Research Quarterly for Exercise and Sport

Vol. 75, No. 2, pp. 176–185

Physical Activity and Executive Control: Implications for Increased Cognitive Health During Older Adulthood

Charles H. Hillman, Artem V. Belopolsky, Erin M. Snook, Arthur F. Kramer, and Edward McAuley

Electrocortical and behavioral responses of low, moderate, and high physically active older adults where compared with a younger control group on neutral and incompatible conditions of a flankers task. Compared to younger adults, high and moderate active older adults exhibited increased event-related potentials component P3 amplitude for the incompatible condition at the frontal electrode site. For the neutral condition, only low active older adults exhibited decreased amplitude at the central-parietal site, compared to younger adults. P3 latency revealed the longest latencies for low active older adults, followed by moderate active, high active, and younger adults, respectively. Reaction time (RT) data revealed that younger adults exhibited faster RT compared to all three older groups. Results suggest that physical activity may improve executive control function in older adults by affecting the distribution of P3 amplitude, which has been related to memory and attentional processes, and by decreasing P3 latency, which relates to the speed of cognitive processing.

Key words: aging, cognitive function, event-related potentials, P3

Decrements in biological and behavioral functioning impacting older persons' health and effective functioning have been well documented. With regard to psychological health, the extant research has established that, compared to compared to younger adults, older adults experience deficits in memory (Federmeier, McLennan, De Ochoa, & Kutas, in press), attention (Milham et al., 2001), cognition (Wecker, Kramer, Wisniewski, Delis, & Kaplan, 2000), and speeded movement responses, such as reaction time (RT; Bashore, 1989; Spirduso, 1980). These deficits have profound effects on older adults' quality of life and overall psychological well being (Brown, 1992; Spirduso & Asplund, 1995) and appear to have a disproportional distribution. For example, it has been argued that tasks or task components requiring executive control function or effortful cognitive processing are especially susceptible to age-related decline when compared to tasks that are more automatic and require less effortful cognitive processing (Dempster, 1992; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; West, 1996).

Executive control refers to a subset of cognitive processes involved in the intentional component of environmental interaction and includes functions relating to the organization of action, mental flexibility, complex discrimination, error monitoring, response selection, and inhibition, as well as other effortful processes (Meyer & Kieras, 1997; Norman & Shallice, 1986). With respect to aging, older adults' behavioral performance (i.e., RT, response accuracy) for tasks that require greater amounts of executive control have revealed marked decrements when compared to younger adults (DiGirolamo et al., 2001; Kramer, Hahn, & Gopher, 1999; Wecker et al., 2000). These age-related differences in performance are substantially smaller for tasks that require lesser amounts of executive control (Kramer et al., 1999; West, 1996).

Interestingly, physical activity, and, in particular, cardiovascular exercise, has been shown to benefit executive control function in older adults (Colcombe & Kramer, 2003; Kramer et al., 1999). Alternatively, findings have been inconclusive for cognitive tasks requiring lesser amounts of executive control, with some studies indicating that older physically active adults perform better than their sedentary peers on these tasks (Madden et al., 1999; Spirduso & Clifford, 1978) and others indicating that physical activity does not benefit task performance

Submitted: November 26, 2002
Accepted: August 17, 2003

Charles H. Hillman, Artem V. Belopolsky, Erin M. Snook, Arthur F. Kramer, and Edward McAuley are with the Department of Kinesiology at the University of Illinois at Urbana-Champaign.

(Kramer et al., 1999). Although the mechanisms underlying the relationship between physical activity and improved executive control function in older adults are poorly understood at this time, several viable hypotheses have been proposed. These hypotheses are based mainly on animal models and suggest that observed differences are related to increases in cerebral vascularization (Isaacs, Anderson, Alcantara, Black, & Greenough, 1992; Jones, Hawrylak, Klintsova, & Greenough, 1998), increased dopamine levels (Spirduso & Farrar, 1981; for a review of this literature, see Churchill et al., in press), and increases in other molecules, such as brain-derived neurotrophin factor (Cottman & Berchtold, 2002), which serves a neuroprotective function and enhances neuronal plasticity.

On a different level of analysis, electroencephalography (EEG) and, in particular, event-related potentials (ERPs), has been used to measure differences in cognitive function across age and physical activity levels (Hillman, Weiss, Hagberg, & Hatfield, 2002). However, this area of study has not specifically examined these factors using tasks with executive control components. ERPs, measured on the surface of the scalp, refer to electrocortical activation time-locked to discrete events. That is, they manifest brain activity in response to or preparation for a stimulus or response (Coles, Gratton, & Fabiani, 1990). One particular ERP component, referred to as the P3, has been useful in understanding underlying cortical activity related to specific psychological processes. The P3 is a positive-going waveform, which occurs approximately 300–800 ms after stimulus onset, and is thought to represent the updating of memory once sensory information has been analyzed (Donchin, 1981). The amplitude of this potential is thought to reflect changes in the neural representation of task relevant information and is proportional to the amount of used attentional resources, with more attention increasing P3 amplitude (Polich & Heine, 1996). The latency of P3 reflects stimulus classification speed (Duncan-Johnson, 1981), and longer latencies are thought to reflect increased processing time.

