on physical activity interventions specifically targeting undernourished children and/or looking at the *cognitive effects* of increasing physical activity for undernourished, young children. That is, of the studies that do collect cognitive data from children (generally older) after a physical activity intervention,[11,73,74] few report BMI, and none that could be found looked at the cognitive effects of physical activity for undernourished children. It is important to note that the evidence-based energetic trade-off hypothesis *does not* suggest that physical activity should be discouraged or curtailed in underweight children, or that attempts to promote physical activity in these groups should be avoided. Rather, in such cases physical activity may still play an important role in early development. Yet, according to this hypothesis, the means of intervention must be carefully considered and the approach taken may necessarily require a departure from simply increasing the energy expenditure of these children through energy-demanding physical activity. Less energy-demanding physical activities–for example, those that emphasize gross motor development–may yield important psychosocial[75-77] and cognitive benefits,[78] while not overburdening an underweight child's already scarce supply of energy. Where possible, it may be beneficial for these initiatives to also be accompanied by nutrition interventions for children with low energy budgets, considering the negative effect of poor nutrition on cognitive development.[46,57]

Conclusions and Future Directions

The implications of the changing metabolic costs of brain development–specifically the down-regulation of energy for physical growth and concomitant up-regulation of energy allocated to brain development in the early years–is an important but under-investigated area. For instance, further research is required to establish the extent to which increases in energy-demanding physical activities may compromise or displace the energy available for human brain development and the extent to which this manifests at the individual level. For instance, the relatively low energy expenditure of humans relative to body mass[34] could be posited as a potential mechanism that could at least partially buffer against this energetic trade-off issue. This possibility appears unlikely, however, in light of available human and primate research. Research with Assamese macaques is at least suggestive in this regard, showing that energy-intensive physical activity may reduce the energy available for physical growth (contrary to previous theorizing that only surplus energy would be used).[42] Alternatively, rather than a direct cause and effect relationship, there may be a set of common factors that negatively impact early physical activity and cognitive development. These may include poor- or under-nutrition, psychosocial stressors, or other factors associated with socioeconomic deprivation.[79,80] As such, future research should seek to further understand how changing metabolic costs, brain development, and physical activity interact over the course of development (and especially in the preschool years). This may involve research investigating the association between body composition (e.g., lean and fat mass) and aspects of physical activity (e.g., intensity, type, dose, patterns) in settings in transition where malnutrition is more prevalent. While there has begun empirical research into these questions in disadvantaged areas of South Africa, early presentation of the energetic trade-off hypothesis serves as: (a) a theoretical basis from which to contextualize this empirical data; (b) a prompt for physical activity researchers to consider these hypotheses in their research, in advance of these initial empirical findings; and (c) a stimulus for international evaluations of this hypothesis using existing and new datasets (to expedite replications that otherwise would await publication of initial empirical data). Even in the absence of this empirical work, there is a plausible hypothesis that suggests physical activity initiatives in the early years should consider the varied energy budgets and nutrition needs of children to optimize both group- and individual-level outcomes.

Funding

Support for this paper was provided by the DST/NRF Centre of Excellence in Human Development.

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