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Age and physical activity influences on action monitoring during task switching

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Abstract

Behavioral and neuroelectric indices of action monitoring were compared for 53 high and low physically active older (60–71 years) and younger (18–21 years) adults during a task-switching paradigm in which they performed a task repeatedly or switched between two different tasks. The error-related negativity (ERN) of a response-locked event-related brain potential (ERP) and behavioral measures of response speed and accuracy were measured during the heterogeneous condition (switching randomly between two tasks) of the switch task. Results indicated that older adults exhibited a greater relative slowing in RT during heterogeneous blocks and smaller ERN amplitude compared to younger adults. Additionally, physical activity differences revealed a relatively smaller global switch cost for physically active older adults and decreased ERN amplitude, as well as increased post-error response slowing for older and younger physically active participants, compared to their less physically active counterparts. The findings suggest that both age and physical activity participation influence behavioral and neuroelectric indices of action monitoring and provide further evidence for the beneficial effects of physical activity on executive control.

Keywords: Aging; Executive control; Exercise; Cognitive function; Error-related negativity (ERN); Event-related brain potentials (ERPs)

1. Introduction

The slowing of cognitive and motor processes with advanced age appears to be a robust phenomenon [55,58], with the extant literature indicating that older adults exhibit relative deficits in performance using a variety of tasks involving attention, cognition, and memory [40,45,46,48,57,59]. These age-related decrements in performance appear to be greater for tasks or task components that involve greater amounts of executive control [16,31,58].

The term “executive control” refers to a subset of processes, related with the selection, scheduling, coordination, and monitoring of computational processes that are responsible for perception, memory, and action [39,44]. Older individuals show notable deficits in performance (i.e., reaction time (RT), accuracy) relative to younger adults across an array of tasks requiring greater amounts of executive control [16,30,31,32]. In contrast, age-related deficits in performance are markedly reduced on tasks that place smaller demands on executive control [58].

Working memory function is critical for executive control [42,49], and task-switching paradigms [1,5,51,52] have been used to study the subset of executive control processes related to working memory function in older adults. In one version of this task, participants view a series of single digit numbers and perform one of two specific rule-based tasks (i.e., indicate if number is odd or even versus greater or less than 5) on each trial. Trials are grouped into homogenous task blocks (trial blocks of exclusively one task rule set) or heterogeneous task blocks (trial blocks of two tasks requiring switches between rule sets across individual trials). Overall

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performance deficits (i.e., RT slowing) in heterogeneous task blocks relative to homogenous task blocks have been labeled "global switch costs" [5,38,51], and index the difficulty of maintaining multiple task sets in working memory and the manipulation/selection among these task sets on each trial [5]. Differences in performance on switch and non-switch trials in the heterogeneous blocks have been identified as "specific switch costs" [5,38,51], and reflect the effectiveness of activating the currently relevant task set and deactivating the previously relevant task set. Research has generally indicated smaller age-related specific switch costs when the effects of overall slowing are taken into account [31,36,52] and larger age-related global switch costs [31,35,36,37, but see also 5 and 52]. These switch costs have been interpreted to indicate working memory deficits in older adults. Moreover, research with a variety of other cognitive tasks (e.g., response compatibility, response inhibition, etc.) that tax working memory function has also documented deficits in older individuals across behavioral [32,33], event-related brain potential (ERPs; [24]), and neuroimaging [16] measures.

Given this evidence of declining executive control and related behavioral impairment with age, the examination of factors associated with the preservation of executive control in older individuals is of great interest in improving their cognitive health and effective functioning. One factor that has been shown to maintain cognitive health, and in particular executive control function, during older adulthood is physical activity [11,23,26,33,55,56]. Generally, research has indicated that increased participation in physical activity benefits behavioral components of cognitive function. Interestingly, physical activity influences on cognitive function appear to be greater for tasks or task component involving extensive executive control [11]. Colcombe et al. [10] extended these finding by documenting the beneficial effects of physical activity on brain function in older adults. Aerobically trained older adults, compared to non-aerobically trained control participants, evidenced increased activation of task-related prefrontal and parietal brain regions involved in executive control. This increase in the recruitment of relevant brain regions for higher-fit individuals suggests "an increase in the ability of the frontal attentional circuitry to bias task-related activation in posterior regions of cortex" ([10], p. 3320).

Although behavioral measures in a variety of cognitive tasks have been used to study physical activity benefits on cognitive function, the use of ERP measures to index underlying processes involved in cognitive function has been limited. In fact, ERP research has focused almost exclusively on the P3 component of the stimulus-locked ERP. P3 is believed to index working memory processes related to target detection and context updating [18,34], and available evidence suggests that physical activity is related to increased amplitude and decreased latency of this component, suggesting greater allocation of attentional resources and faster processing speed, respectively [23,24].

Examination of other components of the ERP may provide for greater understanding of age and physical activity effects on other executive control processes. One such component is the error-related negativity (ERN; [22] or N_e; [19]). The ERN is a negative-going waveform observed in response-locked ERP averages on trials in which an incorrect response was produced. It is maximal over fronto-central recording sites and peaks shortly after responses in speeded RT tasks [19,22]. Researchers have localized the source of the ERN to be at or very near the anterior cingulate cortex (ACC) using dipole localization techniques, and corroborating evidence has been provided by neuroimaging studies [7,15,41].