Robust age-related differences have been observed for P3, with older adults exhibiting decreased amplitude as well as greater equipotentiality of the scalp distribution (i.e., similarity in amplitude across recording sites) and increased latency compared to younger adults (Hillman et al., 2002; Picton, Stuss, Champagne, & Nelson, 1984; Polich, 1997). When cardiovascular fitness is considered, older fit adults exhibit P3 latencies that are faster than their sedentary peers and no different from younger adults (Dustman et al., 1984, 1990; Hillman et al., 2002), suggesting that cardiovascular fitness ameliorates, in part, age-related decrements in cognitive processing speed.

However, previous research has compared only high and low physically active older adults, without including a moderate activity group. Importantly, by only examining extreme groups, little understanding may be gained regarding the amount of physical activity necessary to affect underlying electrocortical processes involved in cognition. Including moderately active older individuals may lead to determining whether physical activity participation affects cognitive processing via a linear or threshold-type manner. That is, the moderate active group may provide greater understanding of how much physical activity is necessary to influence electrocortical processes involved in negotiating cognitive tasks.

Our goal in this study was to determine the influence of physical activity participation on the underlying electrocortical processes involved in executive control during older adulthood. To date, no previous ERP research has examined age and physical activity differences on executive control, nor has a moderate activity group been included. Thus, low, moderate, and high physically active older adults were compared with a younger adult control group on the Eriksen flankers task (Eriksen & Eriksen, 1974). This task requires participants to focus on and respond to a centrally located target stimulus while ignoring flanking distracters. This component of executive control represents the ability to successfully cope with interference from task-irrelevant information (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Previous research has found increased P3 latency for the incompatible compared to the compatible condition (Zeef, Sonke, Kok, Buiten, & Kenemans, 1996).

In the study described herein, the P3 component of an ERP was measured along with RT and response accuracy to better understand the relationship between underlying electrocortical activity and performance based on age and physical activity history. It was predicted that high physically active older adults and younger control participants would exhibit increased P3 amplitude and response accuracy and decreased P3 and RT latency when compared to low physically active older adults. Further, these group differences were expected to show increased P3 amplitudes for the incompatible compared to the neutral condition of the flankers task, given the need to mobilize additional attentional resources in dealing with increased interference on the incompatible trials (Lavie, 1995). Moderately active older adults were expected to exhibit behavioral responses and P3 measures between the two extreme older adult groups, suggesting that physical activity would influence executive control processes in a linear rather than threshold-type manner.

Method

Participants

Thirty-two Caucasian participants (16 men, 16 women) were recruited and placed into one of four gender-balanced groups (high, moderate, and low physically active older adults, and younger adult controls) based on age and self-reported physical activity history. That is, 8 participants comprised each of the four groups. Although older adults were recruited based on physical activity history, this variable was not considered when recruiting the younger adults, because previous research indicated no differences in electrocortical measures based on cardiovascular fitness in younger adult samples (Dustman et al., 1984; Hillman et al., 2002). One younger adult was removed from analyses, because his reaction time latencies were more than 3 standard deviations from the mean. Table 1 lists participants' demographic information and physical activity characteristics derived from the Yale Physical Activity Survey for Older Adults (DiPietro, Casperson, Ostfeld, & Nadel, 1993). Older participants were recruited from the Champaign County, IL, community, and the younger ones from Department of Kinesiology courses at the University of Illinois at Urbana-Champaign. All individuals reported being free of neurological disorders, cardiovascular disease, any medications that influence central nervous system function, and normal (or corrected to normal) vision based on the minimal 20/20 standard.

Procedure

After providing informed consent, participants completed questionnaires regarding health history and hand dominance (Chapman & Chapman, 1987), and an experimenter administered the Yale Physical Activity Survey for Older Adults (Dipietro et al., 1993). Participants were then seated in a comfortable chair in front of a computer screen and prepared for electrocortical measurement according to the Society for Psychophysiological Research guidelines (Picton et al., 2000; Pivik, et al., 1993). Linked mastoid-referenced electroencephalograms were measured from the Fz, FCz, Cz, CPz, Pz, and POz sites **[AQ Where are these sites located?]**. AFz served as the ground electrode and electooculographic activity was collected from electrodes placed above and below the right orbit and on the outer canthus of each eye to assess bipolar eye movements. Impedance values for all electrodes were $\leq$ 10 kohms.

Task instructions were then read to participants, who had an opportunity to ask questions, and 10 practice trials were presented. When the participants were ready, five blocks, each consisting of 144 trials, were administered, with a short rest period between each block. Approximately 35 min were necessary to complete the task. Following completion of the last block, participants were briefed on the purpose of the experiment.

Task

Incompatible and neutral conditions of the Eriksen flankers task (Eriksen & Eriksen, 1974) required participants to respond as quickly as possible to a centrally presented target letter. When "F" was the target stimulus, they responded with their left index finger. When "X" was the target stimulus, they used their right index finger. The incompatible condition had the target response flanked by the opposing target stimulus (i.e., FXF or XFX). The neutral target response was flanked by letters with no response assignment (e.g., LFL, LXL, MFM, MXM). The two conditions were equiprobable; stimuli consisted of black letters on a white background; each letter measured 2.5 cm high and 1.8 cm wide. Trials were presented for 500 ms with a 1,500-ms interstimulus interval.

