The relationship of age and cardiovascular fitness to cognitive and motor processes

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Abstract

Older and younger aerobically trained and sedentary adults participated in an S1-S2-S3 paradigm designed to elicit event-related potential (ERP) and behavioral responses to determine the influence of cardiovascular fitness on cognitive and motor processes. The paradigm provided warning (S1) as to the difficulty level of an upcoming decision task (S2). Participants had to decide the taller of two bars on presentation of S2 but hold their response until S3, to which they indicated their choice motorically. Results revealed age-related differences for ERP measures as older participants showed increased amplitude of the stimulus preceding negativity (SPN) prior to S2, and longer latencies and equipotentiality of P3 in response to S2. Fitness effects were also observed for the contingent negative variation (CNV) with decreased amplitude for fit relative to sedentary individuals. Age interacted with fitness for P3 latency to S2 as older sedentary individuals showed the longest latency followed by older fit and both younger groups. No significant group differences were observed for reaction time (RT) to S3. Therefore, physical fitness is associated with attenuation of cognitive decline in older individuals and greater economy of motor preparation for both young and older participants.

Descriptors: Aging, Older adults, Cardiovascular fitness, Cognition, Physical activity, Event-related potentials

It is well established that cognitive and motor performance declines with advancing age (Dustman, Emmerson, & Shearer, 1994; Spirduso, 1980, 1983, 1995). More specifically, researchers have shown that both cognitive processes and motor responses slow as individuals get older (Polich, 1996; Spirduso, 1980). This decline in performance has profound effects on older individuals' effective functioning in everyday life (Spirduso & Asplund, 1995); however, there is a high degree of individual variability in this decline. For this reason, researchers have attempted to understand the role that individual lifestyle habits play in the aging process. One lifestyle choice that has been shown to enhance the quality of older adults' cognitive and psychomotor performance is the quantity and quality of physical activity in which they regularly engage.

The extant literature on physical activity and cognitive function in the elderly has provided mixed findings with some research showing that physical activity is beneficial to performance and other research suggesting no such relationship (Blumenthal et al., 1991; Boutcher, 2000; Dustman et al., 1994). However, this in-

consistency may be due to the differing cognitive challenges employed by different investigators (Chodzko-Zajko & Moore, 1994; Kramer et al., 1999; Shay & Roth 1992). For example, the most pronounced improvements in cognitive function from cardiovascular fitness have been observed for tasks that are effortful in nature and require fluid intelligence, whereas no relationship has been shown for tasks involving crystallized intelligence (Chodzko-Zajko & Moore, 1994). Additionally, Kramer et al. provided compelling evidence that cognitive processes characterized by executive function are selectively improved by cardiovascular conditioning. Despite the inconsistent methods employed in different studies, meta-analytical reviews summarizing the relationship between exercise and cognitive functioning in older adults have revealed a moderate relationship (effect size [ES] = .31, SD = 0.54) for cross-sectional research (Thomas, Landers, Salazar, & Etnier, 1994), and a small, but statistically significant, relationship (ES = .19, SD = 0.37) for intervention research (Etnier et al., 1997). Furthermore, it appears that cognitive benefits are typically observed only in studies that contrast groups characterized by substantive differences in aerobic fitness (Boutcher, 2000; Dustman et al., 1994). Therefore, careful attention to both the cognitive challenges presented and the magnitude of fitness differences contrasted is needed to further understand the nature of this important relationship.

Additionally, there is evidence that cardiovascular fitness exerts a positive influence in the psychomotor domain. Reaction time (RT) has been used as the primary index of psychomotor performance and has typically been found to be shorter in physically

active compared to sedentary older adults (Sherwood & Selder, 1979; Spirduso, 1980; 1983; Spirduso & Clifford, 1978; Spirduso, MacRae, MacRae, Prewitt, & Osborne, 1988). The importance of this finding is underscored by Spirduso (1983) who proposed RT as a measure of the overall integrity of the central nervous system (CNS). However, the evidence is largely based on cross-sectional studies, as well as work with animal models, and inconsistent findings have been reported in training studies with older men and women (Whitehurst, 1991). As such, the evidence for this relationship is compelling, but still in need of clarification.

Beyond these issues of clarity, there are further concerns regarding the relative influence of fitness on the cognitive and motor domains. For example, endurance activity was shown to positively affect reactive motor behavior in older compared to younger rats (Spirduso & Farrar, 1981). Moreover, MacRae, Spirduso, Walters, Farrar, and Wilcox (1987) found increased striatal dopamine receptor binding affinity in aerobically trained compared to inactive rats. And Isaacs, Anderson, Alcantara, Black, and Greenough (1992) found specific adaptations in the cerebellum of adult rats depending on the nature of the motor activity in which they engaged. These findings support the concept of specificity, which states that physical adaptations are constrained or limited to specific stimulus characteristics (Wilmore & Costill, 1994). Accordingly, using a specificity framework, physical or motor activity should exert its primary influence on the motor structures and processes of the brain.

Alternatively, van Praag and colleagues (van Praag, Christie, Sejnowski, & Gage, 1999; van Praag, Kempermann, & Gage, 1999) have shown evidence of the effects of treadmill running in mice on neuronal growth in the hippocampus and dentate gyrus, areas of the brain linked to memory and learning. Further, Dustman, Emmerson, and Ruhling (1990) expressed the opinion that aerobic exercise promotes increased vascularization of the brain, which would imply a generalized neurological beneficence. This view was empirically supported by Rogers, Meyer, and Mortel (1990), who found evidence of enhanced cerebral blood flow in retirees who maintained an active lifestyle relative to their sedentary counterparts. Finally, it may be that cognitive benefits are also achieved from being physically active through the interrelationship between motor structures and cognition. In this regard, Jonides (2000) recently presented evidence based on fMRI data of the role of the cerebellum during tasks that require executive processing. For this reason, it may be naïve to separate the two domains, as the resultant effects on the brain may be functionally integrated.

