MONOGRAPHS OF THE SOCIETY FOR RESEARCH IN CHILD DEVELOPMENT

I. AN INTRODUCTION TO THE RELATION OF PHYSICAL ACTIVITY TO COGNITIVE AND BRAIN HEALTH, AND SCHOLASTIC ACHIEVEMENT

Charles H. Hillman

ABSTRACT The current pandemic of physical inactivity threatens both physical and cognitive health throughout the lifespan. This monograph describes the multidisciplinary study of aspects of childhood health and its relationship to cognitive and brain function, and scholastic performance. Specifically, we focus on physical activity and physical fitness along with nutrition and obesity; interconnected aspects of health that have declined over the past 30 years in children of industrialized nations. Although much emphasis has been placed on correcting physical aspects of these public health concerns, it is only more recently that attention has been paid to the relation between physical health and cognitive health among school age children. The monograph begins with an overview of current behavioral trends that compete with physical activity engagement and contribute to the failure to achieve the public health recommendations for physical activity among children in the United States. Following the epidemiological overview, the relation of childhood fitness to brain structure and function is examined among children with varying fitness levels. The observed dissimilarities between higher- and lower-fit children are discussed within the context of typical brain development. To broaden the scope of research presented herein, the relation of nutrient intake—among both undernourished and well-nourished children—and obesity on cognition and brain are discussed. Next, novel empirical data are presented from a correlational study that indicates a differential relation between childhood fitness and adiposity on various aspects of cognition. In an effort to provide a more comprehensive review, a later chapter is dedicated to describing a small body of literature investigating the relation of physical activity to special populations of children, including those with learning disorders. In doing so, practical applications as well as challenges and limitations of implementing physical

Corresponding author: Charles H. Hillman, University of Illinois, 317 Louise Freer Hall, MC-052, 906 S. Goodwin Avenue, Urbana, IL 61801, email: chhillma@illinois.edu

Support from the National Institute on Child Health and Human Development (Grants HD055352, HD069381) and the National Institute of Diabetes and Digestive & Kidney Diseases (DK0850317) facilitated the writing of this chapter.

activity into the lives of children with learning disabilities are described. Finally, a detailed review and historical analysis of the relation of physical activity to scholastic performance is provided. This translational chapter provides an important application of the laboratory findings to a real world setting in which children rely upon attention, memory, and learning for scholastic success. Accordingly, this monograph is directed toward timely and important public health issues related to chronic disease prevention as a function of childhood inactivity and obesity with the goal of linking health behaviors to cognitive and brain health, and scholastic performance.

There is a pandemic of physical inactivity among today's human beings. Physical inactivity has rapidly accelerated over the last century, with recent reports forecasting that, over the next few decades, inactivity will continue to rise throughout much of the industrialized world (Ng & Popkin, 2012). Such a trend may be partially a result of our own ingenuity, having engineered physical activity out of many activities (including work, transportation, and play) in our daily lives (Vaynman & Gomez-Pinilla, 2006). For hundreds of years the human genome was selective to environmental pressures due to inconsistent access to food leading to periods of starvation, and a lifestyle that necessitated frequent bouts of physical activity (Booth & Lees, 2006). That is, physical activity was required as a function of the environmental pressures that humans faced, and our genome adapted to meet the metabolic demands necessary to support regular physical activity. By comparison, today, humans are far less active than we once were, despite the fact that we have inherited a genome that evolved to support a chronically active lifestyle. The typical lifestyle experienced today, which has obviated physical activity from our daily lives, has resulted in metabolic dysregulation leading to disorders that accompany a sedentary existence (e.g., obesity, type 2 diabetes, metabolic disorders; Booth & Lees, 2006).

Inactive lifestyles have been found to be detrimental to the health and well-being of children as well (Chapter 2), with contemporary estimates indicating that the current generation of youth will likely live shorter and less healthy lives than their parents for the first time in U.S. history (Fontaine, Redden, Wang, Westfall, & Allison, 2003; Olshansky et al., 2005). United States (U.S.) schools, which reach approximately 55.5 million children between 5 and 17 years of age (Frumkin, 2006), have contributed to the declining health of youth through the implementation of policies aimed at minimizing or replacing physical activity opportunities from the school day in an effort to increase academic performance (IOM, 2013). Unfortunately, such policies have been enacted despite an absence of empirical support. On the contrary, a growing body of empirical findings demonstrates that a greater amount of physical activity is positively related to scholastic performance (Chapter 7). More recently, findings have gone beyond simply illustrating that time spent in physical activity does not come at a cost to academic goals. Rather, growing evidence suggests that physically active children outperform their less active peers in the classroom, providing a thread between physical activity and cognitive and brain health (see Hillman, Erickson, & Kramer, 2008 for review), and suggesting that we do not need to sacrifice children's physical health to achieve academic goals (Sallis, 2010).