Apparatus and Measures

A 64-channel Neuroscan Synamps system (Neurosoft Inc., Sterling, VA) was used to digitally amplify the EEG signal 500 times with a DC to 70 Hz-filter (60-Hz notch filter) and a sampling rate of 500 Hz. Continuous data were recorded online using Neuroscan Scan 4.2 software that was installed on an 850-MHz microcomputer. Stimuli were generated using Neuroscan Stimulus software, installed on a 133-MHz microcomputer with a 21-inch **[AQ: Incl. SI unit.]** monitor, which sent a marker indicating the condition of each trial for off-line sorting, reduction, and analysis. The stimulus software was also used to record RT and response accuracy.

Table 1. Group means and standard deviations for older and younger participants

Measure	High physically active older		Moderate physically active older		Sedentary older		Younger controls	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age (years)	65.9[a]	8.1	65.6[a]	6.3	68.8[a]	5.3	20.4[b]	1.9
Height (cm)	166.5[a]	9.0	171.9[a]	21.5	171.6[a]	12.8	171.0[a]	8.1
Weight (kg)	64.4[a]	7.7	73.3[a]	11.2	75.8[a]	20.6	67.0[a]	17.4
Yale index	78.3[a]	10.5	57.1[b]	5.8	34.4[c]	8.1	63.7[ab]	22.4
Yale total hr	19.7[a]	4.3	21.9[a]	9.7	20.3[a]	9.8	18.0[a]	6.7
Yale kcal/Wk	4,983.5[a]	868.0	5,121.9[a]	1,821.6	4,856.7[a]	2,199.0	4,903.2[a]	2,300.5

Note. M = mean; *SD* = standard deviation; values that share a common superscript are not significantly different at the $p \leq .05$.

Data Reduction

The Semlitsch, Anderer, Schuster, & Presslich (1986) algorithm was used to correct for vertical and horizontal eye movement artifacts. Epochs were created from continuous data and baseline corrected using the 100 ms prestimulus period. Data were filtered using a 30-Hz low pass cutoff (24 dB/octave). Artifact detection excluded trials containing amplitude excursions of ± 100 μV, and artifact-free data accompanied by correct responses were averaged. P3 was defined as the largest positive-going peak within a 250–600 ms latency window. Amplitude was measured as a change score from the prestimulus baseline, and peak latency was defined as the time of the maximum amplitude. Amplitude analyses for group comparisons included the McCarthy and Wood (1985) normalization procedure, which standardizes differences in the topographic distribution of the scalp activity across groups. Such a procedure was used, because previous research has indicated that topographic differences in P3 amplitude occur with age (e.g., West & Alain, 2000). Data were then exported in ASCII format to SPSS 10.1 for statistical analysis.

Statistical Analysis

A 4 x 2 x 6 (Group x Condition x Site) multivariate test with repeated measures was conducted separately for P3 amplitude and latency data. The group factor referred to high, moderate, and low physically active older adults and younger adult control participants. The condition factor represented the incompatible and neutral conditions of the Eriksen flankers task, and the site factor included the following midline electrodes: Fz, FCz, Cz, CPz, Pz, and POz. Behavioral data (i.e., RT, response accuracy) were analyzed separately using a 4 x 2 (Group x Condition) multivariate test with repeated measures. Analyses with three or more within-participant levels used the Wilks' Λ statistic. Post hoc analyses were conducted using univariate analyses of variance and paired samples *t* tests with Bonferroni correction. The alpha level was $p \leq .05$ for all analyses prior to Bonferroni adjustments.

Results

Participant Characteristics

As expected, a significant main effect for age was observed, $F(3, 28) = 125.9$, $p < .001$, effect size (ES) = .93. Follow-up analyses indicated that only the younger adults differed from the three older adult groups, and the older adults groups did not differ from one another ($p \geq .59$). Groups also did not differ in height or weight ($p \geq .42$). Analyses for the three survey subscales indicated that the groups did not differ according to their estimation of total activity hours per week ($p = .82$) or energy expenditure ($p = .99$). However, group differences were observed for the Yale Summary Index, which estimates the average amount of physical activity during the previous month, $F(1, 27) = 16.0$, $p < .001$, ES size = .64. Follow-up analyses revealed that low active older adults reported significantly less physical activity compared to all other groups (moderate and high active older adults, and young adults), $t(1, 13) \geq 3.5$, $p \leq .004$. Moderately active older adults reported less physical activity than high active older adults, $t(1, 14) = 5.0$, $p < .001$, but did not differ from the younger adult group, and high active older adults also were not significantly different from the younger adult group (see Table 1). Importantly, these findings indicate that although the groups estimated the same amount of time and energy spent in daily living activities, they engaged in different activity types, providing evidence that electrocortical differences among groups are due specifically to physical activity, not an increase in overall activity level.

Behavioral Responses

RT data indicated a significant group main effect, $F(3, 27) = 6.2$, $p = .002$, ES = .41, with decreased latency for the younger adults compared to all three older groups, $t(1, 13) \geq 3.1$, $p \leq .009$ (see Table 2). A condition main effect was also observed with increased latency for the incompatible ($M = 507.1$, $SE = 6.6$) compared to

Table 2. Group means and standard deviations for reaction time and response accuracy

Group	Incompatible condition				Neutral condition			
	RT		Accuracy		RT		Accuracy	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Low active	522.3	40.9	93.1	6.0	492.0	42.6	96.9	2.6
Moderate active	530.1	24.8	96.0	1.6	505.7	21.1	98.0	1.5
High active	524.4	41.0	96.4	1.6	494.7	45.6	98.5	0.9
Younger controls	451.5	38.7	91.1	5.1	433.9	41.7	95.8	2.7

Note. RT = reaction time; *M* = mean; *SD* = standard deviation.

the neutral (M = 482.0, SE = 7.0) condition, $F(1, 27)$ = 172.0, $p < .0001$, ES = .86.

