Aerobic Fitness and Executive Control of Relational Memory in Preadolescent Children

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ABSTRACT

CHADDOCK, L., C. H. HILLMAN, S. M. BUCK, and N. J. COHEN. Aerobic Fitness and Executive Control of Relational Memory in Preadolescent Children. *Med. Sci. Sports Exerc.*, Vol. 43, No. 2, pp. 344–349, 2011. **Purpose**: The neurocognitive benefits of an active lifestyle in childhood have public health and educational implications, especially as children in today's technological society are becoming increasingly overweight, unhealthy, and unfit. Human and animal studies show that aerobic exercise affects both prefrontal executive control and hippocampal function. This investigation attempts to bridge these research threads by using a cognitive task to examine the relationship between aerobic fitness and executive control of relational memory in preadolescent 9- and 10-yr-old children. **Method**: Higher-fit and lower-fit children studied faces and houses under individual item (i.e., nonrelational) and relational encoding conditions, and the children were subsequently tested with recognition memory trials consisting of previously studied pairs and pairs of completely new items. With each subject participating in both item and relational encoding conditions, and with recognition test trials amenable to the use of both item and relational memory cues, this task afforded a challenge to the flexible use of memory, specifically in the use of appropriate encoding and retrieval strategies. Hence, the task provided a test of both executive control and memory processes. **Results**: Lower-fit children showed poorer recognition memory performance than higher-fit children, selectively in the relational encoding condition. No association between aerobic fitness and recognition performance was found for faces and houses studied as individual items (i.e., nonrelationally). **Conclusions**: The findings implicate childhood aerobic fitness as a factor in the ability to use effective encoding and retrieval executive control processes for relational memory material and, possibly, in the strategic engagement of prefrontal- and hippocampal-dependent systems. **Key Words:** COGNITION, DEVELOPMENT, EXERCISE, RECOGNITION, PHYSICAL ACTIVITY

Aerobic exercise has been shown to affect brain and cognitive health, particularly because it relates to the functions of the prefrontal cortex and the hippocampus (24). Whereas studies in humans have focused predominantly, but not exclusively, on the relation of aerobic fitness and physical activity to executive control functions mediated by a neural network involving prefrontal structures (5,10,11,16,22,24,26), nonhuman animal research focuses largely on the link between aerobic exercise and memory abilities supported by the hippocampus (13,18,19,27,29,37–39).

The literature on human neurocognitive function has revealed that physical activity and aerobic fitness can affect the brain and cognition across the life span (24). Most investigations have linked low aerobic fitness levels to impaired executive function in older adults (10–12,17,26). However, there is an emerging literature indicating that physical inactivity and low levels of aerobic fitness can also impair executive control functions, including selective attention, response inhibition, and interference control in children (5,6,22–24,33). The present investigation is aimed specifically at the effects of fitness in preadolescents to add to the growing database of studies about aerobic fitness and childhood cognition, given the importance of cognitive health for scholastic performance.

Animal research, operating on somewhat separate lines from the human literature, has particularly emphasized the effects of voluntary aerobic exercise on the hippocampus and related structures in the medial temporal lobe (MTL). For example, in rodent models, wheel running has been found to increase cell proliferation and survival in the dentate gyrus of the hippocampus from young adult to old age (37,38), to enhance hippocampal-dependent learning and memory processes (19,37–39), and to increase hippocampal levels of molecules involved in neuronal survival, synaptic

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development, learning, and angiogenesis, including brain-derived neurotrophic factor, insulin-like growth factor, and vascular endothelial-derived growth factor (13,27,29,39).

The present investigation attempted to bridge the human and nonhuman lines of research by examining the relation of aerobic fitness in preadolescents to the executive control of relational memory encoding and retrieval processes. These functions are presumed to be dependent on two critical brain systems. Prefrontal cortex regions are seen as critical for strategic and flexible use of executive control, including selective attention, response inhibition, and interference control functions mentioned above (10–12,22,26). The hippocampal system is critical for relational memory, that is, the ability to form representations of (or bind) relations among the constituent elements of experience, including information about the co-occurrences of people, places, and/or objects, along with their spatial and temporal contexts (8,9,15).

A behavioral paradigm was designed to recruit the cognitive processes of interest. During the task, preadolescent children studied a series of face–house pairings in each of two conditions, one with instructions to encode the faces and houses individually (or nonrelationally) and the other with instructions to encode the relations among them (i.e., relationally). These two conditions were designed to place differential demands on relational memory encoding and hence on the hippocampus (21).