Based on recent discoveries, efforts have been directed toward understanding the mechanisms (Chapters 3 and 4) that support the relation of physical activity to scholastic achievement with the goal of elucidating factors that relate to the increased cognitive health and effective function across the human lifespan. The burgeoning field of epigenetics offers interesting insight into the effects of environmental substrates such as physical activity on cognitive and brain development. Although an individual's genetic makeup provides the backdrop for growth and maturation, it is experience that shapes much of the brain's development. Thus, brain development is the product of an interaction between an individual's genotype and environmental experience, beginning in early life and continuing throughout the lifespan.

During typical development, experience shapes the pruning process (i.e., a regulatory process by which changes in brain structure occur through a reduction in the number of neurons and synapses to promote greater efficiency of neural function) resulting in the strengthening of neural networks that support relevant thoughts and actions and the elimination of unnecessary or redundant connections (Shonkoff & Phillips, 2000; Taylor, 2006). Greenough and coworkers (Black & Greenough, 1986; Greenough & Black, 1992) differentiate *experience-expectant* from *experience-dependent* influences upon brain development. Experience-expectant influences are those that are typical to a species, and are required for typical nervous system organization (e.g., the visual cortex requires subjection to light and patterned visual information for normal development; Shonkoff & Phillips, 2000). Experience-dependent influences refer to nontypical environments that engender neural growth and/or the sculpting of neural networks to support idiosyncratic experience. In this manner, experience-dependent processes shape an individual's adaptations to the environment at the neural, and ultimately, the behavioral level. Accordingly, the brain responds to experiences in an adaptive manner, resulting in the efficient and effective adoption of thoughts and actions relevant to their unique interactions within their environments.

Examples of neural adaptation in response to idiosyncratic experiences have been demonstrated through neuroimaging studies of vocation (Maguire et al., 2000; Maguire, Woollett, & Spiers, 2006), music (Chan, Ho, & Cheung, 1998; Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Münte, Kohlmetz, Nager, & Altenmüller, 2001), and sport (e.g., Hatfield & Hillman, 2001), which are all activities that are characterized by consistent and repeated participation in order to acquire considerable prowess. Thus, it is reasonable to consider that consistent and repeated exposure to physically active environments or healthy patterns of nutrient intake may trigger similar experience-dependent processes that shape an individual's brain development, and ultimately, their thoughts and actions. In fact, anthropologists have posited that human evolution was shaped during our formative years as hunters (Bortz, 1985); a lifestyle that required considerable physical activity due to prolonged and pertinacious pursuit of prey in hot climates (Fialkowski, 1986). As a product of this environment, it has been speculated that human beings became specialized for (among other behaviors) endurance physical activity (Carrier, 1984), with concomitant physiological adaptations facilitating our enlarged brains (Bortz, 1985; Fialkowski, 1986). Accordingly, brain and body evolved in concert to support the demands of a lifestyle dependent upon strenuous amounts of physical activity.

Over the last two decades, a wealth of empirical data from nonhuman animal models and a variety of neuroimaging tools to applied measures of scholastic performance in the educational environment have suggested a significant relationship between markers for health behaviors (i.e., physical activity, aerobic fitness, body composition), cognition, and brain structure and function. This monograph was assembled to describe the current state of knowledge on the relationship of physical activity to cognitive and brain health during development. In constructing this monograph, literature is reviewed that describes the impact of physical activity (or physical fitness) on brain structure and function (Chapters 3 and 5), but body composition and nutrition (Chapters 4 and 5) are also touched upon due to their shared metabolic mechanisms with physical activity. Beyond sharing simply a metabolic relationship with physical activity, nutrition (Chapter 4) and body composition (Chapters 4 and 5) also appear to have independent relations with cognition, and brain structure and function. However, these literatures have only recently emerged (with the noted exception of clinical nutritional deficiencies), and thus their inclusion in the monograph is cautionary. In addition, multiple levels of analysis, from structural and functional neuroimaging tools (Chapters 3 and 5) to behavior (Chapters 2–6) and scholastic achievement (Chapter 7) are described to provide a foundation for the relation of physical activity to brain health and deliver practical, real-world evidence supporting the link between a healthy body and a healthy mind. Further, empirical data are provided (Chapter 5), which for the first time, demonstrates an independent relation between excess adiposity, aerobic fitness, and various aspects of cognition in preadolescent children. Such findings demonstrate the complexity of studying multiple health factors on brain and cognition, but provide a much-needed basis for understanding the relation of both ends of the metabolic spectrum with cognitive and brain health.