Response accuracy data indicated a significant group main effect, $F(3, 27)$ = 3.0, p = .05, ES = .25; however, Bonferroni-corrected (p = .0083) post hoc tests revealed no differences between groups. A main effect for condition was also observed, $F(1, 27)$ = 43.4, $p < .001$, ES = .62, with increased accuracy for the neutral (M = 97.4, SE = .37) compared to the incompatible (M = 94.3, SE = .73) condition.

P3 Amplitude

Figure 1 depicts P3 waveforms for each group. The omnibus amplitude analysis yielded two significant two-way interactions of Group x Site, $F(15, 66.7)$ = 2.4, p = .008, ES = .33 (see Figure 2), and Condition x Site, $F(15, 24)$ = 2.6, p = .05, ES = .35, that were superseded by a significant three-way interaction of Group x Condition x Site, $F(15, 66.7)$ = 2.0, p = .03, ES = .29. Breaking down the three-way interaction by examining Group x Site for each condition revealed a significant interaction for both the incompatible, $F(15, 66.7)$ = 2.2, p = .01, ES = .32, and neutral, $F(15, 66.7)$ = 2.5, $p < .01$, ES = .33, conditions. Post hoc analyses for the incompatible condition indicated that group differences were only observed at the Fz site, $F(3, 28)$ = 5.5, $p < .01$, ES = .37, with Bonferroni-corrected t tests revealing significantly greater amplitude for moderate and high active older adults compared to younger adults, $t(1, 14) \geq 2.8$, $p \leq .016$. For the neutral condition, post hoc analyses found group differences at the Fz, $F(3, 28)$ = 5.5, $p < .01$, ES = .37, and CPz sites, $F(3, 28)$ = 4.7, $p < .01$, ES = .34. Bonferroni-corrected t tests indicated no group differences at the Fz site, and only the low active older group exhibited decreased amplitude at CPz compared to the younger group, $t(1, 14)$ = 4.1, p = .001. **[F1]**

The omnibus analysis for P3 amplitude also yielded significant main effects for condition, $F(1, 27)$ = 13.0, $p < .001$, ES = .32, with increased amplitude for the neutral compared to the incompatible condition, and for site, $F(5, 23)$ = 21.6, $p < .001$, ES = .82. Post hoc analyses revealed multiple significant differences between sites, $t(1, 31) \geq 3.7$, $p \leq .001$. Generally, decreased amplitude was found toward the frontal (Fz) and occipital (POz) scalp regions, with the largest amplitude at CPz. Last, no main effect was observed for the group factor.

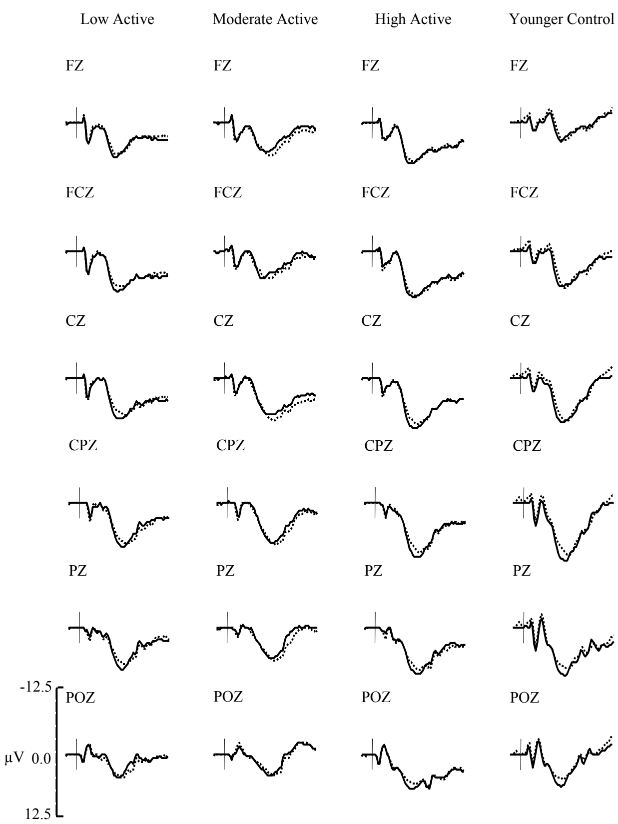

Figure 1. P3 waveforms for each electrode site by group. The dashed line depicts the incompatible condition, and the solid line depicts the neutral condition of the Eriksen flankers task.