Each encoding block was followed by a subsequent recognition memory test, in which half the trials were previously studied pairs and half were pairs of novel items. With each subject having to participate in both item and relational encoding conditions and with recognition test trials amenable to the use of both item and relational memory cues, this task afforded a challenge to the flexible use of appropriate memory encoding and retrieval strategies and hence to the executive control of memory processes. More specifically, although relational representations were encouraged in the relational encoding condition and were discouraged in the individual item/nonrelational encoding condition, neither encoding strategy was ideally matched to the test trials used in the two subsequent recognition tests, where both item and relational memory cues were helpful for performance. The ability to manage the different instructional demands at encoding, to engage relational memory binding processes, and to make effective use of what representations are created to handle the recognition test trials was expected to behaviorally challenge both prefrontal control and hippocampal memory processes.

The dynamic interplay between prefrontal cortex and hippocampus in successful memory is an intriguing possibility arising out of recent neuroimaging work. The activity of both prefrontal and MTL regions at the time of encoding is positively associated with subsequent memory performance (4,40). Moreover, the two systems are apparently capable of trading off dynamically. For example, college-aged students show increased MTL engagement and decreased prefrontal engagement in response to an increased working memory load for faces (31). In addition, older adults with decreased MTL activity show increased prefrontal engagement, a finding that suggests potential prefrontal compensation in an elderly population (20).

In the present experiment, it was expected that lower-fit children would have more difficulty flexibly using cognitive processes dependent on the prefrontal–hippocampal circuit and thus perform more poorly on the recognition memory tests than higher-fit children, especially for materials from the relational memory encoding condition. That is, lower-fit children were predicted to show a deficit in executive control of memory, only when items were encoded relationally rather than nonrelationally. This hypothesis is based on research that shows a negative effect of an inactive lifestyle on executive control in children (5,22,33). Furthermore, a recent study reported that lower-fit 9- and 10-yr-old preadolescents have smaller hippocampal volumes compared with higher-fit children and that smaller hippocampal volumes are associated with lower accuracy on a relational memory task (7). Hence, it is possible that lower-fit children would show impairments in the strategic and flexible use of relational memory. Results about the role of childhood fitness in the executive control of memory will provide a first step in understanding the link between dual cognitive processes that have been shown to be influenced by aerobic fitness and exercise.

METHODS

Participants. Forty-six preadolescent 9- and 10-yr-old children were recruited from a sports camp in East-Central Illinois. Children were tested on several factors that influence cognitive function and physical activity participation. To begin, the Kaufman Brief Intelligence Test (25) was administered to each child to obtain a composite intelligence quotient (IQ) score including both crystallized and fluid intelligence measures, and no scores were more than 1 SD below the mean (85%). Next, a guardian of the child completed the Attention-Deficit/Hyperactivity Disorder (ADHD) Rating Scale IV (14) to screen for the presence of attentional disorders. No child's score exceeded the 85th percentile, which would suggest the presence of ADHD. Pubertal timing was also assessed using a modified Tanner Staging System (34,35) with all included prepubescent participants at or below a score of 2 on a 5-point scale of developmental stages. In addition, socioeconomic status (SES) was determined by creating a trichotomous index based on three variables: 1) participation in a free or reduced-price lunch program at school, 2) the highest level of education obtained by the mother and father, and 3) the number of parents who worked full time (3), and this variable was taken into account in the analyses of behavioral performance.

Furthermore, eligible participants were required to (a) qualify as higher-fit or lower-fit children (see Aerobic fitness assessment section); (b) report no adverse health conditions,

TABLE 1. Participants' mean (SD) demographic and fitness data by aerobic fitness group.

Variable	Lower-Fit	Higher-Fit
n	24 (11 boys)	22 (12 boys)
Age (yr)	9.9 (0.6)	9.9 (0.5)
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})*	35.2 (4.6)	48.7 (3.6)
K-BIT[a] composite score (IQ)	112.1 (12.1)	114.3 (10.9)
Pubertal timing[b]	1.5 (0.4)	1.4 (0.5)
SES[c] (median)**	2.5 (0.7)	2.9 (0.4)
ADHD[d]	9.6 (6.4)	9.1 (5.5)

[a] Kaufman Brief Intelligence Test (25).

[b] Tanner Staging System (34,35).

[c] Birnbaum et al. (3).

[d] Scores on the ADHD Rating Scale V (14).

* Significant difference between higher-fit and lower-fit groups at $P < 0.001$.