Available evidence suggests that the ERN is a neuroelectric correlate of a subset of executive control processes related to action monitoring. However, two distinct theories have been proposed to explain the specific processes that relate to ERN activation. One theory holds that the ERN is generated during error commission as part of a reinforcement learning process [27]. This theory proposes that the function of the ACC is to select between competing mental processes and the ERN is generated through a reduction in dopaminergic activity in response to an error, which disinhibits the ACC. In turn, the ACC selects the appropriate motor controllers to successfully complete the task based upon this input [27]. An alternative theory suggests that the ERN is reflective of a more general conflict monitoring process [6]. This process is part of a system involving the ACC that detects (or monitors) levels of conflict among incompatible processing streams. This information is then transmitted from the ACC to processing control centers, which triggers adjustments in relative influences on processing among the control centers [6].

Consistent with these theories regarding the functional significance of the ERN, researchers have observed that it is largest in situations where the recruitment of additional executive control is required for adaptive task performance [6,19,54,60]. For example, as indicated above, ERN is largest on trials where response errors have occurred, and increased ERN magnitude predicts changes in behavior that suggest increased recruitment and implementation of executive control on subsequent trials (e.g., response slowing, increased accuracy; [22]). Neuroimaging studies have documented that the ACC is activated in task conditions that elicit response conflict in participants (e.g., incongruent trials in the Stroop task; [8,29]). Moreover, similar to the neuroelectric findings for ERN, ACC activation on the current trial task conditions that elicit response conflict predicts recruitment of other prefrontal neural structures believed to be crucial for the subsequent implementation of executive control on the following trials [29].

ERN amplitude has been found to be smaller for older, compared to younger, adults, which may reflect a relative degradation in the output of this action monitoring system in situations that require recruitment of extensive executive control [2,20,43]. To date, the influence of physical activity on ERN amplitude has not been examined. However, neuroimaging research [10] found a relative reduction in both behavioral conflict and ACC activation for aerobically trained older adults. This has been interpreted to suggest that action monitoring processes in ACC were not activated as strongly in fit older adults because behavioral/response conflict was reduced through greater top-down executive control during task performance.

The present study was designed to selectively examine age-related declines in a subset of executive control processes related to action monitoring by evaluating the influence of age and physical activity on task performance and ERN during a task-switching task. With respect to task performance, it was expected that older participants would display significantly larger global and specific switch costs. Physical activity was expected to moderate these age-related deficits, such that switch costs would be reduced and post-error slowing would be prolonged as physical activity increased in older adults. With respect to action monitoring processes indexed by ERN, it was predicted that older participants would exhibit impaired action monitoring (indicated by decreased ERN accompanying impaired task performance). If observed, this would extend the existing literature on age effects on ERN to the task-switching paradigm. If physical activity ameliorates the predicted age-related behavioral switch costs by improving action monitoring processes in older adults, physical activity should moderate the age-related reduction in ERN. Finally, the mediating effects of ERN on factors relating to switch task performance, and the moderating effects of age and physical activity on this relationship were examined to provide initial tests of implicit assumptions about causal relationships between action monitoring processes and switch task performance among older and physically active participants.

2. Method

2.1. Participants

Sixty-six participants (34 men, 32 women) who varied in age and self-reported physical activity history were recruited for this study. Older adults ($n = 32$; 60–71 years) were recruited from the Champaign County area via advertisements and young adults ($n = 34$; 18–21 years) were recruited from undergraduate kinesiology courses. For their participation, older adults received US $20 and younger adults received extra course credit. All participants reported being free of neurological disorders, cardiovascular disease, any medications that influence central nervous system function, and had normal (or corrected to normal) vision based on the minimal 20/20 standard. Thirteen participants were excluded from the current analyses because they did not commit a sufficient number of errors (<5 errors) in the task heterogeneous condition, thus analyses were performed on 53 participants. These participants did not differ significantly from the initial sample in age or physical activity level, $t(64) \leq 0.9$, $p \geq 0.38$.

2.2. Procedure

After providing informed consent in accordance with the Institutional Review Board at the University of Illinois, participants completed the following questionnaires: a health history questionnaire, a handedness inventory [9], the Beck depression inventory (BDI; [4]), the Mini Mental State Exam (MMSE; [21]), and the Yale Physical Activity Survey for Older Adults (YPAS; [17]). The MMSE and the YPAS were administered by the experimenter. Participants were then seated in a comfortable chair in front of a computer screen and prepared for neuroelectric measurement in accordance with the Society for Psychophysiological Research guidelines [47]. Participants were given task instructions and allowed 10 practice trials prior to each of the three task blocks. Following the completion of the last block, participants were briefed on the purpose of the experiment.

2.3. Task

The switch task employed was modified from one previously used by Salthouse et al. [52] with older and younger adults. Participants viewed a series of white numeric digits (digits 1–9, excluding 5) on a black background presented focally on a computer monitor at a distance of 1-m. Each digit was outlined by a solid or dashed box, which completely surrounded the digit. Digits were presented for 200 ms with an inter-stimulus interval (ISI) of 2000 ms. The digits were grouped into three task blocks, with a brief rest period between each block. The first two blocks (i.e., homogeneous tasks) contained 64 trials each on one of two simple tasks that consisted of the same numeric stimuli. These blocks were counterbalanced across participants. The border of the box surrounding the digits indicated which task was performed in each block. In one homogeneous block, participants indicated if each digit was greater or less than the digit “5” by pressing one of two buttons on a small response box held in both hands. In the other homogeneous block, participants indicated if each digit was odd or even using the same two response buttons. In the heterogeneous block, participants performed both tasks with the specific task on each trial indicated by the border (i.e., solid or dashed box). The stimuli were randomly ordered and no more than seven consecutive trials occurred for either task. Participants performed 256 trials (128 of each task) in the heterogeneous block with a brief rest period in the middle of the block. This block contained an equal number of switch and non-switch trials.