P3 Latency

P3 latency analyses revealed three main effects and no interactions. A Group main effect was observed, $F(3, 27)$ = 4.2, p = .01, ES = .32, with post hoc tests revealing that P3 latency for younger adults was faster than the low and moderate physically active older adults, $t(1, 13) \geq$

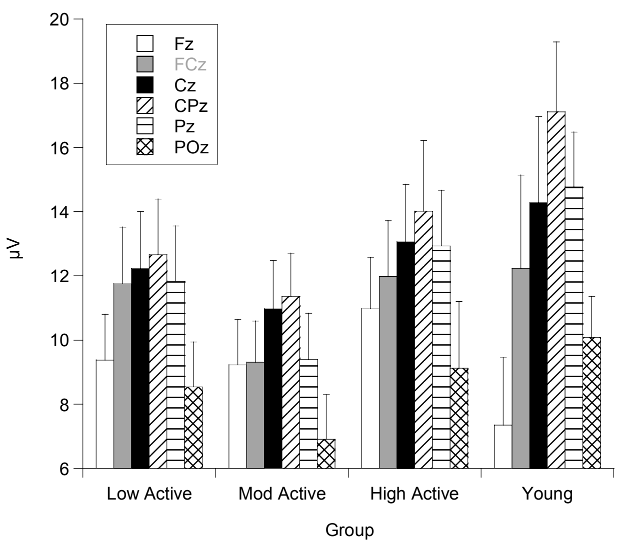

Figure 2. Distribution of P3 amplitude across both conditions of the Eriksen flankers task at midline sites by group.

2.5, $p \leq .03$, and not different from the high physical activity older group (see Figure 3). The high active and low and moderate active older adult groups did not significantly differ. A Condition main effect revealed increased latency for the incompatible relative to the neutral condition, $F(1, 27) = 22.0$, $p < .001$, ES = .45, and a Site main effect, $F(5, 23) = 11.0$, $p < .001$, ES = .70, yielded the following significant differences after post hoc tests: P3 latency at the Fz site was faster than the Cz and CPz sites, and the FCz site was faster than the Cz site, $t(1, 31) = 3.2$, $p \leq .003$.

Discussion

The current findings reveal that physical activity participation may influence the underlying electrocortical processes involved in aspects of older adults' executive control. Compared to younger participants, high and moderately active older adults exhibited increased amplitude at Fz during the incompatible condition. Further, decreased amplitude was observed for low active older adults, relative to the other three groups, at the CPz site during the neutral condition. P3 latency was also affected by age and physical activity history, with older low active adults showing the longest latencies followed by older moderate active, older high active, and younger adults, respectively. Age-related differences in RT replicated previous aging research as increased latency was observed for the three older, compared to the younger, groups.

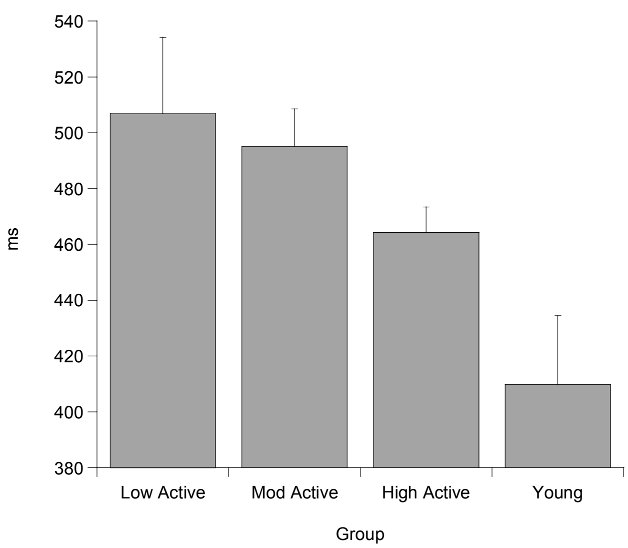

Figure 3. P3 latency by group across both conditions of the Eriksen flankers task.

P3 Amplitude

Robust age-related differences in P3 amplitude have been reported previously, with older adults exhibiting decreased amplitude relative to younger adults (Picton et al., 1984; Polich, 1997). Picton and his colleagues (1984) reported that P3 amplitude declined at a rate of 0.18 mV per year from the third to the eighth decade of life, and the scalp distribution became more frontal due to age-related decreases in amplitude at the vertex (Cz). In the current investigation, a slightly different picture emerged, possibly due to the study's physical activity focus and purposeful inclusion of a heterogeneous older adult sample. Accordingly, differences in P3 amplitude were observed as a function of physical activity participation, which may have prohibited the observation of an overall age effect. Specifically, compared to younger adults, older moderate and high active adults exhibited increased amplitude at Fz only during the incompatible condition, which, presumably, required increased executive control. This effect was not observed in low active older adults, nor was it found for the neutral condition, which required lesser amounts of executive control. However, during the neutral condition, moderate and high active older adults exhibited similar topography to that of younger adults, while low active older adults showed decreased amplitude at the CPz site. This finding is of further interest, because CPz was the site at which P3 reached its maximum amplitude across groups and electrode sites and is in the region where P3 amplitude is usually largest when measured in younger, healthy adults (e.g., Polich, 1997). Together, these findings suggest that physical activity may benefit older adults' cognitive function differentially depending on the cognitive requirements of the task. That is, during tasks that require greater amounts of executive control, older physical active adults may compensate for age-related deficits by recruiting additional cortical regions. In the current dataset, P3 amplitude at the frontal scalp site may reflect greater recruitment. During tasks that require lesser amounts of executive control (i.e., more automated tasks), the current findings suggest that physical activity may serve to ameliorate age-related deficit, allowing older adults to negotiate the task in a manner similar to younger adults, hence, allowing for more efficient cognitive processing.

Previous electrocortical studies have not evidenced topographic differences in P3 as a function of physical activity (Dustman et al., 1985; Hillman et al., 2002). However, none of the previously reported studies used tasks that required greater amounts of executive control. Therefore, the current data indicate that these differences may be observed only in tasks requiring greater amounts of executive control function. Last, given that both moderate and high active older adults had similar P3 distributions, which differed from low active adults, the data suggest that physical activity may influence older adults' cognitive function in a threshold-type manner.