The level of measurement may help to clarify the issue of relative effect. In an attempt to determine the effects of chronic endurance activity on brain processes, researchers have typically examined the motor system using measures other than electrocortical activity. Although behavioral and psychomotor measurements have been extensively employed in studies of exercise and the aging brain, surprisingly little investigation has occurred using electrophysiological measures. To date, only two original reports have appeared in the literature that detail the results of studies using electroencephalographic (EEG) and event-related potential (ERP) measures that specifically examined cortical responses of older individuals characterized by differing levels of aerobic fitness (Bashore, 1989; Dustman, Emmerson, & Ruhling, 1990). Hence, our understanding of this relationship would benefit from a complementary level of analysis (Cacioppo & Berntsen, 1992).

In this regard, RT has been used to assess age- and fitness-related differences in speeded response movement to a stimulus, but the preparatory state that precedes the reaction cue or imper-

ative stimulus has not been examined within the context of cardiovascular fitness and aging. The preparatory state can be indexed by cortical slow potentials (SPs) that precede the presentation of imperative stimuli. Specifically, the stimulus-preceding negativity (SPN) and contingent negative variation (CNV) are both negative-going ERPs that index different components of the preparatory period. That is, the SPN and CNV (as well as other ERPs) occur in response to or in preparation for stimuli that are present in the participant's environment. The protocol typically employed to elicit the SPN and CNV is a two-stimulus (S1-S2) paradigm in which changes in amplitude between warning (S1) and imperative stimuli (S2) are measured. The main difference between the SPN and CNV is that a motor response (e.g., a button press) is required at S2 for the CNV only (Brunia & Damen, 1988). SPN amplitude is thought to index anticipation of task-relevant stimuli (Hillman, Apparies, & Hatfield, 2000), whereas CNV amplitude is thought to relate to motoric preparation (Prescott, 1986; van Boxtel & Brunia, 1994). It should be noted that anticipatory and/or attentional processes are also ongoing during the time in which the CNV is measured and may be reflected in the amplitude of that potential, as it is difficult to respond to a stimulus without activating attentional or anticipatory processes. However, because the SPN occurs in the absence of a motor response, it is believed that the amplitude of this potential is not related to motor preparation. Accordingly, using a specificity framework, physical or motor activity may exert its primary influence on the motor structures and processes of the CNS and, thus, on the motor components involved in the preparatory state (i.e., the CNV) with little or no influence on the nonmotor components (i.e., the SPN).

Furthermore, after the presentation of the imperative stimulus (i.e., the reactive period), other ERP measures have also been associated with physical activity history in older adults. Generally, older individuals show increased latency and decreased amplitude for the P3 when compared to younger adults (Dustman, Shearer, & Emmerson, 1993; Polich, 1996). The P3 is a positive peak of an ERP with a variable latency (approximately 300–800 ms) depending on multiple factors, including age and the stimulus used to elicit it. In general, the latency of this peak has been associated with cognitive processing speed. Habitual participation in cardiovascular activity has been shown to decrease electrocortical performance differences between older and younger individuals, suggesting that cardiovascular exercise, in part, may help to maintain overall CNS health (Dustman et al., 1993; Kempermann, Van Praag, & Gage, 2000). With regard to P3 latency, Dustman, Emmerson, and Ruhling (1990) observed that P3 latency was faster in aerobically trained compared to sedentary older men.

Additionally, Dustman, Emmerson, and Shearer (1996) outlined the results of a number of studies that employed ERP measures to assess inhibitory function of the cerebral cortex, an important process that declines with age. Their work used a comprehensive montage that included sites overlying the lateral regions of the scalp to record EEG activity, allowing for the assessment of inhibitory integrity by examining the relative similarity or equipotentiality between groups that vary in age and fitness. The basic premise was that relative heterogeneity of ERP amplitude across the topography was indicative of greater inhibition and that older fit individuals would be expected to have decreased equipotentiality relative to their sedentary counterparts.

Therefore, due to the complex nature of the stimulus–response relationship, it is unclear as to which specific components underlying psychomotor performance are responsible for the inconsistent findings associated with age and cardiovascular activity. In

this regard, performance differences related to aging may occur due to any number of processes such as: stimulus anticipation (i.e., SPN), stimulus discrimination and/or processing (i.e., P3), and motor initiation and/or motor response (i.e., CNV). Even less is known regarding which aspects of the stimulus–response relationship are affected by physical activity involvement in older individuals. However, subscribing to a specificity framework, and based on the findings observed in the RT and animal literature, it is reasonable to predict that the influence of physical activity involvement may be greatest for those processes specifically associated with motor preparation and response. Alternatively, a more generalized effect of fitness would reveal itself through the processes related to both the motor and cognitive domains.

Method

Participants

Forty-eight participants (24 men, 24 women) were recruited for one of four gender-balanced groups (older aerobically trained, older sedentary, younger aerobically trained, and younger sedentary) based on age, VO_2 max, and self-reported physical activity history. Participants in the two older groups were between the ages of 60 and 70 years and younger participants were between the ages of 18 and 28 years. Physically active older participants were recruited from running clubs in the Washington D.C. metropolitan area and their younger counterparts were recruited from the University of Maryland Cross Country and Triathlon teams. Sedentary older adults were identified through a continuing education program designed specifically for older adults and younger sedentary participants were contacted through undergraduate academic courses, both at the University of Maryland. All individuals reported being free of neurological disorders, cardiovascular disease, any medications that influence CNS function, and had normal (or corrected to normal) vision based on the minimal 20/20 standard. Table 1 presents participants' characteristics.