2.4. Measures

2.4.1. Physical activity

The Yale Physical Activity Survey for Older Adults [17] was used as the measure of physical activity for all participants. Specifically, total energy expenditure (kilocalories) for

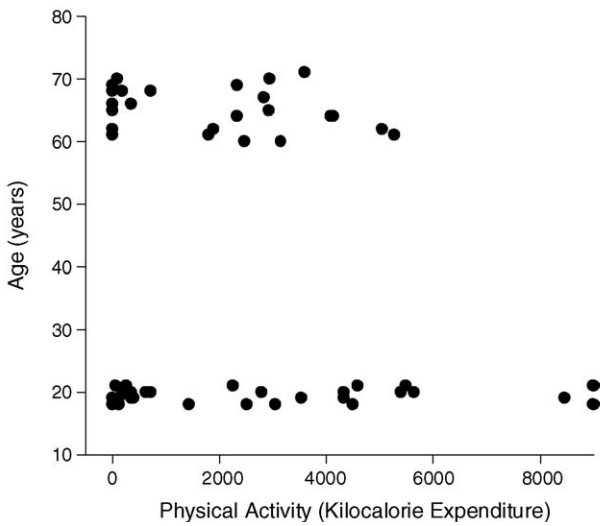

Fig. 1. Distribution of physical activity scores for both older and younger adults.

a typical week during the previous month was calculated from the exercise subsection within the YPAS (for a distribution of physical activity scores for older and younger participants, see Fig. 1).

2.4.2. Error-related negativity (ERN)

Electroencephalographic (EEG) activity was recorded with 13 Ag-AgCl electrodes at F3, Fz, F4, FCz, C3, Cz, C4, CPz, P3, Pz, P4, POz, and Oz, referenced to the left mastoid and re-referenced off-line to average mastoids, while AFz served as the ground electrode. Electrooculographic activity (EOG) was recorded to monitor eye movements using Ag-AgCl electrodes placed above and below the right orbit and on the outer canthus of each eye. All electrodes were positioned according to the international 10–20 system [28] and electrode impedances were kept below 5 kΩ. Neuroscan Synamps bioamplifiers (Neuro Inc., El Paso, TX) were used to continuously digitize (500 Hz sampling rate) and amplify (500×) the raw EEG signal with a 70 Hz low-pass filter, which included a 60 Hz notch filter. EEG activity was recorded using Neuroscan Scan software (v 4.2). Stimulus presentation, timing, and measurement of behavioral response time and accuracy were controlled by Neuroscan Stim software (v 2.0). Off-line EEG processing included: low-pass filtering (15 Hz; 24 dB/octave), eyeblink correction using a spatial filter [13], response-locked epoching (−500 to 1500 ms relative to behavioral response), baseline correction (200–100 ms pre-response period; [43]), and artifact rejection (epochs with signal that exceeded ±100 μV were rejected). Average ERP waveforms for error trials at midline sites (Fz, FCz, Cz, Pz) during the heterogeneous block included a minimum of five error trials. An insufficient number of errors were observed during the homogeneous (i.e., single task) blocks across all participants, and thus these data were not included in ERN analyses. Average ERP waveforms for midline sites for correct trials were matched to error trial waveforms on number of trials and response time to protect against differential artifacts from any stimulus-related activity [12]. Matching involved selecting individual correct trials, without replacement, that matched the response time for each of the error trials. ERN was quantified as the maximum negative deflection between 0 and 200 ms post-response in each of these two average waveforms at each site [22]. For ease of interpretation, scores were inverted such that larger positive values represented greater negative deflections.

2.4.3. Response time and accuracy

Behavioral data were collected on response latency (time in ms from the presentation of the stimulus) and response accuracy (correct and error responses) for all trials across task blocks. Global switch cost was indexed by subtracting each participant's average RT for correct trials in the homogeneous blocks from their average RT for correct trials in the heterogeneous block. Specific switch cost was indexed by subtracting each participant's average RT for correct non-switch trials in the heterogeneous block from their average RT for correct switch trials in the heterogeneous block. Post-error response slowing was calculated by subtracting each participant's average RT for correct trials following a matched-correct trial from their average RT for correct trials following an error.

3. Results

3.1. General analytic strategy

The primary analyses involved multiple regressions with age (old versus young), physical activity, and their interaction as independent variables. This multiple regression approach allowed the use of physical activity as a continuous variable (as measured), rather than forcing an artificial dichotomization of this variable with associated information loss that would be necessary with ANOVA techniques. In addition, these regression analyses facilitated tests of mediation and moderation involving our primary neuroelectric measure of action monitoring processes, ERN. There were three primary sets of regression analyses. In the first set of regression analyses, demographic and other participant characteristics were dependent measures. In the second regression analysis, response time slowing associated with global switch cost (i.e., RT in task heterogeneous minus homogenous blocks), specific switch cost (i.e., RT in switch trials minus RT in non-switch trials in task heterogeneous block) and post-error response slowing (i.e., RT following errors minus RT following matched-correct trials in task heterogeneous block), were used as the dependent measures. In these analyses, we also included overall response speed (measured in the homogenous task block) as a covariate to control for expected age-related differences in overall responding. In the final primary analysis, ERN was the dependent measure. Following these primary analyses, additional regression analyses were conducted to test for mediation and moderation (as outlined by [3]) of significant effects.