** Significant difference between higher-fit and lower-fit groups at $P < 0.05$.

physical incapacities, or neurological disorders; (c) report no use of medications that influence central nervous system function; (d) have a corrected visual acuity of 20/20 and no color-blindness; and (e) sign an informed assent approved by the University of Illinois at Urbana-Champaign. A legal guardian also had to provide written informed consent in accordance with the institutional review board of the University of Illinois at Urbana-Champaign. Subjects were compensated \$10 per hour for study participation.

Aerobic fitness assessment. The sports camp from which subjects were recruited recommended children for study participation who were estimated to fall into higher- and lower-fitness groups based on the camp's physical fitness tests. The guardians of the recommended children were contacted to obtain additional information about each child's participation in organized athletics. Children said to participate in organized athletics four or more days per week were estimated as higher-fit participants, and children said to participate in organized athletics 1 d·wk^{-1} or less were estimated as lower-fit participants.

Aerobic fitness was measured using a maximal oxygen consumption ($\dot{V}O_{2max}$) test on a TrackMaster TMX425C motor-driven treadmill (Full Vision, Newton, KS). Expired gases were analyzed using a TrueOne2400 Metabolic Measurement System (ParMedics, Sandy, UT). Children performed a modified Balke treadmill protocol. The test began with a 3-min warm-up, during which the speed and grade were gradually increased. During the test, the beginning speed and grade were based on the participant's estimated aerobic fitness level, in accordance with the recommendations of the American College of Sports Medicine (1). Lower-fit participants began the test at a speed of 3.2 mph and a grade of 6°, and higher-fit participants began the test at a speed of 5 mph and a grade of 0°. The treadmill speed remained constant during the test, and the grade changed every 2 min, with a 2° increase for lower-fit participants and a 2.5° increase for higher-fit participants. Relative peak oxygen consumption (mL·kg^{-1}·min^{-1}) was based on a maximal effort when participants exhibited three of the following four criteria: (a) plateau in oxygen consumption, (b) HR within 10 bpm of age-predicted maximum, (c) RER ≥ 1.10, or (d) RPE on the Children's OMNI Scale ≥ 9 (36).

Final fitness group assignments (i.e., higher-fit and lower-fit) were based on whether a child's $\dot{V}O_{2max}$ value fell above the 70th percentile or below the 30th percentile according to normative data provided by Shvartz and Reibold (32). All 46 recruited preadolescent children were eligible for participation, and analyses were conducted on 22 higher-fit (12 boys) and 24 lower-fit (11 boys) children. Table 1 provides a list of demographic and fitness information for the sample.

Memory task. Participants completed a modified version of a memory task developed by Henke et al. (21) in which relational encoding elicited greater hippocampal activation than nonrelational encoding. See Figure 1 for an illustration of the stimuli and task used in this study. Participants completed four task blocks (with a 5-min rest period between blocks) in the following order: 1) nonrelational encoding, 2) recognition memory test, 3) relational encoding, and 4) recognition memory test. Each block consisted of 40 face–house pairings, each consisting of a color picture of a face (male or female) and a house (from an inside or outside perspective). Participants also completed 10 practice trials before both the nonrelational and relational encoding blocks. All study and test images were presented focally on a black background for 6000 ms, with an interstimulus interval of 6000 ms. The visual angle of the images subtended 8.6° in the vertical and 12.0° in the horizontal directions. Stimulus presentation, timing, and measurement of reaction time and response accuracy were controlled by NeuroScan Stim software (v2.0, Charlotte, NC).

Nonrelational and relational encoding conditions differed only with regard to task instructions. In the nonrelational encoding block, participants were instructed to make decisions about the presented faces and houses separately, indicating whether each face was male or female and whether each house was an inside or outside view, pressing the appropriate one of four buttons. In the relational encoding block, participants were instructed to make decisions about the faces and houses jointly, indicating whether they believed "the person is visiting the house" or "the person is an inhabitant of the house," pressing the appropriate one of two buttons. There were no right or wrong answers to participants' decisions; the task instructions were solely designed to encourage or discourage participants to create a memory representation of the relation between items.

The two recognition memory test blocks differed only with regard to whether they tested face–house pairings that had been encoded relationally or nonrelationally. On each trial, participants pressed the left button if the face–house pairing had been previously seen or the right button if it were a novel pair (i.e., new face and new house). Of the 40 trials in each recognition test, 20 were previously seen pairs and 20 were novel pairs.

