Teresa D. Hawkes*, Wayne Manselle and Marjorie H. Woollacott

# Tai Chi and meditation-plus-exercise benefit neural substrates of executive function: a cross-sectional, controlled study

**Abstract**

**Background**: We report the first controlled study of Tai Chi effects on the P300 event-related potential, a neuroelectric index of human executive function. Tai Chi is a form of exercise and moving meditation. Exercise and meditation have been associated with enhanced executive function. This cross-sectional, controlled study utilized the P300 event-related potential (ERP) to compare executive network neural function between self-selected long-term Tai Chi, meditation, aerobic fitness, and sedentary groups. We hypothesized that because Tai Chi requires moderate aerobic and mental exertion, this group would show similar or better executive neural function compared to meditation and aerobic exercise groups. We predicted all health training groups would outperform sedentary controls.

**Methods**: Fifty-four volunteers (Tai Chi, n = 10; meditation, n = 16; aerobic exercise, n = 16; sedentary, n = 12) were tested with the Rockport 1-mile walk (estimated $VO_2$ Max), a well-validated measure of aerobic capacity, and an ecologically valid visuo-spatial, randomized, alternating runs Task Switch test during dense-array electroencephalographic (EEG) recording.

**Results**: Only Tai Chi and meditation plus exercise groups demonstrated larger P3b ERP switch trial amplitudes compared to sedentary controls.

**Conclusions**: Our results suggest long-term Tai Chi practice, and meditation plus exercise may benefit the neural substrates of executive function.

***Corresponding author: Teresa D. Hawkes,** 711 Human Performance Wing, Air Force Research Laboratory, Wright Patterson Air Force Base, Dayton, OH; University of Oklahoma, 455 W. Lindsey St., Dale Hall Tower 705, Norman, OK 73019, USA,
E-mail: teresa.hawkes@gmail.com
**Wayne Manselle,** University of Oregon, Eugene, OR, USA
**Marjorie H. Woollacott,** University of Oregon, Eugene, OR, USA

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**Acronyms:** BMI = Body mass index, EEG = electroencephalography, ERP = event-related potential, RT = reaction time, VSTS = visuo-spatial task switch

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## Introduction

Health regimens that benefit executive function are under active investigation. Such regimens include meditation [1] and moderate exercise [2–5]. Tai Chi is an ancient health practice from China, often recommended by somatic therapists for relaxation and balance rehabilitation [6, 7]. We report the first controlled study investigating Tai Chi effects on the neural substrates of executive function.

Executive function, also known as executive attention, has a number of key components, including response inhibition, updating of working memory, and mental set shifting [13, 14]. A key neuropsychological test used to evaluate executive function is the Task Switch test. It is used in combination with EEG event-related potentials (ERPs) to evaluate both behavioral and neural substrate levels of executive attention [8–12].

Event-related potentials (ERPs) are averaged EEG signals time-locked to specific stimulus and response events recorded during performance of cognitive tasks [13]. These deflections are thought to index total neural activity in specialized microcircuits operating in parallel neural networks during task execution [9, 14]. ERPs occur within specified time windows at specified electrodes relative to experimentally defined events of interest (i.e. stimulus onset, trial type, button press response onset, and trial by trial response time and accuracy).

Response inhibition, working memory updating, and mental set shifting tasks routinely evoke the P300, a characteristic positive waveform in the time window ~250–800 ms post-stimulus presentation [9, 15–17].

The P300 has been dissociated into two main components, the P3a (electrode Fz) and P3b (electrode Pz), and is associated with activity in the fronto-temporo-parietal executive network [18].

The P3a is thought to index attentional orienting to a relevant stimulus [9, 19], with larger amplitudes indexing more robust allocation of attentional resources to stimuli [20]. Novel stimuli are associated with larger P3a amplitudes while habituation is associated with P3a amplitude reduction [9, 21].

The P3b is thought to index working memory allocation to stimulus processing. Paradigm structure affects the amplitude of the P3b; more complex tests result in smaller amplitudes and longer latencies. Shorter latencies are thought to index more efficient processing [2]. Characteristics of the P300 can be considered a proxy for measurement of executive neural substrates. Thus, this study included P300 component amplitude and latency as proxies for executive function neural substrates within a Task Switch test.

Studies on the association of exercise training with enhancements to P300 ERPs are numerous [2, 3, 5]. Larger P3b amplitudes are seen in elderly adults who regularly engage in moderate aerobic exercise compared to sedentary elderly [3]. Young and older adults participating in regular physical activity showed larger P3b amplitudes and shorter latencies on a task-switching paradigm compared to inactive adults [2].

