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Physical Activity and Cognitive Function in a Cross-Section of Younger and Older Community-Dwelling Individuals

Charles H. Hillman, Robert W. Motl, and Matthew B. Pontifex
University of Illinois at Urbana–Champaign

Danielle Posthuma, Janine H. Stubbe, Dorret I. Boomsma, and Eco J.C. de Geus
Vrije Universiteit

Previous reports have indicated a small, positive relationship between physical activity and cognition. However, the majority of research has focused on older adults, with few studies examining this relationship during earlier periods of the life span. This study examined the relationship of physical activity to cognition in a cross-section of 241 community-dwelling individuals 15–71 years of age with a task requiring variable amounts of executive control. Data were analyzed with multiple regression, which controlled for age, sex, and IQ. Participants reported their physical activity behavior and were tested for reaction time (RT) and response accuracy on congruent and incongruent conditions of a flanker task, which manipulates interference control. After controlling for confounding variables, an age-related slowing of RT was observed during both congruent and incongruent flanker conditions. However, physical activity was associated with faster RT during these conditions, regardless of age. Response accuracy findings indicated that increased physical activity was associated with better performance only during the incongruent condition for the older cohort. Findings suggest that physical activity may be beneficial to both general and selective aspects of cognition, particularly among older adults.

Keywords: exercise, fitness, Eriksen flanker task, interference control, cognition

The growing segment of the population over 65 years of age has ignited an interest in cognitive function among older adults. Evidence from cross-sectional studies has consistently supported linear age-related declines in cognitive functions that encompass process-based and fluid processes (i.e., processing speed, short-term memory, working memory, and long-term memory; Park et al., 2002). Such age-related decrements in cognition have been associated with changes in brain structure and function (Raz, 2000). Physical activity might play a central role in ameliorating age-associated cognitive losses.

Recent findings from large-scale community-dwelling studies indicate that physical activity is related to the preservation of cognitive health in older adults (Barnes, Yaffe, Satariano, & Tager, 2003; Lytle, Vander Bilt, Pandav, Dodge, & Ganguli, 2004; Weuve et al., 2004; Yaffe, Barnes, Nevitt, Lui, & Covinsky, 2001). Yaffe et al. (2001) used a prospective design to examine the influence of physical activity on the cognitive performance of 5,925 older women ($\geq$ 65 years) during a 6- to 8-year follow-up. Physical activity was measured in terms of self-reported number of city blocks walked and kilocalorie expenditure for a typical week. Global cognitive function was measured with a modified Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975); a screening tool designed to assess cognitive impairment related to concentration, language, and memory. The women who reported greater amounts of physical activity at baseline were less likely to exhibit cognitive decline at the 6- to 8-year follow-up, when compared with their less physically active peers (Yaffe et al., 2001). Two additional large-scale community-dwelling studies (Lytle et al., 2004; Weuve et al., 2004) have provided similar evidence that physical activity may protect against cognitive decline in older adults. Finally, Barnes et al. (2003) reported that greater cardiorespiratory fitness was associated with less cognitive decline across a variety of cognitive measures; however, the most protective influence appeared for measures of global cognition and executive control.

Executive control refers to a subset of processes (i.e., planning, scheduling, working memory, interference control, task coordination, etc.) involved in the intentional component of environmental interaction. Executive control functions decline substantially with age (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; West, 1996) and coincide with a disproportionate loss of brain tissue in the frontal and prefrontal regions that mediate such processes (Colcombe et al., 2003; Raz, 2000). The Eriksen flanker task (Eriksen & Eriksen, 1974) has frequently been used in executive control research to test an individual's ability to manage interference from task-irrelevant information (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). This task requires participants to discriminate between, for instance, two letters that are flanked by an array of other letters that have different action schemas associated with them. Variable amounts of interference control are

Charles H. Hillman, Robert W. Motl, and Matthew B. Pontifex, Department of Kinesiology and Community Health, University of Illinois at Urbana–Champaign; Danielle Posthuma, Janine H. Stubbe, Dorret I. Boomsma, and Eco J.C. de Geus, Department of Biological Psychology, Vrije Universiteit, Amsterdam, the Netherlands.

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Correspondence concerning this article should be addressed to Charles H. Hillman, Department of Kinesiology and Community Health, University of Illinois at Urbana–Champaign, 213 Freer Hall, 906 South Goodwin Avenue, Urbana, IL 61801. E-mail: chhillma@uiuc.edu

required according to the compatibility of the letters that flank the target stimulus. Congruent stimuli (e.g., HHHHH) elicit faster and more accurate responses, whereas incongruent stimuli (e.g., HHSHH) elicit increased error rate and decreased response speed (Eriksen & Schultz, 1979) because the latter condition results in greater response competition (Kramer et al., 1994; Spencer & Coles, 1999).

Interestingly, cross-sectional (Hillman, Kramer, Belopolsky, & Smith, 2006) and randomized intervention (Kramer et al., 1999) research involving older adults has found that moderate amounts of physical activity/aerobic exercise may protect against age-related declines of executive control. Indeed, Colcombe and Kramer (2003) performed a meta-analysis of randomized intervention studies between 1966 and 2001 to examine physical activity effects on human cognitive aging. The findings indicated that aerobic forms of exercise had general and selective effects that were beneficial to cognitive function in older adults. That is, despite their finding that aerobic exercise was beneficial across the breadth of cognitive processes studied (i.e., speed, visuospatial, controlled processing, and executive control), the effects were largest for tasks, or task components, involving extensive executive control (Colcombe & Kramer, 2003). Thus, these collective findings suggest that although cognitive performance declines in a global and linear fashion with age (Park et al., 2002), physical activity and aerobic fitness may serve to protect, in part, against age-related loss of cognitive function, with the greatest benefits derived for processes requiring extensive amounts of executive control (Colcombe & Kramer, 2003; Kramer et al., 1999).