The aerobically trained groups were characterized by a history of 9.2 hours per week ($SD = 4.2$) of high intensity cardiovascular exercise (e.g., running, cycling, swimming, etc.) for an average of 19.1 years ($SD = 12.6$). Specifically, the older fit group averaged 6.7 hours of exercise ($SD = 2.9$) for the previous 24 years ($SD = 12.4$) and the younger fit group averaged 11.8 hours of exercise for the past 10.6 years ($SD = 8.1$). The sedentary groups had no history of aerobic exercise over the previous 5 years. Physical activity habits for all groups were assessed using the Yale Physical Activity Survey for Older Adults (Dipietro, Casperson, Ostfeld, & Nadel, 1993).

Procedure

For each participant, testing occurred on 2 separate days with a maximum of 14 days between sessions. On Day 1, which lasted approximately 1 hr, participants provided informed consent and were screened for health risks prior to participating in a graded exercise test. Older participants were screened by a physician who was present throughout the entire procedure.

Each participant performed a continuous graded exercise test on a treadmill to determine maximal oxygen consumption (VO_2 max; Dengel, Pratley, Hagberg, & Goldberg, 1994). Older participants were monitored for heart rate (HR) and cardiovascular function throughout the test using a 12-lead electrocardiogram and blood pressure monitoring. Younger participants were monitored using a wristwatch HR monitor (Polar Electro Inc., Woodbury, NY). Each test was preceded by a warm-up period of walking or running on a level treadmill. Speed was gradually increased until the participant's HR was 75% of age-predicted HR maximum. The VO_2 max test started at 0% grade and the speed predetermined to elicit 75% of HR maximum. The grade was increased to 4% after the first 2 min of exercise and increased an additional 2% each minute thereafter. The test was terminated when the participant was unable to continue because of fatigue or when any abnormal exercise responses occurred (e.g., chest pain, light-headedness, abnormal ECG, etc.). Thirty-second averages for oxygen uptake (VO_2) and respiratory exchange ratio (RER) were collected throughout the test using a computerized indirect calorimetry system. The system's computer received gas fraction data and expired gas volume data from a mass spectrometer and a ventilation measurement module/turbine flow meter, respectively. VO_2 max was achieved when at least two of the following criteria were met: a plateau in VO_2 despite an increased work rate, RER greater than 1.10, and achievement of age-predicted maximum HR. All participants met this criterion.

On Day 2, which lasted approximately 1.5 hr, participants were administered the Yale Physical Activity Survey for Older Adults (Dipietro et al., 1993). Upon entering the laboratory, all participants were provided a brief overview of the testing procedures and were seated in a comfortable chair in front of a computer screen. The participants were then prepared for electrocortical measurement in accordance with the Society for Psychophysiological Research guidelines (Putnam, Johnson, & Roth, 1992). Participants were asked to refrain from exercising 24 hr prior to testing.

A lycra electrode cap (Electro-Cap International, Eaton, OH) was fitted to the participant's head and nine electrode sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) were prepared using Omni-prep and electrode gel based on the international 10-20 system (Jasper,

Table 1. *Group Means (SD) for Older and Younger Fit and Sedentary Participants*

Measure	Older Fit	Older Sedentary	Younger Fit	Younger Sedentary
Age (yr.)	63.5 (2.8)[a]	65.0 (2.7)[a]	22.1 (3.3)[b]	23.3 (3.3)[b]
Education (yr.)	16.1 (3.8)[a]	17.5 (2.1)[a]	15.6 (2.2)[a]	15.8 (1.9)[a]
Height (cm)	167.7 (7.9)[a]	168.6 (10.0)[a]	169.5 (14.2)[a]	171.3 (9.4)[a]
Weight (kg)	58.6 (8.7)[a]	71.8 (11.3)[b]	63.3 (8.0)[a]	68.8 (9.6)[b]
VO_2 max (mL·kg^{-1}·min)	41.5 (7.7)	23.3 (3.9)	56.0 (7.5)	35.6 (5.3)
Yale total hr	24.7 (11.8)[a]	17.8 (9.5)[b]	32.1 (14.4)[a]	13.4 (8.0)[b]
Yale kcal/wk	6454.2 (2555.7)	3788.5 (1711.0)[b]	9014.5 (2778.5)	3288.9 (2063.4)[b]

Note: All groups are balanced for gender (6 males, 6 females).
Values that share a common superscript are not significantly different at $p \leq .05$.

1958). All sites were referenced to linked ears and the ground electrode was prepared using the midfrontal (FPz) site. Bipolar electro-oculographic activity (EOG) was collected to assess vertical and horizontal eye movement artifact for subsequent off-line editing of the EEG records. Impedance values for all recording electrodes was ≤5 kΩ and all channels were calibrated with a 12-Hz 50-μV signal prior to each testing session.

After an acceptable EEG signal was observed, the lights were dimmed and the participant was given the task instructions. Participants were given the opportunity to ask questions and 10 practice trials were subsequently administered. When the participant was ready, the task was administered in three blocks of 48 trials each with a brief rest period between blocks. Hence, participants received a total of 144 trials, 72 in each of the two difficulty levels (i.e., easy and difficult), with the entire data collection period lasting 30 min. Following the completion of the last block, the electrode cap was removed and the participant was debriefed on the purpose of the experiment.