3.2. Participant characteristics

Participant scores for the MMSE, BDI, and years of education were regressed on age, physical activity, and their interaction. Significant age effects were present for all three variables, with older adults having significantly lower scores on the MMSE, partial correlation (pr) = −0.36, $t(49) = 2.68$, $p = 0.01$ ($M = 28.1$ versus 29.1 for older and younger adults, respectively), significantly higher scores on the BDI, pr = 0.30, $t(49) = 2.21$, $p = 0.03$ ($M = 4.3$ versus 2.6, respectively), and significantly more years of education, pr = 0.62, $t(49) = 5.55$, $p < 0.001$ ($M = 17.4$ versus 13.7, respectively). However, it is important to note that all participants scored within the normal range for these tests (i.e., MMSE, BDI), indicating that none of the participants exhibited signs of dementia or depression (i.e., all MMSE scores >23 on a maximum score of 30; all BDI scores <13 on a maximum score of 63). Additionally, due to the fact that none of the younger participants had completed their bachelor's degree, the age effect on years of education was also expected. No significant physical activity or age × physical activity effects were observed.

3.3. Response time and accuracy

3.3.1. Global switch cost

As expected, RT on correct trials was significantly slower during the heterogeneous task blocks ($M = 1009.4$ ms, S.D. = 216.0) compared to the homogeneous task blocks ($M = 547.2$ ms, S.D. = 100.4), $t(52) = 20.99$, $p < 0.001$, $\eta^2 = 0.89$, indicating the expected global switch cost. The magnitude of this global switch cost (i.e., difference in RT between heterogeneous and homogeneous blocks) was regressed on age, physical activity, and their interaction to determine if these factors affected the switch cost. Overall response speed was entered into the first step as a covariate in this analysis. The overall regression model was significant, $R^2 = 0.58$, $F(4, 48) = 16.39$, $p < 0.001$. As expected, the overall response speed covariate was also significant, pr = 0.34 $t(51) = 2.56$, $p = 0.01$, indicating that individuals who responded slower overall also tended to exhibit greater global switch costs. A significant main effect of age was observed, pr = 0.69, $t(48) = 6.60$, $p < 0.001$, indicating that older participants ($M = 580.1$ ms, S.D. = 81.5) exhibited greater relative global switch cost compared to younger participants ($M = 355.5$ ms, S.D. = 132.7). A significant age × physical activity interaction was also observed, pr = −0.34, $t(48) = 2.48$, $p < 0.02$. To further examine this interaction, it was decomposed into separate zero-order correlations between physical activity and global switch cost in older and younger participants. A significant negative correlation was observed among older adults, $r = -0.61$, $p = 0.002$, indicating that increased physical activity was associated with a smaller relative global switch cost (i.e., less behavioral slowing) during the heterogeneous block. In contrast, no significant relationship between physical activity and global switch cost was observed among younger participants, $r = 0.17$, $p = 0.37$. No significant effects were found for response accuracy.

3.3.2. Specific switch cost

Within heterogeneous task blocks, RT on correct switch trials was significantly slower ($M = 1084.6$ ms, S.D. = 262.1) than RT on correct non-switch trials ($M = 934.1$ ms, S.D. = 176.2), $t(52) = 9.63$, $p < 0.001$, $\eta^2 = 0.64$, indicating the expected specific switch cost. The specific switch cost (i.e., difference in response latencies between switch and non-switch trials in the heterogeneous blocks) was regressed on age, physical activity, and their interaction to determine if these factors affected the specific switch cost. Again, overall response speed was entered into the first step as a covariate in this analysis. The overall regression model was significant, $R^2 = 0.54$, $F(4, 48) = 14.38$, $p < 0.001$. As expected, the overall response speed covariate was also significant, pr = 0.54, $t(51) = 4.60$, $p < 0.001$, indicating that individuals who responded slower overall also tended to exhibit greater specific switch costs. A significant main effect of age was observed, pr = 0.53, $t(48) = 4.28$, $p < 0.001$, indicating that older participants ($M = 229.58$ ms, S.D. = 112.04) exhibited greater relative specific switch cost compared to younger participants ($M = 85.02$ ms, S.D. = 62.74). A significant age × physical activity interaction was also observed, pr = −0.33, $t(48) = 2.43$, $p < 0.02$. To further examine this interaction, it was decomposed into separate zero-order correlations between physical activity and specific switch cost in older and younger participants. No significant correlations were observed for either older or younger participants. However, a non-significant negative correlation was observed among older adults, $r = -0.23$, $p = 0.27$, while a

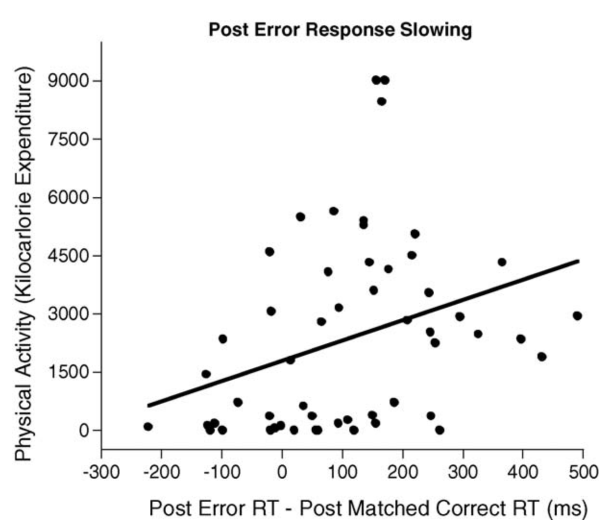

Fig. 2. Scatter plot of physical activity effect on response slowing.

non-significant positive correlation was observed among younger participants, $r = 0.26$, $p = 0.18$, which would account for the significant age × physical activity interaction.