Exercise has also been shown to lead to improvements in aerobic capacity (i.e. estimated, submaximal, and maximal $VO_2$ Max). Aerobic capacity is the ability of tissues subserving neuromotor behavior to uptake and utilize $O_2$ [22]. Exercise and higher $VO_2$ Max are associated with improvements in cognitive capacity [2, 4, 5]. Importantly, Tai Chi has been shown to require moderate aerobic exertion [23].

Meditation training is also associated with improvements in executive function [1]. Meditation requires focused attention [24], and thus, mental exertion. Importantly, meditation does not require aerobic exertion [25]. Interestingly, Tai Chi is a form of moving meditation [26]. Thus Tai Chi may be considered a practice requiring mental and aerobic exertion.

As noted, Tai Chi effects on aerobic capacity have been documented [23], but there have been no studies examining its training effects on the P300 neuroelectric proxy for executive function [27]. Therefore this study aimed to determine if persons who were long-term Tai Chi practitioners would show enhancements to executive function and aerobic capacity. This pilot cross-sectional observational study compared the performance of individuals who had chronic training in Tai Chi, meditation plus exercise, or aerobic exercise alone to individuals practicing a sedentary lifestyle on estimated $VO_2$ Max and P300 latency and amplitude.

# Materials and methods

## Subjects

Participants were recruited by local Craigslist and newspaper ads, and flyers posted throughout Eugene and Springfield, Oregon. Inclusion criteria were (1) no self-reported neurological or physical disorders, (2) living independently, and (3) aged 20–75. Sedentary participants were required to have (1) a generally inactive lifestyle for 5 or more years, and (2) no prior experience with meditation or Tai Chi. Health regimen practitioners (Tai Chi, Meditation, or Exercise) were required to (1) have practiced at least 5 years or more, three times/week, 30 minutes/session. All participants had self-selected into their preferred level and type of exercise activity. Fifty-nine participants responding to the health regimen recruitment campaign agreed to 4 h of testing scheduled at their convenience. Because acute exercise may positively affect cognitive performance [28, 29], we scheduled cognitive and exercise testing separately. Two participants who could not use a computer effectively were excluded as our executive attention tests were administered via computer. Two subjects did not complete testing. One subject who presented with bipolar disorder was excluded. Thus, 54 subjects completed all tests and were included in this analysis (female = 27). Final group composition was (1) 10 Tai Chi (female = 3), (2) 16 meditation plus exercise (female = 6), (3) 16 aerobic exercisers (female = 8), and (4) 12 generally sedentary (female = 10) participants. Body mass index (BMI) as kg weight/height $m^2$ was recorded (see Table 1). Subject recruitment and experimental protocol were approved by the University of Oregon Institutional Review Board. Subjects gave informed consent and were compensated for their participation.

## Multivariate cross-sectional observational design

In multivariate designs, multiple dependent variables are measured on subjects who are assigned membership in carefully defined groups. In observational designs key

**Table 1** Participant physiological scores.

| Group | n | Females | Age, years | | $VO_2$ Max, mL/kg/min $O_2$ | | BMI, kg/$m^2$ | |
|---|---|---|---|---|---|---|---|---|
| | | | M | SD | M | SD | M | SD |
| Tai Chi | 10 | 3 | 55.4 | 12.99 | 34.14 | 6.34 | 29.3 | 3.77 |
| Meditation | 16 | 6 | 48.63 | 15.00 | 41.83 | 9.04 | 23.3 | 3.53 |
| Aerobics | 16 | 8 | 44.09 | 16.2 | 45.66 | 9.67 | 23.78 | 2.62 |
| Sedentary | 12 | 10 | 46.92 | 12.81 | 28.68 | 5.76 | 27.93 | 6.37 |

Global ranges: Age: 22–75 years; BMI: 18.50–37.90 kg/$m^2$; estimated $VO_2$ Max: 17.23–60.00 mL/kg/min $O_2$.

variables known to affect individual outcomes between subjects should be measured, included in the design, or controlled for statistically. Executive function is known to be affected by aerobic capacity, age, and chronic exercise practice. Thus, our quasi-independent factor was long-term lifestyle (group) divided into three health practice groups: (1) Tai Chi, (2) meditation, and (3) aerobic fitness versus (4) sedentary (non-practicing) controls. Unexpectedly, during data collection our meditation participants all self-reported sufficient aerobic activity to qualify for the aerobic fitness group as well. Thus we had two health practice groups who engaged in combined chronic mental and exercise training. Indeed, each training group reported similar amounts of moderate exercise; thus our health regimen groups were equated on exercise effects. The difference between these groups was attentional focus required to perform their respective health regimens (24, 28): focused while moving, focused while sitting, and unfocused (Tai Chi, meditation, and exercise, respectively). Our dependent measures were: (1) physiological (age, estimated $VO_2$ Max, BMI, P3a and P3b amplitude, and latency) and (2) cognitive [switch reaction time (SwRT) and % local switch costs]. As noted, since age effects have been routinely associated with physiological and cognitive variables, and we were evaluating a large age range, age was entered into our model as covariate.