Task

The task consisted of an S1-S2-S3 paradigm. S1 was a visual warning displayed for 500 ms on the computer screen in front of the participant. Specifically, the words "EASY" or "HARD" appeared to cue the participant as to the level of difficulty for the upcoming task. Following S1, a 4-s interstimulus interval (ISI) occurred before the presentation of S2, which lasted 200 ms. A discrimination task was used at S2, which consisted of two bars differing in height. The participant's task was to decide which bar (the right or the left) was taller. However, the participant was instructed not to respond to S2, but merely to decide which bar *was* taller. In the easy discrimination condition, there was a 7.68 cm difference in bar height. In the hard condition the bars differed in height by 0.032 cm. Previous research (Hillman et al., 2000) reported a success rate of approximately 99% and 65% for the easy and hard conditions, respectively. Four seconds after the discrimination task (S2), a box was presented (S3) for 500 ms and the participant was instructed to respond as quickly as possible by pressing the button on a mouse that corresponded to the taller bar. In other words, participants pressed the right mouse button if the right bar was taller and the left mouse button if the left bar was taller. Throughout all trials, a small plus sign ("+") was used to provide a fixation point for the participants. The two discrimination conditions were equiprobable and counterbalanced and trials were separated by a 4–8-s intertrial interval (ITI), which was also randomized to reduce temporal conditioning.

Apparatus and Measures

The EEG signal was amplified 50,000 times via band-pass filters set from 0.01 to 100 Hz (i.e., time constant = 16 s) using a Grass Model 12 Neurodata Acquisition amplifier system. A 60-Hz notch filter was also implemented. The analog EEG data were converted using a NeuroScan Analog/Digital converter, recorded online with NeuroScan Scan 4.03 software installed on a 133-MHz Gateway computer, and collected continuously. The visual stimuli were generated by NeuroScan Stim software installed on a Dell 486 computer. For each trial, the NeuroScan Stim software delivered an event marker to the NeuroScan Scan computer for each of the stimuli (S1, S2, S3) and task conditions (easy vs. hard) to sort, reduce, and analyze the data off-line. RT latency and percentage of correct responses were recorded and saved using NeuroScan Stim software. From the continuous EEG data, several ERP measures were recorded as follows:

P3 amplitude and latency. Amplitude was defined as the difference from baseline of the largest positive peak between 250 and 600 ms following the N1-P2-N2 complex after S1 and S2 onset. This complex refers to the observed peaks that often occur in an ERP prior to the onset of the P3. Latency was the time at which the largest positive peak occurred after stimulus presentation.

SPN amplitude. Change from baseline amplitude was quantified during the 4-s ISI between the S1 and S2 period. The SPN was defined as the difference in amplitude between the baseline and the average of the 200-ms period just prior to S2.

CNV amplitude. Changes from baseline amplitude were examined during the 4-s ISI between the S2 and S3 period. The CNV was defined as the difference in amplitude between the baseline and the average of the 200-ms period just prior to S3.

Data Reduction

Electrocortical data reduction occurred off-line using NeuroScan Edit software. Continuous data were corrected for vertical, followed by horizontal, eye movement artifacts using a correction algorithm developed by Semlitsch, Anderer, Schuster, and Presslich (1986). Each trial was then epoched and resultant epochs containing amplitude excursions of ±75 μV were excluded from further analyses. Using this criterion, 60% of the trials were accepted for analysis. The remaining epochs were averaged for each participant based on condition (easy vs. hard), baseline corrected using the 100 ms prior to S1, and filtered. Slow wave ERPs (SPN, CNV) were filtered using a low-pass filter with a 5-Hz cutoff frequency and P3 data were filtered using a low-pass filter set at 15 Hz. Averaging as well as peak and latency picking algorithms were then implemented as described in the previous section. Lastly, each participant's averaged data for the easy and difficult conditions were output in ASCII format for statistical analysis using SPSS 9.0.

Statistical Analysis

Analyses were conducted using separate 2 × 2 × 2 × 3 (Age × Fitness Level × Condition × Site) mixed-model multivariate tests with repeated measures on Condition and Site (Fz, Cz, Pz) and a 2 × 2 × 2 × 3 × 2 (Age × Fitness Level × Condition × Location × Hemisphere) mixed-model multivariate test with repeated measures for Condition, Location, and Hemisphere for the lateral sites (F3, F4, C3, C4, P3, P4), respectively. These analyses tested the interaction of age and fitness level for each of the six derived measures, separately (i.e., P3 amplitude to S1, P3 latency to S1, SPN, P3 amplitude to S2, P3 latency to S2, and CNV). One older and one younger sedentary individual were removed from the SPN and CNV analyses and two younger sedentary participants were removed from the P3 analyses due to an insufficient number of trials.

Behavioral measures were analyzed using 2 × 2 × 2 (Age × Fitness Level × Condition) mixed-model multivariate tests with repeated measures on the Condition factor. The Wilks' Lambda statistic was used to control for possible nonhomogeneity of the variance–covariance matrix. Follow-up analyses were conducted where appropriate using univariate ANOVAs and paired samples *t* tests. The alpha level was set at $p \leq .05$ for all analyses.

Results

Psychophysiological Measures

Separate analyses were conducted on the different ERP measures elicited by the paradigm. Generally, the morphology of the participants' waveforms consisted of a positive-going shift in amplitude to S1 (i.e., P3) followed by a negative-going slow potential (i.e., the SPN) up to the presentation of S2. After S2, a positive-going ERP that included a P3 component was observed followed by a negative-going slow potential (i.e., the CNV) that terminated at the presentation of S3. The morphology is illustrated in Figure 1.

P3 to the Warning Stimulus (S1)

Analyses of ERP amplitude and latency following the warning stimulus (S1) were not conducted due to an inability to determine and quantify a P3 component in older participants. That is, no discernible P3 morphological structure could be identified for the older group. Alternatively, younger participants displayed a clear P3 potential with an average amplitude of 2.75 μV and latency of 380 ms.

SPN

Midline. The SPN analysis on midline electrode sites revealed a three-way interaction of Age $\times$ Condition $\times$ Site, $F(2, 41) = 4.3$, $p < .025$, as older adults exhibited increased amplitude at frontal and central sites for the easy condition and at frontal and parietal

sites for the hard condition, compared to younger participants. However, follow-up analyses indicated no significant age or condition effects at the different sites.