3.3.3. Post-error response slowing

The magnitude of post-error response slowing (i.e., difference in RT for correct trials following error trials compared to correct trials following matched-correct trials) was regressed on age, physical activity, and their interaction to determine if these factors affected post-error response slowing. Overall response speed was included in the first step as a covariate in this analysis. The overall regression model was significant, $R^2 = 0.20$, $F(4, 48) = 2.91$, $p = 0.03$. A significant effect of physical activity was observed, pr = 0.33, $t(48) = 2.92$, $p = 0.005$, indicating that post-error response slowing increased as physical activity increased, regardless of participant age (see Fig. 2). Further, response accuracy following errors was regressed on age, physical activity level, and their interaction to determine if these factors affected post-error accuracy. The overall regression model was non-significant, $R^2 = 0.11$, $F(3, 49) = 1.93$, $p = 0.14$, suggesting that age, physical activity, and their interaction did not influence accuracy following an incorrect response.

3.4. Error-related negativity

An accuracy (correct versus incorrect) × site (Fz, FCz, Cz, Pz) multivariate repeated measures ANOVA [50] was conducted on ERN magnitude to verify that these data indicated the expected topography and accuracy effects for ERN (for ERP waveforms by site, see Fig. 3). As expected, significant accuracy, $F(1, 52) = 16.02$, $p < 0.001$, $\eta^2 = 0.24$, site, $F(3, 50) = 21.85$, $p < 0.001$, $\eta^2 = 0.57$, and accuracy × site, $F(3, 50) = 6.26$, $p = 0.001$, $\eta^2 = 0.27$, effects were observed. Decomposition of the accuracy × site interaction into simple accuracy effects at each midline site revealed the expected significant and largest accuracy effect (ERN magnitude larger on incorrect versus correct trials) at Cz, $F(1, 52) = 20.58$, $p < 0.001$, $\eta^2 = 0.28$, with smaller but significant effects at

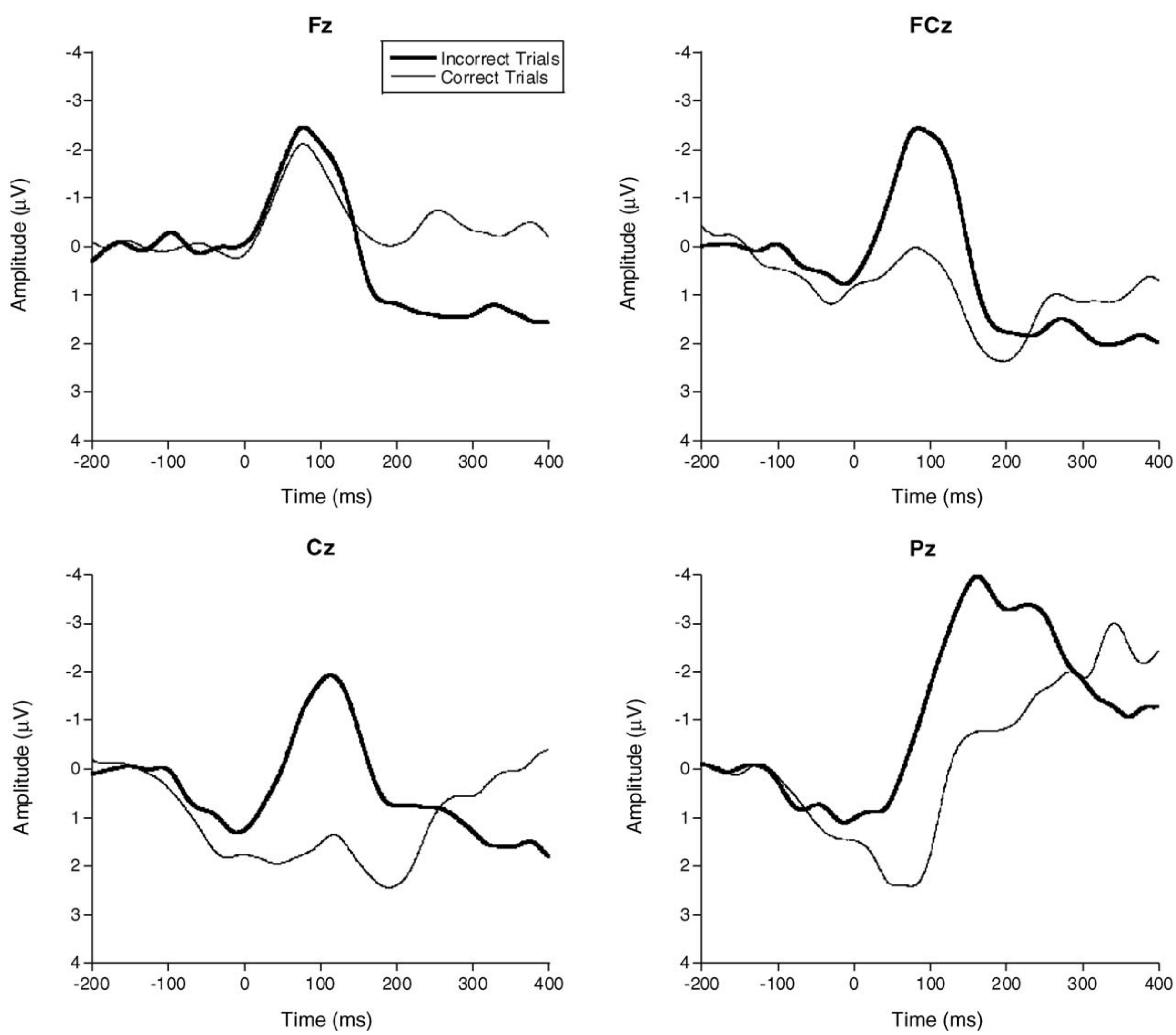

Fig. 3. Grand averaged response-locked waveforms at the four midline electrode sites (Fz, FCz, Cz, Pz) for incorrect and correct responses.