## Testing measures

### Lifetime health activities self-report

Participants self-reported average daily (minutes) and weekly (days) aerobic exercise, meditation, or Tai Chi practice, and total number of years of practice.

### Aerobic capacity – Rockport 1-mile walk [22, 30]

The Rockport 1-mile walk was administered to all participants according to the protocol of Kline et al. [22]. Ending heart rate, weight, gender, age, and walk time were entered into an online java applet (ExRx.net) [31]. Estimated $VO_2$ Max controlled for age, weight, and gender was obtained (aerobic capacity in mL/kg/min $O_2$ utilized during exercise) [25].

### Executive function test

Visuo-spatial task switch (VSTS) test with dense-array EEG 256-hydrocel, NetAmps 300 system [32] was used. The VSTS was a randomized alternating runs, non-cued VSTS test developed at the Mayr Laboratories, University of Oregon [33]. A red dot stimulus was displayed in a horizontally oriented fixation rectangle on a computer monitor located ~24 inches (60.96 cm) in front of the participant. Participants were trained to respond as quickly and accurately as possible to stimulus appearance using a two-button mouse. In this ecologically valid paradigm, the next stimulus appeared immediately subsequent to each response.

### Button press response rules

Rules 1 and 2 dictated how to indicate the spatial location of a randomly appearing dot within the fixation rectangle. For Rule 1, button press was compatible with dot location. For Rule 2, button press was incompatible with dot location. Trials in which a switch of response rule was not required were designated no-switch trials. For switch trials (Rule 3) participants switched between Rules 1 and 2 on every other trial. In the case of error, participants were provided with visual feedback. They corrected their error and continued the trial block. Participants practiced each rule until they achieved at least 85% accuracy. Rules 1 and 2 consisted of two blocks of 48 trials. Rule 3 consisted of 12 blocks of 48 trials. The test was coded in E-Prime (Psychology Software Tools) for use with dense-array EEG. Events were (1) stimulus type (congruent right, congruent left; incongruent right, incongruent left); (2) trial type (congruent switch, congruent no-switch, incongruent switch, incongruent no-switch); and response (correct or incorrect). This coding allowed us to precisely identify reaction time (RT) associated with each type of trial and stimulus. Percent local switch costs were calculated thus to control for any possible speed-accuracy trade-off effects: (SwRT – No-SwRT)/No-SwRT. P300 ERPs were extracted (see below). Only switch and no-switch trials were evaluated.

### EEG data collection

Dense-array EEG was collected with a 256-electrode Electrical Geodesics (EGI) EEG System 300 and digitized with a 24-bit A/D converter (EGI, Eugene, OR). Data were collected at 250 Hz. Channels were referenced to VREF. Scalp electrode impedances were at or below 5 kΩ. Data were collected in a sound attenuated, EM-shielded booth [32]. Participants were provided with a Table Clamp chin rest.

### EEG data analysis

EGI Netstation EEG data processing workflow for ERP extraction was performed [34]: (1) 2 Hz first-order high-pass and (2) 30 Hz low-pass filters were applied. Data were segmented thus: 300 ms before event to 500 ms after event. Artifact detection (bad channels, eye blinks, and eye movements) was performed. Artifact containing segments were eliminated. All data were hand inspected to identify any remaining bad segments. Bad channel replacement through interpolation from surrounding channels was performed. Segments were averaged by channel, this average was re-referenced to a computed average reference, and then baseline corrected from 300 ms pre-stimulus to 500 ms post-stimulus (32). P300 a and b waveforms were plotted at Fz and Pz, respectively. Magnitude of amplitude and latency were extracted and plotted from baseline-corrected files in the time window 300 ms pre- to 500 ms post-stimulus. The largest-going waveform post-stimulus was defined as peak amplitude (μV). Latency was defined as time (ms) between stimulus onset and waveform peak value.