Lateral. Lateral analyses revealed main effects for both age, $F(1, 42) = 4.3$, $p < .05$, and condition, $F(1, 42) = 7.8$, $p < .01$, with increased amplitude for older, $M = -0.84$, $SE = 0.56$, relative to younger, $M = 0.78$, $SE = 0.55$, participants and for the easy, $M = -1.1$, $SE = 0.45$, compared to the difficult, $M = 0.99$, $SE = 0.61$, task.

P3 Latency to the Decision Task

Midline. The omnibus midline analysis revealed an age main effect, $F(1, 42) = 31.4$, $p < .001$, with older adults, $M = 484.6$, $SE = 12.0$, exhibiting longer P3 latency compared to younger participants, $M = 387.6$, $SE = 12.5$.

Lateral. Similar to the midline analysis, lateral analyses revealed an age main effect, $F(1, 42) = 39.2$, $p < .001$, as older adults, $M = 479.7$, $SE = 10.2$, exhibited longer P3 latency relative to younger adults, $M = 386.6$, $SE = 10.8$. Further, an Age $\times$ Fitness interaction was observed, $F(1, 42) = 5.6$, $p < .025$. Post hoc analyses indicated that both older groups (aerobically trained and sedentary) exhibited increased P3 latency compared to both younger groups, $p < .05$. However, further inspection of the group means showed that older sedentary participants exhibited the long-
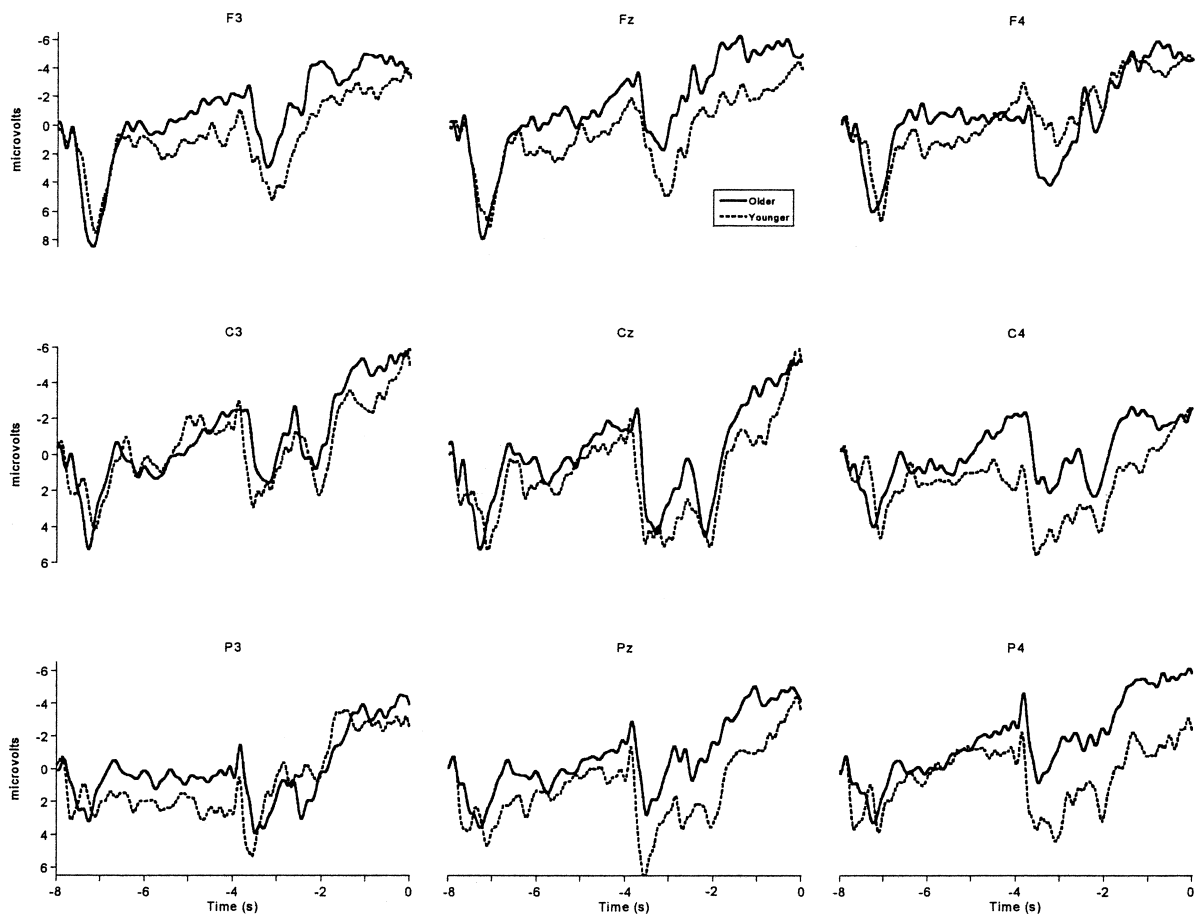

Figure 1. The waveform morphology for the entire period for older (solid line) and younger (dashed line) participants.
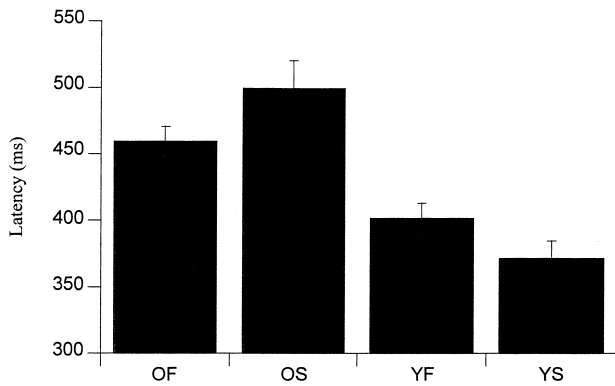
Figure 2. Age × Fitness interaction for P3 latency to S2. OF = older fit, OS = older sedentary, YF = younger fit, and YS = younger sedentary participants.