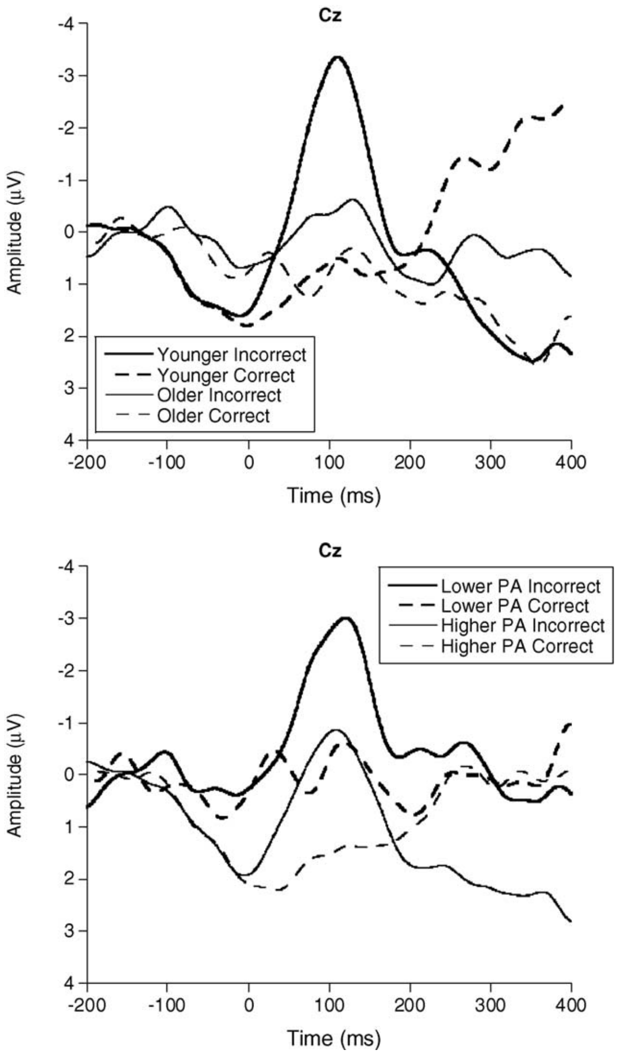

Fig. 4. Grand averaged response-locked waveforms for age and physical activity (PA) effects on incorrect and correct trials at the Cz electrode site. A median split was performed for physical activity to facilitate the display of these data.

surrounding sites, FCz, $F(1, 52) = 14.31$, $p < 0.001$, $\eta^2 = 0.22$ and Pz, $F(1, 52) = 14.24$, $p < 0.001$, $\eta^2 = 0.22$. No significant simple effect of accuracy was observed at Fz ($p = 0.852$). Accordingly, all subsequent analyses involving ERN use magnitude scores from the error trial waveforms at Cz [14].

ERN was regressed on age, physical activity level, and their interaction. The overall regression model was significant, $R^2 = 0.19$, $F(3, 49) = 3.85$, $p < 0.02$. A significant main effect of age was observed, pr = −0.39, $t(49) = 2.98$, $p = 0.005$, indicating that ERN was smaller in older ($M = -1.8$ μV, S.D. = 2.2) relative to younger participants ($M = -4.3$ μV, S.D. = 4.4). Similarly, a significant main effect of physical activity was observed, pr = −0.29, $t(49) = 2.12$, $p < 0.04$, indicating that ERN decreased as physical activity increased. No significant interaction was observed for these two factors ($p = 0.893$). See Fig. 4 for grand-averaged ERN waveforms by age and physical activity.

Table 1
Age, physical activity, and ERN effects on global switch cost

Variable	B	S.E. B	β	pr	t	Sig.
Step 1						
Baseline RT	0.54	0.21	0.34	0.34	2.56	0.013
Step 2						
Baseline RT	0.06	0.18	0.04	0.05	0.34	0.734
Age	225.0	34.1	0.70	0.69	6.60	<0.001
PA	0.001	0.01	0.01	0.001	0.002	0.998
Age × PA	−0.04	0.01	−0.24	−0.34	2.48	0.017
Step 3						
Baseline RT	−0.402	0.17	−0.01	−0.02	0.11	0.915
Age	263.2	35.7	0.82	0.73	7.36	<0.001
PA	0.004	0.01	0.06	0.09	0.61	0.542
Age × PA	−0.04	0.01	−0.22	−0.34	2.48	0.017
ERN	−10.85	4.3	−0.25	−0.34	2.51	0.015

Steps 1 and 2 represent the global switch cost analysis, and Step 3 represents the inclusion of the mediation analysis.

3.5. ERN mediation of switch task effects

Previous analyses demonstrated significant age and age × physical activity effects on both global and specific switch costs. Moreover, age significantly affected ERN. Therefore, it is possible that ERN might mediate the age or age × physical activity effects on switch task performance. A hierarchical regression was performed to test for ERN mediation [3]. The first and second steps of this regression reproduce analyses reported above with global switch cost regressed on age, physical activity, and their interaction (see Table 1). ERN was added to this model in the third step. A significant effect of ERN was observed, pr = −0.34, $t(48) = 2.51$, $p < 0.02$, indicating that greater ERN was associated with increased global switch cost, consistent with the proposed functional significance of ERN in action monitoring processes that track the response conflict associated with this behavioral interference. However, the addition of ERN did not reduce magnitude of the age or age × physical activity effects, indicating that ERN did not mediate these effects. In other words, variation in the activation of the action monitoring processes indexed by ERN did not explain either the switch cost deficit observed overall in older adults or the reduction in this deficit among physically active older adults. The addition of ERN to the regression models regarding specific switch costs and post-error response slowing did not result in significant effects, suggesting that ERN amplitude was not associated with the magnitude of either specific switch costs or post-error response slowing.