Overall, this monograph is directed toward timely and important public health issues related to chronic disease prevention as a function of childhood inactivity and overweight and obesity. The chapters appearing here link these pervasive societal issues with brain health and cognition, and have implications for the educational environment and the context of learning. The overarching goal of this program of research is to provide an empirical basis for improving the physical health of individuals during their developmental years in order to maximize brain health and learning, which in turn stands to improve cognitive health and effective function across the lifespan.

REFERENCES

Black, J. E., & Greenough, W. T. (1986). Induction of pattern in neural structure by experience: Implications for cognitive development. In M. E. Lamb, A. L. Brown, & B. Rogott (Eds.), *Advances in developmental psychology* (Vol. 4, pp. 1–50). Hillsdale, NJ: Lawrence Erlbaum.

Booth, F. W., & Lees, S. J. (2006). Physically active subjects should be the control group. *Medicine & Science in Sports & Exercise*, **38**, 405–406.

Bortz, W. M., II. (1985). Physical exercise as an evolutionary force. *Journal of Human Evolution*, **14**, 145–155.

Carrier, D. R. (1984). The energetic paradox of human running and hominid evolution. *Current Anthropology*, **25**, 483–495.

Chan, A. S., Ho, Y., & Cheung, M. (1998). Music training improves verbal memory. *Nature*, **396**, 128.

Elbert, T., Pantev, C., Weinbruch, C., Rockstroh, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science*, **270**, 305–307.

Fialkowski, K. R. (1986). A mechanism for the origin of the human brain: A hypothesis. *Current Anthropology*, **27**, 288–290.

Fontaine, K. R., Redden, D. T., Wang, C., Westfall, A. O., & Allison, D. B. (2003). Years of life lost due to obesity. *The Journal of the American Medical Association*, **289**, 187–193.

Frumkin, H. (2006). Introduction: Safe and healthy school environments. In H. Frumkin, R. J. Geller, I. L. Rubin, & J. Nodvin (Eds.), *Safe and healthy school environments* (pp. 3–10). New York: Oxford University Press.

Greenough, W., & Black, J. (1992). Induction of brain structure by experience: Substrate for cognitive development. In M. R. Gunnar & C. A. Nelson (Eds.), *Minnesota symposia on child psychology 24: Developmental behavioral neuroscience* (pp. 155–200). Hillsdale, NJ: Lawrence Erlbaum.

Hatfield, B. D., & Hillman, C. H. (2001). The psychophysiology of sport: A mechanistic understanding of the psychology of superior performance. In R. N. Singer, H. A. Hausenblaus, & C. M. Janelle (Eds.), *The handbook of research on sport psychology* (2nd ed., pp. 362–386). New York, NY: John Wiley.

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience*, **9**, 58–65.

Institute of Medicine (IOM). (2013). *Educating the student body: Taking physical activity and physical education to school.* Washington, DC: National Academies Press.

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences of the United States of America*, **97**, 4398–4403.

Maguire, E. A., Woollett, K., & Spiers, H. J. (2006). London taxi drivers and bus drivers: A structural MRI and neuropsychological analysis. *Hippocampus*, **16**, 1091–1101.

Münte, T. F., Kohlmetz, C., Nager, W., & Altenmüller, E. (2001). Superior auditory spatial tuning in conductors. *Nature*, **409**, 580.

Ng, S. W., & Popkin, B. M. (2012). Monitoring food and nutrients sold and consumed in the United States: Dynamics and challenges. *Journal of the Academy of Nutrition and Dietetics*, **112**, 41–445.

Olshansky, S. J., Passaro, D. J., Hershow, R. C., Layden, J., Carnes, B. A., Brody, J., Hayflick, L., Butler, R. N., Allison, D. B., & Ludwig, D. S. (2005). A potential decline in life expectancy in the United States in the 21st century. *The New England Journal of Medicine*, **352**, 1138–1145.

Sallis, J. F. (2010). We do not need to sacrifice children's health to achieve academic goals. *Journal of Pediatrics*, **156**, 696–697.

Shonkoff, J., & Phillips, D. (2000). *From neurons to neighborhoods: The science of early childhood development* (pp. 182–217). Washington, DC: National Academy Press.

Taylor, M. J. (2006). Neural bases of cognitive development. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 15–26). Oxford, UK: Oxford University Press.

Vaynman, S., & Gomez-Pinilla, F. (2006). Revenge of the "Sit": How lifestyle impacts neuronal and cognitive health through molecular systems that interface energy metabolism with neuronal plasticity. *Journal of Neuroscience Research*, **84**, 699–715.