Several viable mechanisms for the observed relationship between physical activity and executive function have been suggested. Animal models have found increased levels of brain-derived neurotrophin factor in the hippocampus, as well as other neurochemicals (e.g., dopamine, serotonin), which have been associated with increases in neuronal survival, brain plasticity, and synaptic function related to improved learning and performance (Cotman & Berchtold, 2002; Neeper, Gomez-Pinilla, Choi, & Cotman, 1995). Other animal research has evidenced the development of new capillaries in the cerebellum with aerobic forms of exercise (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990). In humans, aerobic fitness has been related to changes in both structure and function of the frontal, prefrontal, and parietal cortices (Colcombe et al., 2004), which have been found to exhibit the greatest amount of age-related decline (Raz, 2000). Interestingly, these brain regions play an integral role in mediating executive functions, and as such, the selective improvements observed for physically active adults on tasks requiring more extensive amounts of executive control may be related to changes in the health of these neural structures.

To date, most of the evidence for a beneficial effect of physical activity on cognition derives from samples of elderly participants. Very little is known about the relationship between physical activity and cognition during earlier periods of the human life span. In one of the few studies examining younger periods of the life span, Richards, Hardy, and Wadsworth (2003) examined the relationship between physical activity and verbal memory in a sample of 1,919 middle-age adults. Physical activity was assessed with the Minnesota leisure time physical activity questionnaire when participants were 36 years of age, and tests of verbal memory were performed at 43 and 53 years of age. Results indicated that self-reported exercise at 36 years of age was associated with a slower rate of memory decline at 43 and 53 years of age, suggesting that physical activity may protect against cognitive aging during later periods of middle adulthood (Richards et al., 2003). Several smaller cross-sectional studies (e.g., Hillman, Belopolsky, Snook, Kramer, & McAuley, 2004; Hillman et al., 2006; Spirduso & Clifford, 1978; Sherwood & Selder, 1979) have used higher and lower physically active young adults as control groups in which to compare physical activity–related findings in their older adult samples. Results have been inconsistent in these younger samples, with some studies indicating that physical activity participation is related to better performance on certain cognitive tasks (e.g., task switching; Hillman et al., 2006) and other studies indicating that physical activity does not influence performance on other cognitive tasks (e.g., stimulus discrimination; Hillman, Weiss, Hagberg, & Hatfield, 2002). Thus, with the noted exception of old age, little research has systematically examined the relationship between physical activity and cognitive function during the various periods of the human life span.

This study involved a cross-sectional comparison of physical activity influences on executive control function in community-dwelling individuals. Participants from two different age cohorts completed congruent and incongruent conditions of the Eriksen flanker task and provided information regarding their physical activity habits as well as intelligence quotient (IQ). We hypothesized that replicating previous research, IQ would be positively associated with task performance (e.g., Posthuma, Mulder, Boomsma, & de Geus, 2002) and aging would be negatively associated with task performance (Zeef, Sonke, Kok, Buiten, & Kenemans, 1996) on a flanker task. We further hypothesized that greater participation in physical activity would be globally associated with higher performance (i.e., faster response speed and increased accuracy) across conditions of the flanker task, supporting previous meta-analytic research (Colcombe & Kramer, 2003). However, we hypothesized that this relationship would be larger for the incongruent condition, which requires greater amounts of interference control, suggesting that physical activity is selectively related to tasks, or task components, requiring more extensive amounts of executive control (Kramer et al., 1999). On the basis of the robust age-related decrements in executive control that have been reported previously, we predicted that physical activity would have a greater influence on the cognitive performance of older, compared with younger, adults.

Method

Study Sample and Testing Site

Participants were recruited from the Netherlands Twin Registry as part of a large project on the genetics of cognition and adult brain functions (Posthuma et al., 2001). Adult twins and their nontwin siblings were asked to participate in a 4.5-hr protocol of cognitive function testing. Specifically, the twins came to the laboratory on the same day and alternated between 2 hr of cognitive testing with the Wechsler Adult Intelligence Scale—Third Edition (WAIS-III; Wechsler, 1997) and other neuropsychological tests and 2.5 hr of electroencephalography testing, both of which were administered by trained research assistants. The original sample with complete data on the IQ and the flanker task consisted of 674 family members from 301 twin families in two age cohorts: a younger cohort (M = 25.5 years, SD = 4.4 years) and an older cohort (M = 49.6 years, SD = 7.8 years).

Participating families consisted of one to seven siblings (including twins). On average, 2.5 participants per family participated. For 626 participants, additional survey information was available on physical activity. To avoid spurious correlation resulting from familial resemblance (especially in monozygotic twins), we selected only a single member from each family. Selection from all available siblings was pseudorandom in that it favored the siblings with complete information. In total, 241 participants were selected who had information on IQ, flanker task performance, and physical activity. There were 7 non-Caucasian participants in the sample. Full participant characteristics are shown in Table 1.

Eriksen Flanker Task

For the flanker test, participants were in a supine position facing a monitor at 80 cm distance in a dimly lit, sound-attenuated, and electrically shielded chamber. Two response boxes each containing an upper and a lower button were placed to the left and right in front of the participant. A total of 120 randomized trials were admistered to all participants, who responded using their index fingers. Each trial was initiated when the participant simultaneously pressed the lower buttons on the left and right response boxes, which simultaneously triggered a tone (1 KHz, 100 ms) and a fixation dot in the center of the monitor. After 1,000 ms, the stimulus array was presented for 100 ms. Stimuli consisted of a horizontal array of five arrowheads, which were equally likely to point to the left (<<<<<) or the right (>>>>>). Further, the flanking stimuli (i.e., the four arrowheads surrounding the centrally placed target stimulus) were equally likely to be congruent (>>>>>) or incongruent (>><>>) with the target arrow. In other words, four conditions were presented, with each condition containing 30 trials: left congruent (<<<<<), right congruent (>>>>>), left incongruent (>><>>), and right incongruent (<<><<).