Figure 3. Age × Region interaction for P3 amplitude to S2. Older adults are depicted by black bars and younger adults are illustrated by white bars.

est latencies, followed by older fit, younger fit, and younger sedentary individuals (see Figure 2).

Additionally, an Age × Region × Hemisphere interaction was observed, $F(2,41) = 4.9$, $p < .025$. Follow-up tests revealed a significant age main effect across all regions, $Fs(1,44) \geq 23.0$, $p < .001$, with older adults exhibiting increased latency relative to younger participants. Further, follow-up tests revealed an Age × Hemisphere interaction only for the parietal region, $F(1,44) = 7.5$, $p < .01$, such that older participants exhibited longer P3 latencies at both parietal sites (i.e., P3 and P4), $Fs(1,44) \geq 24.3$, $p < .001$, but the magnitude of age difference was greatest at the left site.

P3 Amplitude to the Decision Task (S2)
Midline. Midline analyses for P3 amplitude revealed a main effect of site, $F(2,41) = 8.2$, $p < .001$. Decomposition of this main effect indicated that Fz exhibited decreased amplitude compared to Cz and Pz, $ts(1,45) \geq 3.6$, $p < .001$, whereas no differences were observed between Cz and Pz.

Lateral. Analyses conducted on the amplitude for lateral electrodes indicated an Age × Region interaction, $F(2,41) = 3.6$, $p < .05$. Post hoc analyses revealed that older individuals showed no differences in amplitude across the three regions (i.e., frontal, central, parietal). However, P3 amplitude differed significantly in younger participants across regions, $F(2,20) = 7.5$, $p < .01$, as the frontal region showed decreased amplitude compared to both the central and parietal regions, $ts(1,21) \geq 3.1$, $p < .01$. Further, post hoc tests indicated that older participants exhibited increased P3 amplitude frontally compared to younger individuals, $t(1,44) = 3.0$, $p < .01$, an effect not observed for central and parietal sites (see Figure 3).

Additionally, analyses revealed an Age × Hemisphere interaction, $F(1,42) = 5.4$, $p < .05$, as older participants had increased P3 amplitude in the right, $M = 5.4$, $SE = 0.55$, relative to the left, $M = 4.6$, $SE = 0.51$, hemisphere, $F(1,23) = 5.7$, $p < .025$. No such effect was observed in younger participants (right: $M = 3.8$, $SE = 0.57$; left: $M = 4.1$, $SE = 0.53$).

CNV
Midline. The midline analysis revealed main effects of fitness, $F(1,42) = 3.9$, $p = .05$, and condition, $F(1,42) = 4.9$, $p < .05$, with increased CNV amplitude for sedentary, $M = -4.2$, $SE = 0.9$,
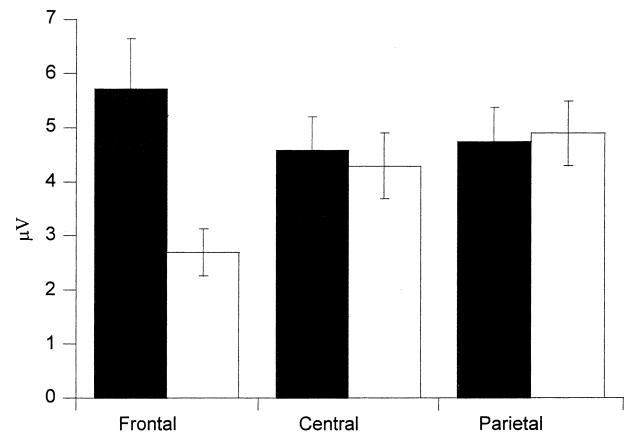
relative to aerobically trained participants, $M = -1.7$, $SE = 0.9$, and for the easy, $M = -3.9$, $SE = 0.7$, compared to the difficult conditions, $M = -2.0$, $SE = 0.8$.

Lateral. An Age × Hemisphere interaction was observed, $F(1,42) = 4.0$, $p = .05$. Younger participants showed increased amplitude in the left relative to the right hemisphere, $t(1,22) = 2.4$, $p < .025$, whereas older participants exhibited no such hemisphere effect (see Figure 4). Further, main effects of condition, $F(1,42) = 5.1$, $p < .05$, and hemisphere, $F(1,42) = 5.4$, $p < .025$, were found as increased amplitude was exhibited for easy compared to hard trials and in the left relative to the right hemisphere.

Behavioral Measures
Separate 2 × 2 × 2 (Age × Fitness × Condition) multivariate repeated measures analyses were conducted for reaction time (RT) and percentage of correct responses. Results showed no significant differences for RT (see Table 2) and only a main effect of condition for percentage of correct responses. Participants responded cor-
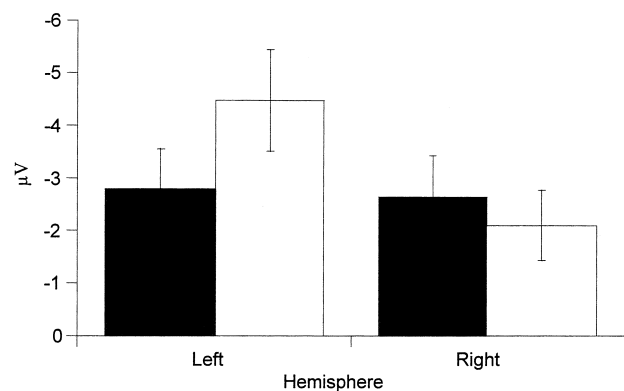

Figure 4. Age × Hemisphere interaction for CNV amplitude. Older adults are depicted by black bars and younger adults are depicted by white bars.