The current data add to the extant literature, which has suggested that aging results in disproportional changes in brain function, structure, and cognition. In general, the disproportionate changes in brain structure across the adult lifespan parallel findings of age-specific changes in executive control and a subset of memory processes supported largely by prefrontal and temporal regions of the brain (Robbins et al., 1998; Schretlen et al., 2000). Indeed, a recent study (Colcombe et al., 2003) found that high levels of fitness are associated with moderate changes in brain structure. Older high fit individuals showed smaller decreases in brain volume, particularly in prefrontal, temporal, and parietal cortex, than older low fit individuals. The present data add to this literature by elucidating age-related functional brain changes that are moderated by physical activity.

P3 Latency

Similarly, the P3 latency data also suggest that physical activity participation may be beneficial to cognitive processing during older adulthood. With regard to age-related differences, the findings are consistent with previous reports in which older adults exhibited increased latency relative to younger adults, indicating the increased processing time necessary for stimulus discrimination and classification (Hillman et al., 2002; Polich 1997; Picton et al., 1984). However, replicating Zeef et al. (1996), P3 latency differences for age and condition did not interact but instead displayed a general trend for both the neutral and incompatible conditions. Such data might belie our argument that the beneficial effects of physical activity extend beyond executive control processing, which may be the case (see Colcombe & Kramer, 2003). However, it is also the case that experimental conditions requiring minimal executive control for younger adults often require greater amounts of executive control for older adults (DiGirolamo et al., 2001), including multiple conditions in the response compatibility task (Colcombe et al., 2002). Clearly, additional research will be needed to further examine the loci of physical activity and aging effects with respect to perceptual, cognitive, and motor processes.

Decreases in P3 latency were also associated with increases in physical activity participation, indicating that physical activity participation may benefit cognitive processing speed during advanced aging. Interestingly, the beneficial effects of physical activity participation were great enough that no significant differences were observed between older high active and younger groups. This finding supports earlier electrocortical investigations that compared older and younger physically active adults (Dustman et al., 1990; Hillman et al, 2002; Polich & Lardon, 1997) and extends this literature to include executive control processes. Given that differences in P3 latency were not observed between older active and younger adults or between older active and older low or moderate active adults, conclusions regarding whether the effect of physical activity on cognitive processing speed may be described via a linear or threshold-type mechanism cannot be determined from these data.

Motor Performance

Although previous investigations reported age-related differences in RT (Spirduso, 1980), and others have shown that fitness ameliorates these differences (Sherwood & Selder, 1979), the present study only provided partial support for these effects. Specifically, a group main effect indicated that younger adults exhibited faster RT latencies compared to all older adults, regardless of group assignment, an effect not novel to this report and one proven to be robust in the extant executive control literature (e.g., Kramer et al., 1999). However, RT differences based on physical activity participation were not observed, despite the observed differences in the electrocortical data, suggesting either a specific influence of physical activity on the subset of processes reflected by the P3 or differential sensitivity of RT and P3 to the effects of physical activity.

Limitations

Despite the demonstrated relationships between physical activity and older adults' cognitive function reported herein, several limitations must be noted. The small number of participants included in this study is one concern. Previous electrocortical studies that examined similar factors tended to use slightly larger sample sizes (e.g., 12 or more participants per group). Despite this limitation, similar findings were observed in the current dataset compared to previous reports (i.e., Dustman et al., 1990; Hillman et al., 2002; Polich & Lardon, 1997), providing a basis for examining the novel contributions reported herein. In addition, effects sizes are reported throughout the results section to better determine the meaningfulness of the findings.

A second limitation is that self-reported measures of physical activity were favored over an objective measure of fitness (e.g., oxygen uptake). However, previous research has indicated that the Yale Summary Index is highly correlated with peak oxygen uptake in adults ages 60–80 years (Young, Jee, & Appel, 2001), suggesting an association between this self-report measure of physical activity and more objective measures of cardiovascular fitness. In addition, the Yale survey has shown reduced validity for assessing light-intensity physical activities (Young et al., 2001). Despite the fact that all groups reported similar kilocalorie expenditure and total hours of activity per week, with difference only in activity types for each group (i.e., physical versus nonphysical activities), it is possible that some inaccuracy in measuring light-intensity physical activities differences may have occurred across groups.

Finally, younger adults were not grouped according to physical activity in the same manner as the older groups. This limitation did not allow for the analysis of age and physical activity to gain an increased understanding of the interaction of these factors on executive control. However, previous reports have not found differences in younger adult samples based on cardiovascular fitness (Dustman et al., 1985; Hillman et al., 2002), suggesting that including multiple younger groups would not have provided additional information.

Summary

In conclusion, age-related differences in electrocortical concomitants of executive control were examined based on physical activity participation. Findings suggested that increased amounts of physical activity involvement may benefit older adults' cognitive processing speed, as measured via P3 latency, and influence P3 modulation differentially according to the task demands. These data support the notion that moderate and high levels of physical activity may provide a protective effect against cognitive decline, as measured via P3 amplitude, thus, suggesting that a threshold for physical activity participation exists. However, the data regarding whether physical activity enhances cognitive processing speed, as measured via P3 latency through a threshold-type or linear mechanism, still remains unclear. The findings are consistent with the notion that physical activity participation may benefit cognitive health during advanced aging.