Participants were instructed to respond with the left hand if the central arrowhead (i.e., the target stimulus) pointed to the left and with the right hand if the central arrowhead pointed to the right. Responding meant releasing the lower "home" button and pushing the upper "response" buttons. The home button served to separate decision time (release of the home button) and movement time (time from home button release to pressing of the response button); however, these data are not presented herein. Participants were asked to respond as quickly and accurately as possible and to ignore the flanking arrowheads. Visual feedback ("right," "wrong," or "too slow" messages and total current points) was presented 1,000 ms after the onset of the stimulus array for a duration of 1,500 ms. Participants gained 1 point for each correct response and lost 5 points for each incorrect response or responses that were deemed too slow. Incorrect button presses incorporated all premature responses, incorrect home button releases, and incorrect response button presses. Responses were counted as too slow when they exceeded the maximum response time of 1,000 ms. Trials were separated by an intertrial interval of 1,500 ms, after which the next trial started as soon as both home buttons had been pressed.

Home button release time and time of response button pressing were stored for all trials as was the number of too slow responses (>1,000 ms) and incorrect button presses. Performance measures were accuracy, decision time, movement time, total RT, and the number of incorrect and too slow responses. These measures were all averaged over left- and right-hand trials. For accuracy, too slow responses and incorrect button presses were counted and converted to a percentage, because in a small number of participants, timing information on a few of the 120 trials was lost. Reaction time (RT) was used for response speed, which was computed as the time interval between stimulus onset and time of response button pressing. RT was not computed for 1 participant because fewer than 10 correct trials were available for the incongruent condition. Before recording, all participants received 30 practice trials.

Intelligence Testing

Psychometric IQ was measured with the Dutch adaptation of the WAIS-III (Wechsler, 1997). Unstandardized individual scores for each subtest except Digit Symbol Substitution were calculated by weighting the observed score by the maximum possible score on that subtest multiplied by 100 (i.e., percentage correct on each subtest). For Digit Symbol Substitution, the number of correct items per 60 s was calculated. Nine subtests were used: Information measures general knowledge and information gathered from daily life. In Similarities, the participant is asked to describe in which aspect two verbally presented concepts are similar. In Vocabulary, the respondent is asked to verbally describe the meaning of a specified term. Arithmetic requires the participant to solve arithmetic questions within a certain time limit without paper and pencil. In Letter–Number Sequencing, the participant is asked to repeat a random sequence of up to

Table 1
Mean (and Standard Deviation) Demographic Information for the Younger and Older Cohorts

Variable	Younger cohort *M* (*SD*)	Older cohort *M* (*SD*)
Sample size (*n*)	118 (60 F, 58 M)	123 (77 F, 46 M)
Age (years)	25.5 (4.9)	49.6 (7.8)
Age range (years)	15.3–39.3	40.3–71.0
Physical Activity (days per week)	1.7 (1.3)	1.3 (1.2)
Height (cm)	175 (8.5)	172 (10.0)
Weight (kg)	72.1 (14.3)	76.6 (17.1)
WAIS-III Verbal Comprehension	65.4 (11.9)	62.1 (13.3)
WAIS-III Working Memory	63.2 (13.4)	59.9 (12.6)
WAIS-III Perceptual Organization	82.1 (9.9)	69.6 (12.7)
WAIS-III Processing Speed	84.3 (13.0)	74.4 (14.8)
WAIS-III Verbal IQ (standardized)	96.3 (12.5)	93.4 (14.0)
WAIS-III Performance IQ (standardized)	103.2 (10.2)	99.6 (13.8)
WAIS-III total IQ (standardized)	98.9 (10.1)	93.0 (11.9)
Flanker Congruent RT (ms)	670.3 (75.4)	741.9 (75.7)
Flanker Incongruent RT (ms)	761.8 (68.3)	817.9 (68.5)
Flanker Congruent Accuracy (%)	96.3 (7.2)	91.6 (11.6)
Flanker Incongruent Accuracy (%)	88.3 (13.5)	76.6 (22.9)

Note. Untransformed scores are given for the dimensions of the Wechsler Adult Intelligence Scale—Third Edition (WAIS-III). F = female; M = male. RT = reaction time.

eight numbers and letters and to put them in numerical and alphabetical order. In Block Design, the participant needs to copy within a certain time limit a red-and-white pattern using red and white blocks. Matrix Reasoning requires the participant to decide which alternative of five is most reasonably the missing part from a logical sequence. In Picture Completion, the participant needs to state which essential part has been omitted from a given picture. In Digit–Symbol Substitution, the respondent needs to replace numbers with specified symbols as quickly and accurately as possible.

According to the WAIS-III guidelines (Wechsler, 1997), the following four dimensions were calculated: Verbal Comprehension (the mean percentage correct of the Information, Similarities, and Vocabulary subtests), Working Memory (the mean percentage correct of Arithmetic and Letter–Number Sequencing), Perceptual Organization (the mean percentage correct of the Block Design, Matrix Reasoning, and Picture Completion subtests), and Processing Speed (the number of correct items per 60 s of Digit–Symbol Substitution). The validity of these four dimensions was recently confirmed by a reanalysis of the WAIS manual data by Deary (2001).