Statistical analysis. First, participants' demographic variables were compared using independent *t*-tests. Then, two univariate ANCOVA were conducted to assess recognition memory performance for nonrelationally and relationally

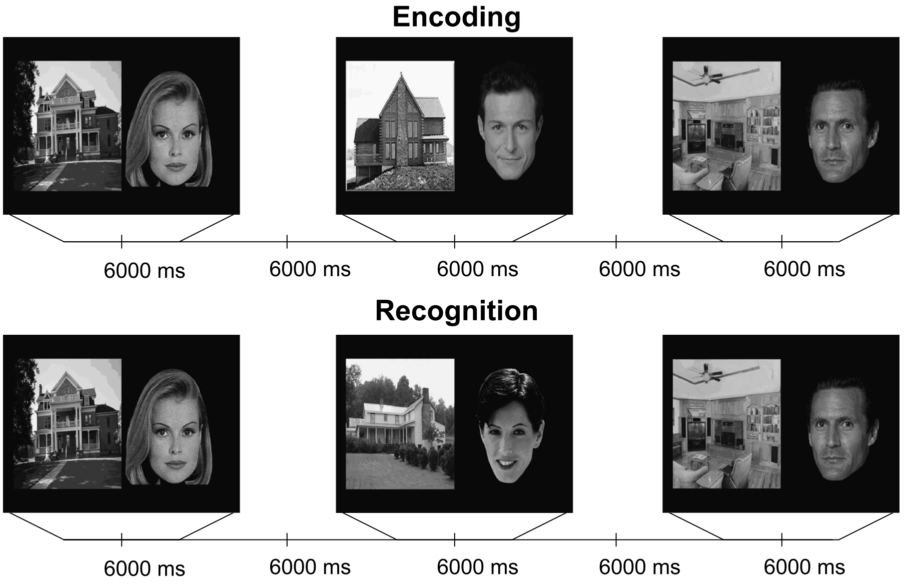

FIGURE 1—Sample encoding face–house pairs and sample recognition face–house pairs.

encoded materials as a function of aerobic fitness group, with SES as a covariate.

RESULTS

Participants' demographics. Participants' demographic and fitness data are provided in Table 1. Fitness comparisons using independent *t*-tests indicated that lower-fit participants (mean = 35.2 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, SD = 3.6 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) had significantly lower $\dot{V}O_{2\max}$ scores than higher-fit participants (mean = 48.7 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, SD = 4.6 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) ($t(44) = 11.0$, $P < 0.001$), confirming the aerobic fitness groupings. With the exception of SES, demographic variables (i.e., age, IQ, pubertal timing, ADHD) did not differ between fitness groups. Because higher-fit participants (mean = 2.9, SD = 0.4) reported greater SES than lower-fit participants (mean = 2.5, SD = 0.7) ($t(44) = 2.5$, $P < 0.05$), SES was used as a covariate in statistical analyses of the performance data.

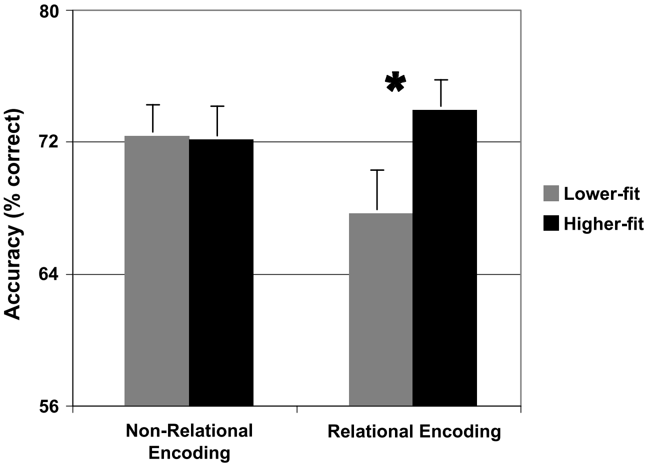

FIGURE 2—Recognition memory performance (percent correct) for nonrelational and relational encoding conditions as a function of aerobic fitness group. Error bars, SEM. *Significant difference between higher-fit and lower-fit groups at $P < 0.05$.

Aerobic fitness and nonrelational and relational memory performance. As predicted, lower-fit participants showed poorer performance than the higher-fit group, specifically for materials encoded relationally ($F(1,43) = 5.5$, $P = 0.02$, $\eta^2 = 0.113$), whereas there were no fitness-based differences in accuracy for the nonrelational memory encoding condition ($F(1,46) = 0.04$, $P = 0.85$, $\eta^2 = 0.001$; Fig. 2 and Table 2). The interaction between aerobic fitness group and encoding condition barely missed reaching significance ($F(1,43) = 3.6$, $P = 0.06$).