References

Bashore, T. R. (1989). Age, physical fitness, and mental processing speed. *Annual Review of Gerontology and Geriatrics, 9,* 120–144.

Brown, D. R. (1992). Physical activity, ageing, and psychological well-being: An overview of the research. *Canadian Journal of Sport Science, 17,* 185–193.

Cabeza, R., Grady, C. L., Nyberg, L., McIntosh, A. R., Tulving, E., Kapur, S., Jennings, J. M., Houle, S., & Craik, F. I. M. (1997). Age-related differences in neural activity during memory encoding and retrieval: A positron emission tomography study. *The Journal of Neuroscience, 17,* 391–400. **[AQ: Include in text or delete.]**

Chapman, L. J., & Chapman, J. P. (1987). The measurement of handedness. *Brain and Cognition, 6,* 175–183.

Churchill, J. D., Galvez, R., Colcombe, S., Swain, R. A., Kramer, A. F. & Greenough, W. T. (in press). Exercise, experience and the aging brain. *Neurobiology of Aging.*

Coles, M. G. H., Gratton, G., & Fabiani, M. (1990). Event-related brain potentials. In J. T. Cacioppo & L. G. Tassinary (Eds.), *Principles of psychophysiology: Physical, social, and inferential elements* (pp. 413–355). New York: Cambridge University Press.

Colcombe, S., Kramer, A. F., Erickson, K., Belopolsky, A., Webb, A., Cohen, N., McAuley, E., & Wszalek, T. (2002). An fMRI examination of models of age-related decline in cognitive functioning. *Proceedings of the 2002 Cognitive Aging Conference,* Atlanta, Georgia.

Colcombe, S. J., Erickson, K. I., Raz, N., Webb, A. G., Cohen, N. J., McAuley, E., & Kramer, A. F. (2003). Aerobic fitness reduces brain tissue loss in aging humans. *Journal of Gerontology: Medical Sciences, 58,* 176–180.

Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. *Psychological Science, 14,* 125–130.

Cottman, C. W., & Berchtold, N. C. (2002). *Exercise: A behavioral intervention to enhance brain health and plasticity. Trends in Neuroscience,* 25, 295–301.

Craik, F. I. M., & Byrd, M. (1982). Aging and cognitive deficits: The role of attentional resources. In F. I. M. Craik & S. Trehub (Eds.), *Aging and cognitive processes* (pp. 191–211). New York: Plenum Press. **[AQ: Include in text or delete.]**

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review, 12,* 45–75.

DiGirolamo, G. J., Kramer, A. F., Barad, V., Cepeda, N. J., Weissman, D. H., Milham, M. P., Wszalek, T. M., Cohen, N. J., Banich, M. T., Webb, A., Belopolsky, A. V., & McAuley, E. (2001). General and task-specific frontal lobe recruitment in older adults during executive processes: A fMRI investigation of task-switching. *Neuroreport, 12,* 2065–2072.

DiPietro, L., Casperson, C. J., Ostfeld, A. M., & Nadel, E. R. (1993). A survey for assessing physical activity among older adults. *Medicine & Science in Sports & Exercise, 25,* 628–642.

Donchin, E. (1981). Surprise!…Surprise? *Psychophysiology, 18,* 493–513.

Duncan-Johnson, C. C. (1981). P3 latency: A new metric of information processing. *Psychophysiology, 18,* 207–215.

Dustman, R. E., Ruhling, R. O., Russell, E. M., Shearer, D. E., Bonekat, H. K., Shigeoka, J. W., Wood, J. S., & Bradford, D. C. (1984). Aerobic exercise training and improved neuropsychological function of older individuals. *Neurobiology of Aging, 5,* 35–42.

Dustman, R. E., Emmerson, R. Y., Ruhling, R. O., Shearer, D. E., Steinhaus, L. A., Johnson, S. C., Bonekat, H. W., & Shigeoka, J. W. (1990). Age and fitness effects on EEG, ERPs, visual sensitivity, and cognition. *Neurobiology of Aging, 11,* 193–200.

Eriksen, C. W., & Eriksen, B. A. (1974). Effects of noise letters upon the identification of a target letter in a non-search task. *Perception and Psychophysics, 16,* 143–149.

Federmeier, K. D., McLennan, D. B., De Ochoa, E., & Kutas, M. (in press). The impact of semantic memory organization and sentence context information on spoken language processing by younger and older adults: An ERP study. *Psychophysiology.*

Hillman, C. H., Weiss, E. P., Hagberg, J. M., & Hatfield, B. D. (2002). The relationship to age and cardiovascular fitness to cognitive and motor processes. *Psychophysiology, 39,* 1–10.

Isaacs, K. R., Anderson, B. J., Alcantara, A. A., Black, J. E., & Greenough, W. T. (1992). Exercise and the brain: Angiogenesis in the adult rat cerebellum after vigorous physical activity and motor skill learning. *Journal of Cerebral Blood Flow and Metabolism, 12,* 110–119.

Jones, T. A., Hawrylak, N., Klintsova, A. Y., & Greenough, W. T. (1998). Brain damage, behavior, rehabilitation recovery, and brain plasticity. *Mental Retardation and Developmental Disabilities Research Review, 4,* 231–237.

Kramer, A. F., Hahn, S., & Gopher, D. (1999). Task coordination and aging: Explorations of executive control processes in the task switching paradigm. *Acta Psychologica, 101,* 339–378.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. B., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9,* 491–512.