Physical Activity Assessment

Surveys on lifestyle and mental and physical health are sent biannually to all participants of the Netherlands Twin Registry. Most participants filled out the survey at around the time of cognitive testing. In the case of 40 participants,[1] the survey preceded the measurements by 6 to 12 months, and 8 participants had filled out their last survey more than a year earlier. Physical activity was assessed through a categorical "sweat index," ranging from 0 to 4 (Gionet & Godin, 1989; Philippaerts, Westerterp, & Lefevre, 1999; Shepard & Bouchard, 1995). Participants were asked "Are you at least once a week sufficiently physically active to start sweating?" A "no" response was coded as 0. If the participant responded "yes," he or she was further asked to indicate the approximate number of times per week this occurred: "*once a week*" (coded 1), "*twice a week*" (coded 2), "*three times a week*" (coded 3), or "*4 times a week or more often*" (coded 4). See Table 2 for the physical activity demographics by age cohort.

Results

Initial Pearson product–moment correlation analyses were conducted on scores for the four dependent variables from the flanker task (RT and response accuracy scores for congruent and incongruent conditions), physical activity, age, sex (coded as 0 = female, 1 = male) and scores from the four factors of the WAIS-III (i.e., Perceptual Organization, Processing Speed, Verbal Comprehension, Working Memory). The other variables (i.e., sex and IQ) were included to identify covariates for inclusion in the regression analyses. Results indicated that physical activity was negatively associated with RT and positively associated with response accuracy for the congruent and incongruent conditions of the flanker task ($p < .025$). Age was positively associated with RT and negatively associated with accuracy for the four dependent variables ($p < .01$). Additionally, the four subtests of the WAIS-III were negatively associated with RT and positively associated with accuracy for the four dependent variables ($p < .05$). Two of the WAIS-III subtests (i.e., Processing Speed and Perceptual Organization) were negatively associated with age ($p < .01$), but none of the four WAIS-III subtests was associated with physical activity ($p > .32$). Sex was significantly correlated with response accuracy during the congruent condition and with physical activity ($p < .01$). Because of correlations with either physical activity or age, the two subscales of the WAIS-III (i.e., Processing Speed and Perceptual Organization) and sex were treated as covariates in the subsequent regression analyses of the four dependent variables from the flanker task, age, and physical activity (see Tables 3 and 4 for intercorrelations for all participants and by cohort, respectively).

We performed a series of three-step hierarchical regression analyses. In the first step, the dependent variables from the flanker task were regressed on the two subscales of the WAIS-III and sex. In the second step, age and physical activity were entered into the regression analysis, and in the third step, an Age × Physical Activity interaction term (based on a product of mean-centered scores) was entered into the regression analysis. The third step was conducted to examine whether physical activity effects on task performance were dependent upon age (i.e., an interaction effect among a dichotomous and continuous variable).

The Step 1 regression analysis on RT during congruent trials indicated a significant overall effect, adjusted $R^2 = .13$, $F(3, 237) = 13.4$, $p < .001$. There were significant effects for both of the WAIS-III subscales: Perceptual Organization, *pr* (partial correlation) = −.22, $t(237) = 3.53$, $p = .001$, $\beta = -.24$, and Processing Speed, $pr = -.19$, $t(237) = 2.9$, $p < .005$, $\beta = -.20$. The Step 2 regression analysis was also significant, $\Delta R^2 = .09$, $F(2, 235) = 14.5$, $p < .001$. There were significant effects of age, $pr = .26$, $t(235) = 4.6$, $p < .001$, $\beta = .30$, and physical activity, $pr = -.14$, $t(235) = 2.4$, $p < .02$, $\beta = -.14$. This indicated that the older cohort exhibited slower RT in comparison with the younger cohort and that increased physical activity was associated with faster RT. The Step 3 regression analysis was not significant, $\Delta R^2 < .01$, $F(1, 234) = 1.5$, $p = .23$, indicating that the interaction did not add to the prediction of RT during congruent trials (see Table 5).

The Step 1 regression analysis on RT during incongruent trials indicated a significant overall effect, adjusted $R^2 = .11$, $F(3, 234) = 10.5$, $p < .001$. There were significant effects for both of the WAIS-III subscales: Perceptual Organization, $pr = -.19$, $t(234) = 3.0$, $p < .005$, $\beta = -.21$, and Processing Speed, $pr = -.17$, $t(234) = 2.8$, $p < .01$, $\beta = -.19$. The Step 2 regression analysis was also significant, $\Delta R^2 = .09$, $F(2, 232) = 12.5$, $p < .001$. There were significant effects of age, $pr = .22$, $t(232) = 3.8$,

Table 2
Number of Participants by Age Cohort for Days per Week of Physical Activity

Sweat index (days per week)	Younger cohort	Older cohort
0	25 (17 F, 8 M)	40 (27 F, 13 M)
1	31 (19 F, 11 M)	33 (20 F, 13 M)
2	32 (15 F, 17 M)	28 (18 F, 10 M)
3	17 (6 F, 11 M)	13 (7 F, 6 M)
4 or more	13 (3 F, 10 M)	9 (4 F, 5 M)

Note. F = female; M = male.

[1] Analyses were conducted, which excluded the 40 participants whose physical activity assessment occurred at an interval of 6 or more months from the time of cognitive testing. Results indicated that all significant effects and interactions observed in the overall sample remained after the 40 participants were removed.