3.6. Moderation of ERN/switch task relationship

The previous mediation analyses demonstrated that ERN magnitude was significantly related to global switch cost (i.e., increasing ERN associated with increasing switch costs). A hierarchical regression was performed to determine if the ERN relationship with global switch cost was moderated by either age or physical activity [3]. In the first step of this

Table 2
Hierarchical regression results to test age and physical activity moderators

Variable	B	S.E. B	β	pr	t	Sig.
Step 1						
Age	262.0	32.7	0.82	0.75	8.01	<0.001
PA	−0.004	0.01	0.06	0.09	0.63	0.529
ERN	−10.97	4.4	−0.26	−0.33	2.48	0.017
Step 2						
Age	260.8	31.1	0.82	0.77	8.38	<0.001
PA	0.004	0.01	0.06	0.09	0.61	0.542
ERN	−10.87	4.2	−0.25	−0.35	2.58	0.013
PA × ERN	−0.005	0.01	−0.23	−0.36	2.62	0.012
Age × ERN	6.57	10.7	0.06	0.09	0.62	0.541

regression, global switch cost was regressed onto ERN with age and physical activity included to control for these factors (see Table 2). In the second step, age × ERN and physical activity × ERN interaction terms were added to test if either of these factors moderated the ERN–switch cost relationship. The age × ERN interaction was not significant ($p = 0.54$). However, a significant physical activity × ERN interaction was observed, pr = 0.36, $t(47) = 2.62$, $p = 0.01$, indicating that the magnitude of the ERN relationship with global switch cost varied according to physical activity. To further examine this moderating effect of physical activity, a median split was performed on physical activity (i.e., kilocalorie expenditure) to divide the sample into lower active and higher active participant groups. The partial correlation (controlling age) between ERN and global switch cost was significant in higher active participants, pr = 0.45, $p = 0.02$, but not lower active participants, pr = 0.17, $p = 0.40$. In other words, the ERN–switch cost relationship, with increased ERN tracking the increased response conflict indexed by the global switch cost, was observed only in the higher active but not lower active participants (see Fig. 5).

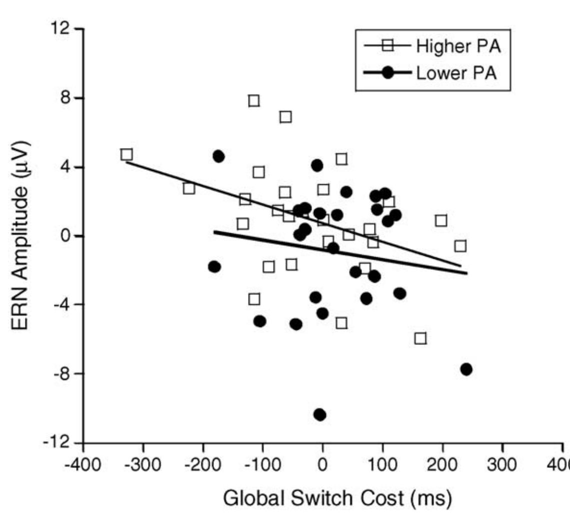

Fig. 5. Scatter plot for the relationship between residuals for physical activity (PA) and global switch cost after controlling for the influence of age. A median split was performed for physical activity to facilitate the display of these data.

4. Discussion

The present study confirmed conclusions from the existing research on age-related decrements in cognitive performance. Older adults exhibited relatively greater global and specific switch costs than younger adults, corroborating previous research indicating that age-related declines are evident for tasks involving extensive executive control [36,37]. Further, the present investigation examined the role of physical activity in older adults. Findings revealed cognitive benefits of physical activity on older participants in relation to global switch costs, and suggest that physical activity may exhibit a larger influence on global switch costs due to the increased working memory load required for task heterogeneous blocks compared to task homogeneous blocks, replicating previous research that has examined the influences of physical activity on task performance in older adults [33]. These data suggest that adopting a more physically active lifestyle may impart processing benefits for older adults, and may extend to tasks requiring extensive amounts of executive control associated with working memory load.

Analysis of the ERN component of the response-locked ERP provided a test of the contribution of action monitoring processes to the observed age and physical activity effects on task-switching performance. First, ERN magnitude covaried positively with global switch costs, such that increased ERN was observed with increased response time slowing in task heterogeneous blocks. This relationship is consistent with current views of ERN as an index of action monitoring processes triggered by the detection of task errors and/or response conflict. Task heterogeneous blocks are characterized by both increased error rates and conflict between competing task sets. Thus, increased ERN is expected to result from detection of the associated task performance problems in these blocks. Furthermore, activation of these action monitoring processes in response to task performance decrements would be expected to result in the recruitment of additional top-down attentional control to improve performance on subsequent trials (e.g., [29]).

Age-related differences in ERN amplitude have been observed previously using flanker [20,43], choice RT [20], and mental rotation [2] tasks, with older adults exhibiting decreased ERN amplitude relative to younger adults. Falkenstein et al. [20] have suggested that these age-related decreases in amplitude are evidence for a relative weakening of action monitoring processes in older adults. The current findings extend these observations of age-related ERN deficits to the task-switching paradigm, a task that places large demands on working memory function. Despite significant relative decrements in task performance among older adults, robust activation of action monitoring processes that are typically recruited when errors or conflict is detected was not observed.