Table 2. *Group Means (SD) for Reaction Time Latency (ms)*

Group	Easy Condition	Hard Condition
Older Fit	338.1 (97.2)	335.1 (66.9)
Older Sedentary	352.3 (149.3)	354.4 (162.3)
Younger Fit	320.0 (100.3)	324.2 (104.5)
Younger Sedentary	347.6 (169.2)	353.1 (171.6)

rectly 95.3% ($SD = 9.2$) of the time for the easy condition and 64.0% ($SD = 9.5$) of the time for the difficult condition, $F(1,42) = 608.2$, $p < .001$.

Discussion

Taken together, the results suggest that older adults exhibited electrocortical deficits in stimulus–response negotiation across all components of the relationship compared to younger participants. Specifically, older adults showed increased SPN and frontal P3 amplitude, longer P3 latency, and increased equipotentiality for P3 to the decision task, as well as increased equipotentiality for CNV prior to the response stimulus. Moreover, older adults failed to show a quantifiable P3 component to the warning stimuli, which was in contrast to younger adults.

As predicted by the specificity framework, fitness effects were observed for the CNV as cardiovascularly trained individuals exhibited decreased CNV amplitude relative to sedentary participants. Additionally, as predicted by the generality framework, fitness interacted with age for P3 latency to the decision task as aerobically trained and sedentary older adults showed increased latency compared to both younger groups (i.e., aerobically trained and sedentary), albeit to different extents. In other words, older aerobically trained participants had shorter P3 latencies compared to older sedentary participants. These electrocortical findings are noteworthy considering that the behavioral data (i.e., RT, percentage of correct responding) did not differ based on age or fitness groupings. This lack of significant findings for the behavioral data was expected, as the duration between the task (S2) and the response cue (S3) was fixed, thus allowing individuals to anticipate the response cue. The following discussion is divided into two subsections: the nonmotor period and the motor period.

The Nonmotor Period

P3 to the warning stimulus. A traditional P3 component was not observed for older adults following the warning stimulus (i.e., S1). Specifically, younger adults exhibited a clear ERP that contained a P3 component to warning stimuli, whereas a lack of quantifiable positivity was observed in older participants. Additionally, a true N1-P2-N2 complex was not apparent prior to the P3 component, further corroborating its absence in the older participants (Anderer, Semlitsch, & Saletu, 1996).

Reduced P3 amplitude in older adults has been observed previously (Friedman, Kazmerski, & Cycowicz, 1998; Polich, 1997); however, it is unusual that an absence of a P3 component was found in older adults. This finding may be due to several factors. First, the instructions for the warning stimulus (S1) that were used to elicit the P3 may explain this finding, as older adults exhibited a robust P3 to the decision task (S2). Because the warning stimulus was a passive task, participants were instructed not to make any decision or movement in response to the warning. Hence, participants passively observed the warning stimulus. Previous research has shown that P3 amplitude is reduced for passive or ignored tasks compared to attended tasks that require a behavioral response (Friedman et al., 1998).

Second, the two conditions (i.e., easy and hard) signaled by the warning stimulus at S1 were equiprobable. Previous research has incorporated the oddball protocol when studying the effect of aging on the P3 component. In that protocol, the probability of the two P3-eliciting stimuli are altered such that the standard stimulus is presented 75–90% and the rare stimulus is presented 10–25% of the time. This probability manipulation has been shown to have a robust effect on P3 amplitude (Polich, 1997). The fact that the current study did not manipulate probability may also have played some role in the absence of P3 to S1 in the older adults.

SPN. Results from the current investigation revealed that older participants exhibited increased SPN amplitude compared to younger participants at both the midline and lateral sites, suggesting that increased neural resources were allocated in preparation for the imperative task (S2). As such, one could argue that older men and women are not as efficient in their neural processing as they anticipate the presentation of an upcoming event. However, no differences between the groups were observed on the basis of fitness. Because the SPN does not reflect motor activation or preparation, such a finding is consistent with the notion that fitness effects are specific to the motor domain.

P3 to the decision task. Older adults exhibited increased P3 latency relative to younger participants both at the midline and lateral sites. Previous research has suggested that the latency of P3 indexes the time necessary to cognitively process a stimulus (Duncan-Johnson, 1981). Therefore, the present findings imply decreased speed of cognitive processing when compared with younger adults. The current findings also extend previous aging research, as the paradigm used to elicit the P3 differed from that of previous tasks. That is, equiprobable stimuli were used in favor of an oddball paradigm that employs probability of expectancy to elicit differential P3 components (Polich, 1996). Because expectancy was held constant in this experiment, the current findings provide additional support that increased P3 latency observed in older adults is related to decreased cognitive processing speed and not to age-related differences in expectancy.

Importantly, cardiovascular fitness interacted with age such that both of the older groups exhibited increased P3 latency at the lateral sites compared to the younger groups and the older fit individuals exhibited shorter latency compared to older sedentary adults. However, post hoc inspection of the means revealed that this latter difference did not attain significance. Also, no such interactive effect was observed at the midline sites. Despite the lack of significant post hoc findings, the omnibus test of significance for the lateral sites, in conjunction with the trend for group differences, is consistent with earlier research that revealed a significant decrease in P3 latency for older aerobically trained compared to sedentary adults (Bashore, 1989; Dustman, Emmerson, & Ruhling, 1990). However, the effect was not robust. As such, the present P3 results appear to contradict the specificity hypothesis and support a more generalized influence of fitness on nonmotor aspects of cortical function, as the P3 measure is related to the cognitive domain.