Table 3
Intercorrelations Between Variables for All Participants

Subscale	1	2	3	4	5	6	7	8	9	10	11
1. Physical activity	—										
2. Age	−.18*	—									
3. Sex	−.22*	.07	—								
4. WAIS-III VC	−.03	−.10	−.15*	—							
5. WAIS-III WM	.02	−.12	−.20*	.57*	—						
6. WAIS-III PO	.06	−.52*	−.10	.42*	.44*	—					
7. WAIS-III PS	−.02	−.39*	.19*	.19*	.34*	.43*	—				
8. Congruent RT	−.19*	.47*	.08	−.15*	−.17*	−.33*	−.29*	—			
9. Incongruent RT	−.21	.42*	.08	−.14*	−.16*	−.30*	−.26*	.92*	—		
10. Congruent accuracy	.15*	−.30*	−.16*	.22*	.22*	.29*	.27*	−.29*	−.18*	—	
11. Incongruent accuracy	.22*	−.38*	−.12	.34*	.35*	.45*	.40*	−.37*	−.34*	.68*	—

Note. WAIS-III = Wechsler Adult Intelligence Scale—Third Edition; VC = Verbal Comprehension; WM = Working Memory; PO = Perceptual Organization; PS = Processing Speed. Congruent and incongruent reaction time (RT) and accuracy refer to the conditions of the Eriksen flanker task.
* $p < .05$

$p < .001$, $\beta = .26$, and physical activity, $pr = -.17$, $t(232) = 2.8$, $p = .005$, $\beta = -.17$. This indicated that the older cohort exhibited slower RT in comparison with the younger cohort and that increased physical activity was associated with faster RT. The Step 3 regression analysis was not significant, $\Delta R^2 < .01$, $F(1, 231) = 1.9$, $p = .17$, indicating that the interaction did not add to the prediction of RT during incongruent trials (see Table 6).

The Step 1 regression analysis on response accuracy during congruent trials indicated a significant overall effect, adjusted $R^2 = .13$, $F(3, 237) = 13.2$, $p < .001$. There were significant effects of WAIS-III Perceptual Organization, $pr = .17$, $t(237) = 2.6$, $p < .01$, $\beta = .18$, and Processing Speed, $pr = .21$, $t(237) = 3.3$, $p = .001$, $\beta = .23$, as well as sex, $pr = -.19$, $t(237) = 3.0$, $p < .01$, $\beta = -.19$, indicating that better performance on the Perceptual Organization and Processing Speed subtests of the WAIS-III was associated with greater accuracy and that female participants were more accurate than male participants. The Step 2 regression analysis was not significant, $\Delta R^2 = .01$, $F(2, 235) = 1.8$, $p = .16$. However, the Step 3 regression analysis was significant, $\Delta R^2 = .01$, $F(1, 234) = 3.9$, $p < .05$. The significant effect

Table 4
Intercorrelations Between Variables for Older and Younger Cohorts

Subscale	1	2	3	4	5	6	7	8	9	10	11
Older cohort ($n = 123$)											
1. Physical activity	—										
2. Age	−.09	—									
3. Sex	−.11	−.13	—								
4. WAIS-III VC	.08	−.08	−.21*	—							
5. WAIS-III WM	.18*	−.11	−.32*	.61*	—						
6. WAIS-III PO	.00	−.38*	−.02	.40*	.41*	—					
7. WAIS-III PS	.06	−.39*	.19*	.18*	.27*	.47*	—				
8. Congruent RT	−.24*	.30*	−.01	−.21*	−.23*	−.26*	−.30*	—			
9. Incongruent RT	−.27*	.26*	.01	−.15	−.13	−.15	−.23*	.89*	—		
10. Congruent accuracy	.21*	−.28*	−.18*	.26*	.30*	.30*	.28*	−.16	−.01	—	
11. Incongruent accuracy	.33*	−.35*	−.12	.36*	.38*	.40*	.40*	−.40*	−.29*	.70*	—
Younger cohort ($n = 118$)											
1. Physical activity	—										
2. Age	−.18*	—									
3. Sex	−.29*	.07	—								
4. WAIS-III VC	−.19*	.23*	−.05	—							
5. WAIS-III WM	−.16	.14	−.06	.51*	—						
6. WAIS-III PO	−.01	.06	−.09	.42*	.47*	—					
7. WAIS-III PS	−.24*	.11	.30*	.14	.37*	.10	—				
8. Congruent RT	−.06	.07	.08	.01	−.04	−.04	−.01	—			
9. Incongruent RT	−.08	.09	.08	−.05	−.12	−.13	−.07	.92*	—		
10. Congruent accuracy	−.03	.01	−.09	.10	.06	.02	.08	−.33*	−.26*	—	
11. Incongruent accuracy	−.04	−.04	−.05	.26*	.29*	.30*	.23*	−.10	−.25*	.54*	—

Note. WAIS-III = Wechsler Adult Intelligence Scale—Third Edition; VC = Verbal Comprehension; WM = Working Memory; PO = Perceptual Organization; PS = Processing Speed. Congruent and incongruent reaction time (RT) and accuracy refer to the conditions of the Eriksen flanker task.
* $p < .05$.

Table 5
Summary of Hierarchical Regression Analysis for Variables Predicting Reaction Time Speed During Congruent Flanker Trials

Variable	*B*	*SE B*	β
Step 1			
WAIS-III PO	−1.5	0.44	−.24*
WAIS-III PS	−1.1	0.39	−.20*
Sex	15.8	10.5	.09
Step 2			
Age	50.6	11.1	.30*
Physical activity	−9.2	3.9	−.14*
Step 3			
Age × Physical Activity	−9.3	7.7	−.10

Note. WAIS-III = Wechsler Adult Intelligence Scale—Third Edition; PO = Perceptual Organization; PS = Processing Speed.
* $p < .05$.

of this interaction term, $pr = .13$, $t(234) = 2.0$, $p < .05$, $\beta = .17$, is displayed in Figure 1. This interaction may be explained by the older cohort exhibiting a significant physical activity effect, $pr = -.19$, $t(113) = 2.1$, $p < .05$, $\beta = .17$, with increased physical activity associated with greater accuracy on congruent trials. No such effect was observed for the younger cohort, $pr = -.04$, $t(113) = 0.4$, $p = .71$, $\beta = -.04$ (see Table 7).