Kramer, A. F., Sowon, H., Cohen, N. J., Banich, M. T., McAuley, E., Harrison, C. R., Chason, J., Vakil, E., Bardell, L., Boileau, R. A., & Colcombe, A. (1999). Ageing, fitness, and neurocognitive function. *Nature, 400,* 418–419.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 451–468.

Madden, D. J., Turkington, T. G., Provenzale, J. M., Denny, L. L., Hawk, T. C., Gottlob, L. R., Coleman, R. E. (1999). Adult age differences in the functional neuroanatomy of verbal recognition memory. *Human Brain Mapping. 7,* 115–135.

McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology, 62,* 203–208.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multi-task performance: Part 1. Basic mechanisms. *Psychological Review, 104,* 3–65.

Milham, M. P., Erickson, K. I., Banich, M. T., Kramer, A. F., Webb, A., Wszalek, T., & Cohen, N. J. (2001). Attentional control in the aging brain: Insights from an fMRI study of the stroop task. *Brain and Cognition, 49,* 277–296.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49–100.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, and D. Shapiro (Eds.), *Consciousness and self-regulation* **[AQ: Incl. pp. #s.]**. New York: Plenum Press.

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., Jr., Miller, G. A., Ritter, W., Ruchkin, D. S., Rugg, M. D., & Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology, 37,* 127–152.

Picton, T. W., Stuss, D. T., Champagne, S. C., & Nelson, R. F. (1984). The effects of age on human event-related potentials. *Psychophysiology, 21,* 312–325.

Pivik, R. T., Broughton, R. J., Copolla, R., Davidson, R. J., Fox, N., & Nuwer, M. R. (1993). Guidelines for the recording and quantitative analysis of electroencephalographic activity in research contexts. *Psychophysiology, 30,* 547–558.

Polich, J. (1997). EEG and ERP assessment of normal aging. *Electroencephalography and Clinical Neurophysiology, 104,* 244–256.

Polich, J., & Heine, M. R. D. (1996). P3 topography and modality effects from a single-stimulus paradigm. *Psychophysiology, 33,* 747–752.

Polich, J., & Lardon, M. T. (1997). P300 and long-term physical exercise. *Electroencephalography and Clinical Neurophysiology, 103,* 493–498.

Robbins, T.W., James, M., Owen, A. M., Shaakian, B. J., Lawrence, A. D., McInnes, L., & Rabbitt, P. M. A. (1998). A study of performance from tests from the CANTAB battery sensitive to frontal lobe dysfunction in a large sample of normal volunteers: Implications for theories of executive functioning and cognitive aging. *Journal of the International Neuropsychological Society, 4,* 474–490.

Salthouse, T. A. (1988). Resource-reduction interpretations of cognitive aging. *Developmental Review, 8,* 238–272. **[AQ: Include in text or delete.]**

Schretlen, D., Pearlson, G. D., Anthony, J. C., Aylward, E. H., Augustine, A. M., Davis, A., & Barta, P. (2000). Elucidating the contributions of processing speed, executive ability, and frontal lobe volume to normal age-related differences in fluid intelligence. *Journal of the International Neuropsychological Society, 6,* 52–61.

Semlitsch, H. V., Anderer, P., Schuster, P., & Presslich, O. (1986). A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology, 23,* 695–703.

Sherwood, D. E., & Selder, D. J. (1979). Cardiorespiratory health, reaction time and aging. *Medicine & Science in Sports & Exercise, 11,* 186–189.

Spirduso, W. W. (1980). Physical fitness, aging, and psychomotor speed: A review. *Journal of Gerontology, 6,* 850–865.

Spirduso, W. W., & Asplund, L. A. (1995). Physical activity and cognitive functioning in the elderly. *Quest, 47,* 395–410.

Spirduso, W. W., & Clifford, P. (1978). Replication of age and physical activity effects on reaction and movement times. *Journal of Gerontology, 33,* 26–30.

Spirduso W. W., & Farrar, R. P. (1981). Effects of aerobic training on reactive capacity: An animal model. *Journal of Gerontology, 35,* 654–662.

Wecker, N. S., Kramer, J. H., Wisniewski, A., Delis, D. C., & Kaplan, E. (2000). Age effects on executive ability. *Neuropsychology, 14,* 409–414.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120,* 272–292.

West, R. L., & Alain, C. (2000). Age-related decline in inhibitory control contributes to the increased stroop effect observed in older adults. *Psychophysiology, 37,* 179–189.
Young, D. R., Jee, S. H., & Appel, L. J. (2001). A comparison of the Yale Physical Activity Survey with other physical activity measures. *Medicine & Science in Sport & Exercise, 33,* 955–961.
Zeef, E. J., Sonke, C. J., Kok, A., Buiten, M. M., & Kenemans, L. J. (1996). Perpetual factors affecting age-related differences in focused attention: Performance and psychophysiological analyses. *Psychophysiology, 33,* 555–565.
[AQ: Are "in press" articles still in press?]

Authors' Notes

This work was supported in part by a University of Illinois Research Board Award to the first author. Please address all correspondence concerning this article to Charles H. Hillman, Department of Kinesiology, University of Illinois at Urbana-Champaign, 213 Freer Hall, 906 S. Goodwin Avenue, Urbana, IL 61801.

E-mail: chhillma@uiuc.edu