On the other hand, the classification of motor and nonmotor domains is not dichotomous, and the two domains are not distinc-

tive. For example, the current task may be considered as an executive control challenge and Kramer and colleagues (1999) have shown that such processes are subserved by the frontal lobes, which are essential to motor control. Furthermore, Jonides (2000) reported that the cerebellum, also integral to motor processes, is active during the negotiation of executive control processes by older men and women. Interestingly, Isaacs et al. (1992) reported significant changes in rat cerebellum as a result of physical activity. Collectively, these findings suggest that motor adaptations that accrue from physical activity involvement may also be related to benefits in the cognitive domain (i.e., P3).

In addition to age-related differences in P3 latency to the discrimination task (S2), older adults showed equipotentiality (i.e., reduced heterogeneity) of amplitude across the cortical regions relative to that observed in younger adults. This finding corroborates previous aging research in which increased homogeneity of P3 amplitude was related to a breakdown of "functional autonomy of areas within the aging brain" (Dustman et al., 1996).

In the current investigation, age-related differences in P3 amplitude were confined to the frontal regions as increased amplitude was found for older, compared to younger, participants. The notion that the frontal lobes exhibit the greatest decline with age has received support from other researchers as well. Dempster (1992) reviewed the role of the frontal lobes in cognitive development and stated that they are "one of the first to show signs of deterioration with age" and that there is a significant decrease in blood flow, brain weight, and cortical thickness in these regions. Kramer and his colleagues (1999) have also implied that frontal lobe decline is largely responsible for age-related differences in performance on laboratory tasks. That is, decreased performance in older adults was observed for tasks mediated by executive control processes (e.g., planning, scheduling, inhibition, working memory), but not for other tasks (e.g., simple RT), suggesting that frontal lobe decay is responsible for age-related performance decrements. The frontal lobes are implicated in this research, as they are thought to mediate executive control functions (Kramer et al., 1999). Hence, the current P3 amplitude findings support previous aging research, which suggest the frontal lobes are primarily responsible for changes in cognitive processes across the life span.

However, differences based on fitness were not observed for P3 amplitude to the decision task. This suggests that although age influences the updating of memory processes associated with decision tasks, especially in the frontal regions, no such influences can be attributed to differences in aerobic training or physical activity history.

The Motor Period

CNV. The final ERP measured in the three-stimulus paradigm was the CNV, which occurred between the decision task (S2) and the response cue (S3), and emerged following the completion of the P3 waveform to S2. Age differences were observed across hemispheres as younger adults exhibited increased CNV amplitude in the left compared to the right hemisphere, an effect not found for older participants. Namely, younger adults exhibited the expected amplitude increase in the contralateral left hemisphere that has been previously found in research, which implemented right-handed tasks to elicit the CNV (Brunia & Vingerhoets, 1980). Upon inspection of the means, it was apparent that older participants not only showed decreased amplitude in the left hemisphere, but they also exhibited increased amplitude in the right hemisphere compared to younger participants. Because these findings have not been previously reported in the literature, interpretation is made

using the P3 amplitude literature on aging (Dustman, Emmerson, & Shearer, 1990). Specifically, the lack of amplitude differentiation between hemispheres in older adults would suggest greater relative homogeneity in regional neural activity, whereas the effect observed for younger adults may be characterized by increased regional specificity (Dustman, Emerson, & Shearer, 1990). Decreased regional specificity or the increased allocation of neural resources may have been necessary for older adults to prepare for the upcoming motor task (S3). Alternatively, younger adults allocated specific motor resources to execute task demand.

A significant main effect for fitness was also observed along midline electrode sites with increased CNV amplitude for sedentary compared to aerobically trained participants. This was the strongest and clearest finding regarding the influence of fitness on the neural processes during the protocol and is consistent with the specificity hypothesis. One possible interpretation for this result is that sedentary adults, regardless of age, allocate increased neural resources to prepare for motor execution relative to aerobically trained participants. This finding is especially interesting given that the behavioral findings (RT and percentage of correct responses) did not differ between the four groups, suggesting that differences in CNV amplitude may relate to the efficiency of neural resource allocation necessary for task execution. Given that the fit participants allocated decreased neural resources (i.e., decreased CNV amplitude) compared to sedentary participants, their motor preparation may be characterized by increased efficiency (Hatfield & Hillman, 2001; Sparrow, 1983).

Behavioral responses. While previous investigations have found age-related differences in RT (Spirduso, 1980) and others have shown that these differences are ameliorated by fitness (Sherwood & Selder, 1979), the present study employed a unique reactive-task protocol. Other research incorporated tasks in which participants were unable to prepare for the behavioral cue (Sherwood & Selder, 1979; Smulders, Kenemans, Schmidt, & Kok, 1999). That is, the ISI varied between the warning and imperative stimuli so that participants were prevented from anticipating the presentation of the response cue prior to responding. The current study, by necessity, employed a fixed fore period prior to the imperative stimulus (S3) in order to derive the CNV and maximize its amplitude. Therefore, participants were more likely to anticipate when the response cue would occur. However, CNV amplitude reached its maximum at S3 and RT latencies were within the expected range, suggesting that although participants were able to anticipate the response cue, they did not execute their decision until the presentation of that stimulus.

An alternative explanation for the lack of observed age- and fitness-related differences for RT may have been due to an insufficient sample size for this particular measure. Although observed power was sufficient for ERP measures, lower power was found for RT. Hence, future research will have to incorporate larger sample sizes when exploring age and fitness RT differences using a fixed ISI period. Lastly, as differences in percentage of correct responses did not differ between groups, and the findings are similar to previous reports using this task (Hillman et al., 2000), it is suggested that fitness-related differences in CNV amplitude are due to motor preparation rather than other cognitive processes involved in decision-making.

Summary

The results are consistent with the literature regarding the electrophysiological changes with aging. Furthermore, some support was

found for the influence of fitness on cognition, but a stronger relationship was found with motor processes (i.e., preparation). As such, it appears that the specificity hypothesis was supported to a greater degree than that of a more generalized nature, implying that physical activity involvement is primarily associated with adaptations of motor structures.

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