The Step 1 regression analysis on response accuracy during incongruent trials indicated a significant overall effect, adjusted $R^2 = .27$, $F(3, 237) = 29.8$, $p < .001$. There were significant effects of WAIS-III Perceptual Organization, $pr = .30$, $t(237) = 4.9$, $p < .001$, $\beta = .31$, and Processing Speed, $pr = .29$, $t(237) = 4.7$, $p < .001$, $\beta = .30$, as well as sex, $pr = -.16$, $t(237) = 2.5$, $p = .01$, $\beta = -.15$, indicating that better performance on the Perceptual Organization and Processing Speed factors of the WAIS-III was associated with greater accuracy and that women were more accurate than men. The Step 2 regression analysis also indicated a significant overall effect, $\Delta R^2 = .03$, $F(2, 235) = 5.4$, $p = .005$. There was a significant effect of physical activity, $pr = .20$, $t(235) = 3.2$, $p = .002$, $\beta = .18$, indicating that greater physical activity participation was associated with greater task performance. Lastly, the Step 3 regression analysis further indicated a significant overall effect, $\Delta R^2 = .03$, $F(1, 234) = 11.3$, $p = .001$. The significant effect of this interaction term, $pr = .21$, $t(234) = 3.4$, $p = .001$, $\beta = .26$, is displayed in Figure 1. This interaction may be explained by the older cohort exhibiting a significant physical activity effect, $pr = .34$, $t(118) = 3.9$, $p < .001$, $\beta = .30$, with increased physical activity associated with greater accuracy on incongruent trials. No such effect was observed for the younger cohort, $pr = -.02$, $t(113) = 0.2$, $p = .87$, $\beta = -.02$ (see Table 8).

Finally, regression analyses were conducted to assess whether the relationship between age, physical activity, and cognitive function is disproportionately larger for tasks requiring greater amounts of executive control according to the magnitude of the interference

Table 6
Summary of Hierarchical Regression Analysis for Variables Predicting Reaction Time Speed During Incongruent Flanker Trials

Variable	*B*	*SE B*	β
Step 1			
WAIS-III PO	−1.2	0.40	−.21*
WAIS-III PS	−1.0	0.36	−.19*
Sex	14.9	9.5	.10
Step 2			
Age	38.1	10.1	.26*
Physical activity	−10.0	3.5	−.17*
Step 3			
Age × Physical Activity	−9.7	7.0	−.12

Note. WAIS-III = Wechsler Adult Intelligence Scale—Third Edition; PO = Perceptual Organization; PS = Processing Speed.
* $p < .05$

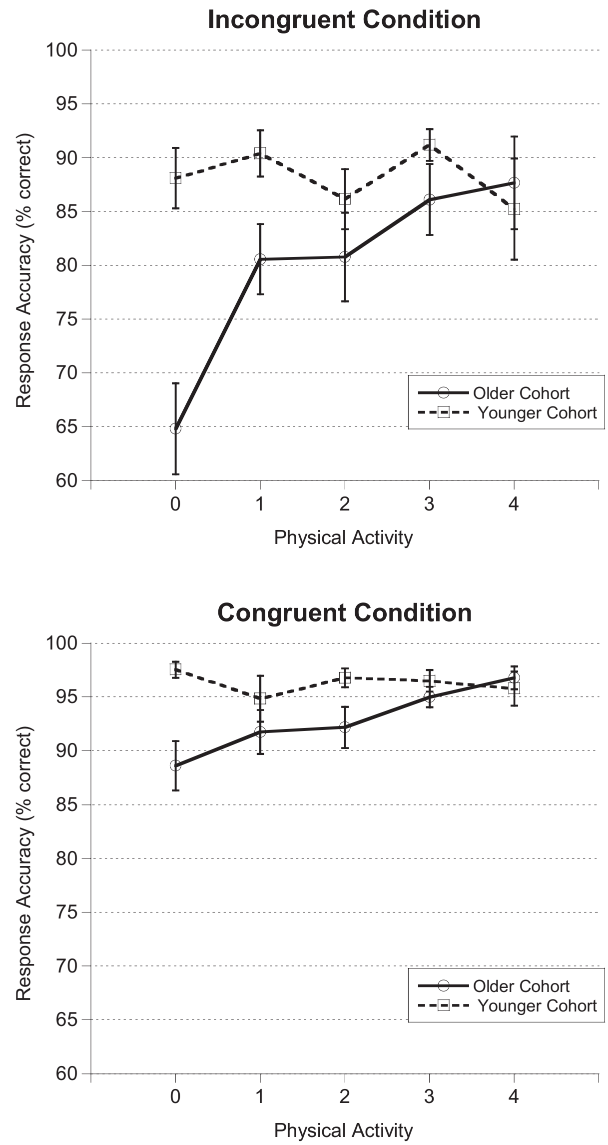

Figure 1. Response accuracy for older and younger cohorts as a function of physical activity to the congruent and incongruent conditions of the flanker task.