However, mediation analyses suggest that the ERN-indexed deficits in action monitoring do not account for the increased switch costs among older adults. Specifically, in mediation analyses that controlled for variation in ERN, older adults continued to display increased switch cost deficits relative to younger participants. This suggests that both reduced ERN and increased behavioral switch costs may result from impairment in other cognitive processes that are earlier in the processing stream for the task-switching paradigm. Although speculative, an age-related working memory deficit represents one such candidate process. As indicated, previous research with the task-switching paradigm and other tasks strongly suggest that working memory function is relatively impaired in older adults. Failure to robustly encode and manipulate the two task sets in heterogeneous task blocks will impair performance and may account for the increased switch costs in older participants. However, this failure to fully encode task sets due to impaired working memory would also be expected to compromise the ability to monitor task performance and detect task errors. In fact, basic research on action monitoring processes has documented that impaired action monitoring can result from "data limitations" related to working memory failures [53]. Thus, both behavioral deficits (i.e., increased switch costs) and impaired action monitoring (i.e., reduced ERN despite increased switch costs) may be secondary to deficient working memory function in older adults.

An overall effect of physical activity, regardless of age, was observed on ERN magnitude. Specifically, as physical activity increased, ERN magnitude decreased, with no sacrifice of task performance (i.e., active participants did not display increased switch costs concurrent with this reduced ERN). This suggests that physical activity may be associated with increased executive control with associated reduction of task-related behavioral conflict. This is consistent with previous theory, indicating that ERN reflects conflict-monitoring processes [6]. This theory suggests that ACC and ERN activation are greater due to the presence of response conflict during task completion. If this conflict is reduced, whether due to increased executive control or decreased concurrent activation of incompatible processing streams, ACC and ERN activation will be reduced as well. This theory suggests that response conflict is reduced on correct trials relative to error trials, suggesting that ERN activation is present during correct trials at a decreased magnitude, which is consistent with our findings. Similarly, if physical activity reduces conflict, ACC and ERN activation would still be evident for physically active individuals, but reduced relative to those individuals who are less physically active. For example, activation of action monitoring processes in the ACC during Stroop task performance can be decreased by manipulations that increase top-down executive control [8]. This has been interpreted to indicate that increased executive control in Stroop decreases response conflict and, by extension, activation of the system designed to respond to indicants of task performance problems such as response conflict. With respect to physical activity, Colcombe et al. [10] demonstrated similar reduced activation of ACC during a flanker task in aerobically fit older adults. Moreover, neuroelectric research has documented increased P3 amplitude in physically active adults to suggest greater working memory function in these individuals [24,25]. The observed reduction in ERN as physical activity increased is consistent with these other observations and suggests that increased top-down executive control among physically active individuals decreased activation of action monitoring processes.

Physical activity also influenced response slowing following response errors, which provides additional support for the notion of increased top-down executive control among physically active individuals. Specifically, a positive linear relationship was observed between post-error response slowing and physical activity. Post-error response slowing is a behavioral indicator of increased recruitment and implementation of additional top-down attentional control to improve performance [22,29]. Therefore, the observed increase in post-error response slowing with increases in physical activity suggests that physically active individuals are allocating more top-down executive control following an error in order to enhance subsequent task performance.

Moreover, the relationship between ERN and global switch cost magnitude was also moderated by physical activity such that the strength of this relationship was greater in higher physically active participants, while no such relationship was observed for lower physically active participants. This suggests a tighter coupling between the action monitoring system and task performance in the physically active participants. Overall, higher physically active individuals showed less activation of action monitoring processes as indexed by ERN. However, for those higher physically active individuals that had greater difficulty with the task (i.e., increased global switch costs), ERN magnitude increased sizably.

Although the synthesis of current finding with other available evidence supports our assertion of increased executive control among active individuals, other interpretations are possible. For example, decreased ERN amplitude in physically active participants could be due to a relative attenuation in attention directed toward behavioral response execution. As just indicated, neuroelectric evidence suggests greater allocation of working memory for attentional resources to task stimuli among higher, relative to lower, physically active individuals [24,26]. Accordingly, physically active individuals may be directing a larger proportion of their finite attentional resources externally toward the task stimuli, instead of internally toward their responses to the stimuli. Consequently, the attentional strategy employed during task negotiation may be different in less physically active adults (i.e., greater attentional resource allocation toward response selection), perhaps leading to a relative increase in ERN amplitude.

5. Limitations

Despite the demonstrated relationships between age, physical activity, ERN, and switch costs and the conduct of mediation and moderation analyses to test implicit causal assumptions, the cross-sectional nature of this study, as well as the lack of random assignment of physical activity participation, limits the strength of the findings because the effects may be attributable to other factors. However, the higher and lower physically active participants were matched on the demographic factors described in the results section, which helps limit other potential influences. Additionally, physical activity was assessed with a self-report measure. Future research should implement a more objective measure of aerobic fitness (e.g., VO_2) to better assess the relationship between physical activity and action monitoring. Despite this limitation, previous research has exhibited a high correlation between the Yale Summary Index and VO_2 peak in 60–80 year old adults [61], suggesting a relationship between this self-report measure and more objective measures of aerobic fitness.

5.1. Summary

In sum, age and physical activity influences on action monitoring processes were examined. Findings suggest that age-related decrements in neuroelectric and behavioral measures of action monitoring extend to the task-switching paradigm. However, the action monitoring and behavioral deficits in older participants may both be secondary to degradation in other executive control processes. Additionally, findings indicate that physical activity benefits working memory function as measured by global switch cost in older adults. These findings add to the growing literature on the beneficial relationship of physical activity on cognitive function and extend this database to include action monitoring.

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