DISCUSSION

The current findings that children with lower aerobic fitness levels were disadvantaged in their recognition memory performance relative to higher-fit children, specifically when the to-be-remembered faces and houses were encoded relationally, confirmed our predictions. The nature of the current task placed great demands on managing the different instructional requirements at encoding, engaging relational memory binding processes, and making strategic use of relational memory

TABLE 2. Participants' mean (SD) recognition memory performance for relational and nonrelational encoding conditions by aerobic fitness group.

	Lower-Fit	Higher-Fit
Relational memory encoding		
Accuracy (percent correct)*	67.92 (11.72)	74.17 (7.53)
Hits	12.88 (3.80)	14.09 (3.41)
Misses	7.13 (3.80)	5.91 (3.41)
False alarms	5.71 (3.18)	4.86 (2.34)
Correct rejections	14.29 (3.18)	15.14 (2.34)
Nonrelational memory encoding		
Accuracy (percent correct)	72.60 (8.16)	72.39 (8.40)
Hits	11.71 (3.59)	11.41 (3.16)
Misses	7.46 (3.04)	8.59 (3.16)
False alarms	2.92 (2.34)	2.45 (2.56)
Correct rejections	16.25 (4.13)	17.55 (2.56)

* Significant difference between higher-fit and lower-fit groups at $P < 0.05$.

representations in recognition test trials amenable to the use of both relational and nonrelational/item memory cues. Hence, it is likely that both executive control and relational memory functions were required to perform the task well. The results serve to potentially link human and nonhuman animal exercise–cognition studies by suggesting that lower-fit children have more difficulty than more aerobically fit children in using executive control and relational memory processes. The behavioral methods used in this study do not permit direct conclusions about the specific neural circuitry implicated in the fitness-related findings, but neuroimaging investigations are expected to show that lower-fit children are unable to fully engage prefrontal–hippocampal circuitry.

The results add to the growing literature on the detrimental effects of low aerobic fitness levels and physical inactivity on the cognitive task performance of developing populations (5,6,22–24,33). The findings also contrast with studies used in Sibley and Etnier's (33) meta-analysis that suggested that physical activity is unrelated to memory abilities in children between the ages of 4 and 18 yr. Instead, the investigation may supplement the report indicating that higher-fit preadolescents have larger hippocampal volumes compared with lower-fit children and that hippocampal volume is related to relational memory performance (7). Given the specificity of the aerobic fitness effects in the current findings to memory performance for materials encoded relationally, it is possible that higher-fit and lower-fit children exhibit differential hippocampal volumes, which would affect relational and nonrelational memory differently. Again, further research, especially using neuroimaging techniques, is needed to directly address this claim.

Although the present study provides an additional step in understanding the relationship between fitness and childhood cognition, the use of a cross-sectional design raises the possibility that the observed fitness-related behavioral differences were caused by another factor (e.g., motivation, genes, personality characteristics, nutrition, intellectual stimulation). Randomized clinical trials are necessary to account for potential selection bias and to establish a direct relationship between aerobic fitness and the executive control of memory in children. Furthermore, methodological considerations motivated presenting the four task blocks in a fixed sequence for all participants, as in the study of Henke et al. (21), to ensure that subjects did not use a relational memory strategy during the nonrelational memory encoding condition. It is possible that part of the performance differences observed across conditions was due to fatigue, learning, or a combination of both. Future investigations may consider counterbalancing the order of the task blocks to test this idea.

The present results carry significant public health and educational implications. Children are becoming increasingly sedentary and unfit, and reports indicate that inactivity during childhood can increase the prevalence of obesity as well as several diseases and disorders throughout the life span (e.g., depression, anxiety, cardiovascular disease, colon cancer, type 2 diabetes) (2,28,30). Unfortunately, childhood inactivity continues to rise with opportunities for physical activity being reduced or eliminated in favor of academic subjects, as educators come under increased pressure to improve the scholastic performance of their pupils. The current study adds to the literature indicating that a physically inactive lifestyle may negatively affect cognitive function. Specifically, the present results raise the possibility that physical activity during childhood encourages cognitive development; hopefully, educational and health care policy leaders will consider the role of aerobic fitness in improving the cognitive potential of children.

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