Table 7
Summary of Hierarchical Regression Analysis for Variables Predicting Response Accuracy During Congruent Flanker Trials

Variable	*B*	*SE B*	β
Step 1			
WAIS-III PO	0.14	0.05	.18*
WAIS-III PS	0.15	0.05	.23*
Sex	−3.7	1.3	−.19*
Step 2			
Age	−1.2	1.4	−.06
Physical activity	0.78	0.50	.10
Step 3			
Age × Physical Activity	1.9	0.96	.17*

Note. WAIS-III = Wechsler Adult Intelligence Scale—Third Edition; PO = Perceptual Organization; PS = Processing Speed.

effect (i.e., congruent minus incongruent responses for the RT and response accuracy variables) as a dependent variable. The Step 1 regression analysis on RT was not significant, adjusted $R^2 < .01$, $F(3, 234) = 0.5$, $p = .69$, indicating that there was no overall effect of sex or of either the Perceptual Organization or the Processing Speed factor of the WAIS-III. The Step 2 regression analysis indicated a significant overall effect, $\Delta R^2 = .03$, $F(2, 232) = 4.0$, $p < .02$. There was a significant effect of age, $pr = .17$, $t(232) = 2.7$, $p < .01$, $\beta = .20$, indicating a smaller interference effect for the older cohort ($M = 79.9$, $SD = 33.5$), as compared with the younger cohort ($M = 91.5$, $SD = 30.4$). The Step 3 regression analysis was not significant, $\Delta R^2 < .01$, $F(1, 231) = 0.6$, $p = .43$, indicating that the interaction did not add to the prediction of the interference effect. For response accuracy, the Step 1 regression analysis displayed an overall significant effect, adjusted $R^2 < .19$, $F(3, 237) = 20.2$, $p < .001$, which was due to significant effects of WAIS-III Perceptual Organization, $pr = .28$, $t(237) = 4.4$, $p < .001$, $\beta = .29$, and Processing Speed, $pr = .23$, $t(237) = 3.6$, $p < .001$, $\beta = .24$. The Step 2 regression analysis also displayed a significant overall effect, $\Delta R^2 = .03$, $F(1, 235) = 4.3$, $p < .02$. There was a significant effect of physical activity, $pr = .19$, $t(235) = 2.9$, $p < .005$, $\beta = .17$, indicating that decreased participation in physical activity was associated with a larger interference effect. The Step 3 regression analysis further indicated a significant overall effect, $\Delta R^2 = .03$, $F(1, 234) = 7.9$, $p = .005$. This interaction may be explained by the older cohort exhibiting a significant physical activity effect, $pr = .30$, $t(118) = 3.5$, $p = .001$, $\beta = .28$, with decreased physical activity associated with a larger interference effect. No such effect was observed for the younger cohort, $pr < .01$, $t(113) = 0.6$, $p = .95$, $\beta < .01$.

Discussion

In a cross-section of community-dwelling individuals between 15 and 71 years of age, we investigated the relationship between physical activity and behavioral performance on an executive control task designed to test variable amounts of interference control. After controlling for sex and Perceptual Organization and Processing Speed dimensions of IQ, we found that age was significantly associated with general decrements in RT speed across conditions of the Eriksen flanker task, and physical activity was significantly associated with general improvements in RT speed across conditions of the Eriksen flanker task. In addition, physical activity was associated with task performance for the older cohort, as greater amounts of physical activity participation were related to greater response accuracy during congruent and incongruent trials, whereas physical activity was not associated with response accuracy for the younger cohort. Lastly, the findings indicated that physical activity was more strongly related to performance during task conditions requiring greater amounts of interference control.

Nonselective decrements in processing speed with age have been well documented with the use of a variety of cognitive tasks (e.g., Kramer et al., 1994; Spirduso, 1980; Zeef et al., 1996). The data reported herein corroborate these findings, as age-related slowing of RT was observed across conditions of the Eriksen flanker task. Further, selective improvements in RT speed for older adults during tasks, or task components, requiring greater amounts of executive control have also been reported (Kramer et al., 1999; however, see Colcombe & Kramer, 2003, for a review). The data reported herein partially corroborate these findings as well. Specifically, Kramer et al. (1999) conducted a randomized control trial with 124 previously sedentary older adults (60–75 years) who were trained for 6 months in either aerobic (i.e., walking) or anaerobic (i.e., stretching and toning) exercise. At the completion of the 6-month exercise intervention, the aerobically trained group exhibited faster RT speed across tasks for conditions requiring greater amounts of executive control in comparison with the anaerobically trained group (Kramer et al., 1999). No differences between the groups were observed for those task conditions containing smaller executive control components, indicating that aerobic fitness selectively protects against cognitive aging on tasks requiring extensive executive control (Kramer et al., 1999). Although the current data support Kramer et al.'s (1999) finding that physical activity is related to improved performance on tasks with large executive components, improvement was also observed on trials with small executive components, indicating a more general relationship between physical activity and cognitive performance. Although speculative, the inconsistent findings for tasks with small executive components may be due to characteristics of the sample, such as physical activity or fitness levels and differences in the tasks used to measure executive control.

Similar findings were observed with regard to physical activity and task performance. Unlike RT, response accuracy measures do

Table 8
Summary of Hierarchical Regression Analysis for Variables Predicting Response Accuracy During Incongruent Flanker Trials

Variable	*B*	*SE B*	β
Step 1			
WAIS-III PO	0.47	0.10	.31*
WAIS-III PS	0.40	0.09	.30*
Sex	−5.8	2.3	−.15*
Step 2			
Age	−0.91	2.5	−.02
Physical activity	2.8	.88	.18*
Step 3			
Age × Physical Activity	5.7	1.7	.26*

Note. WAIS-III = Wechsler Adult Intelligence Scale; PO = Perceptual Organization; PS = Processing Speed.

not exhibit robust age-related decrements (Hawkins, Kramer, & Capaldi, 1992; Zeef et al., 1996), which perhaps may reflect changes in the speed–accuracy tradeoff during task performance with age. Indeed, consistent improvements in response accuracy with increased participation in physical activity also have not been observed (Colcombe et al., 2004; Hillman et al., 2006; Kramer et al., 1999). However, a relationship between accuracy and physical activity was observed in the current data set, which may be due to the larger sample size recruited herein. Previous research has involved smaller samples (e.g., Colcombe et al., 2004; Hillman et al., 2006). Thus, if the influence of physical activity on cognitive performance is small (as one meta-analysis suggests; Etnier et al., 1997), perhaps physical activity-related improvements may not have emerged because of low statistical power. In the current data set, the older cohort evidenced improved performance for both the congruent and incongruent trials after controlling for sex and IQ, suggesting that physical activity is generally associated with improved performance in older adults. However, the findings further indicated that the relationship between physical activity and task performance was stronger for trials with greater interference (i.e., incongruent trials) and was quite small (i.e., accounted for less than 2% change in variance) for trials with less interference (i.e., congruent trials). This finding suggests that despite the apparent global relationship between physical activity and cognitive performance, there is a disproportionately larger influence of physical activity on tasks requiring greater amounts of executive control. No such relationship was observed for physical activity and task performance in the younger cohort. Accordingly, these data suggest that although regular physical activity may be associated with better cognitive performance across the life span, physical activity appears to exert a greater influence on older adults' performance.

It is of interest to speculate on why physical activity may have both general and selective effects on cognitive performance and, further, why physical activity appears to exert a greater influence on cognitive performance during the later stages of the life span. Colcombe and Kramer's (2003) meta-analysis on randomized interventions indicated that aerobic activity had general effects on cognition, such that performance improved across various types of cognitive tasks in older adults. However, their meta-analysis also indicated that the greatest effects were found for tasks with large executive control components. The data reported herein add to the physical activity–cognition database, as faster response speed was observed in physically more active participants (regardless of age) across both conditions of the flanker task, whereas general and selective improvements in response accuracy were observed across task condition only for the older cohort, such that a disproportionately larger influence of physical activity was observed for incongruent trials. Although the specific mechanisms underlying this selective advantage have not been fully elucidated, several viable changes in brain structure and function associated with aerobic activity have been observed (Colcombe et al., 2003).

Previous research has not examined the influence of physical activity on cognition across the life span, as the majority of studies have focused exclusively on older adult populations (e.g., Barnes et al., 2003; Kramer et al., 1999; Lytle et al., 2004), with the noted exception of Richards et al. (2003), who focused on a middle-age adult sample. Recent trends indicate that physical inactivity is a growing public health epidemic (U.S. Department of Health and Human Services, 2000), pointing to the increased importance of studying this relationship in younger individuals. Further, few studies have focused on the relationship between physical activity and executive control. As noted above, Barnes et al. (2003) found the largest improvement for global cognitive performance and executive control in their prospective study of community-dwelling older adults, and Kramer et al. (1999) found selective improvement for tasks with large executive control components in older adults using a randomized control design. The current data corroborate these findings and suggest that physical activity may delay cognitive aging during earlier periods of the life span as well.

With regard to the other variables included in the regression analyses, sex and the Perceptual Organization and Processing Speed subtests of the WAIS-III were inversely correlated with physical activity and age, respectively. The inverse correlation between sex and physical activity is consistent with the large literature indicating that women are less active than men (Trost, Owen, Bauman, Sallis, & Brown, 2002). The inverse correlation between the two WAIS subtests (i.e., Perceptual Organization and Processing Speed) and age are also consistent with previous reports of the relationship between IQ and age (Ryan, Sattler, & Lopez, 2000), which indicates that there is greater decline for measures of fluid than for crystallized intelligence with advanced aging. Further, consistent with Posthuma, Mulder, Boomsma, and de Geus (2002), higher scores on the WAIS-III were negatively related to RT speed and positively related to response accuracy on an Eriksen flanker task. The analyses included sex as a potential confounding variable because significant bivariate associations between sex, physical activity, and WAIS-III factors were observed. After controlling for sex, we still identified physical activity, and age by physical activity effects on cognitive performance. Thus, the data suggest that despite the influence of sex on these variables, the relationship between physical activity and cognitive performance is still evident. Future research should include larger samples to better account for sex and the interaction of sex with other variables (e.g., physical activity) in the effort to further determine the relationship to cognitive performance.

There are several limitations of this research. First, the study used a cross-sectional design and, therefore, the performance effects attributed to variable amounts of physical activity may be due to other factors. Given that age, sex, and IQ were controlled, this possibility was reduced, but not eliminated, as other potential factors that were not collected may account for the observed findings. A second limitation is the use of self-reported measures of physical activity rather than objective measures of activity (e.g., pedometer or accelerometer) and fitness (e.g., VO_2). Temporal stability of our measure, however, was as good as that of these objective measures. The interclass correlation for the sweat index from data collected three years apart (1997, 2000) was .60. This still leaves open the possibility that some participants may have purposefully misreported their physical activity on both occasions. Such misreport has been shown to be unlikely (Motl, McAuley, & DiStefano, 2005). Third, the self-reported physical activity measure only allowed for a broad assessment of participation and did not account for such factors as intensity, duration, or history of participation. Future research should consider examining the differential effects on cognition of moderate versus vigorous physical activity, as well as the amount of physical activity. Additionally, sweating is strongly influenced by individual differences and may not reflect changes in intensity of physical activity. Finally, our sample did not include any individuals younger than 15 years of age and was predominately Caucasian. Important developmental changes occur during the preadolescent and adolescent years, and future research should further understanding of the influence of physical activity on cognitive health during this period of the life span. Additionally, these data may not be generalizable to non-Caucasian individuals.

In conclusion, physical activity is associated with behavioral aspects of cognition across the life span, after controlling for sex and IQ. Physical activity was found to benefit response speed and accuracy during a task requiring variable amounts of interference control—one aspect of executive control. These findings, together with previous reports of older individuals, suggest that physical activity may be beneficial to cognition during early and middle periods of the human life span and may continue to protect against age-related loss of cognitive function during older adulthood.

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