## Overall data analysis

A multivariate analysis of covariance (MANCOVA) and Levene's test for homogeneity of variance were performed. The conservative Sidak correction (a variant of the Bonferroni correction) was used for post hoc analyses. α was set at 0.05 for the main MANCOVA. A bivariate correlation was run on all variables. To control for α slippage for multiple analyses, a Bonferroni correction was applied, and α was set at 0.0125 for the correlations. Our quasi-independent variable was group. Because normal aging is associated with degradation of cognitive and physiological function, age was included as a covariate. Dependent variables were estimated $VO_2$ Max, BMI, SwRT, percent local switch costs, P3a switch amplitude, P3a switch latency, P3b switch amplitude, and P3b switch latency. Groups were dummy coded as: Tai Chi, 1; meditation plus exercise, 2; aerobic fitness, 3; and sedentary control, 4. All analyses were run with PSAW Statistics 19 (IBM, Chicago, IL). Effect size profile for physiological and cognitive variables was calculated.

### Model

Because age and lifestyle strongly affect cognitive capacity, we compared measures from two key domains: (1) physiological and (2) cognitive between four lifestyle groups (Tai Chi, meditation plus exercise, exercise, and sedentary lifestyle).

# Results

## P300

A P300 complex was observed at midline electrode sites in the time window 300 ms pre- to 500 ms post-stimulus. The P3a and P3b were present across all subjects and groups at Fz and Pz, respectively (see Figure 1). P3a amplitude and latency did not differ between groups, suggesting orientation to incoming stimuli was similar for all participants. P3b amplitude and latency did differ between groups and were included in our model as executive function measures along with SwRT and percent local switch costs.

## MANCOVA

Levene's statistic indicated our data were suitable for the MANCOVA procedure. Our MANCOVA was significant (Wilk's lambda (Λ) ($F(24, 26) = 1{,}417.561$, $p < 0.001$, *partial eta* square = 0.999). This indicates 99% of the variance is explained in our outcome measures. This is

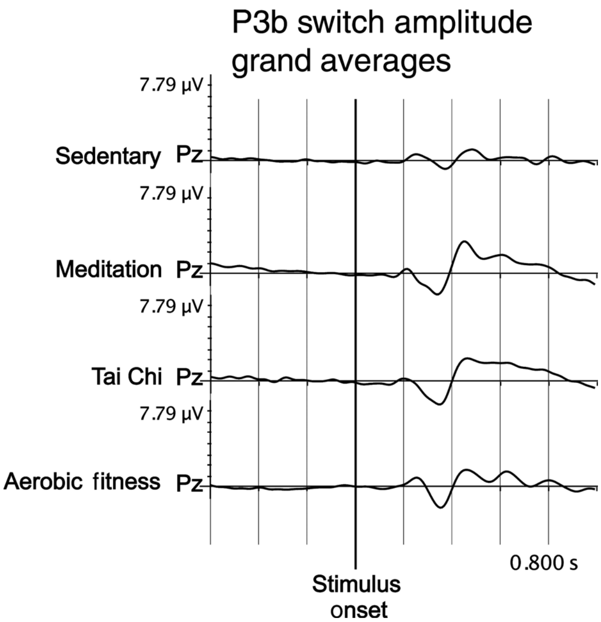


**Figure 1** P3b switch amplitude grand averages by group: Tai Chi, meditation + exercise, aerobic exercise, and sedentary. 800 ms time window.

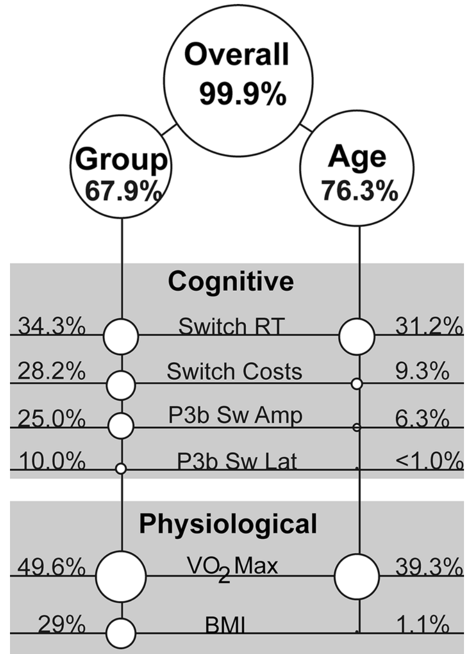


**Figure 2** Effect size profile of group (Tai Chi, meditation + exercise, aerobic exercise, and sedentary) and age in years for key cognitive and physiological variables.
SwRT (ms), percent local switch costs, P3b switch amplitude (µV), age in years, estimated $VO_2$ Max (mL $O_2$/kg/min), and BMI (kg/m$^2$)

unusual and may be due to the inclusion age as covariate in a model with cognitive and physiological measures. Age and group strongly impacted both physiological and cognitive function [2, 20]. Age (Wilk's lambda (Λ) (F(24, 26) = 3.488, p = 0.001, *partial eta* square = 0.763) and group membership (Wilk's lambda (Λ) (F(72, 78.562) = 2.321, p < 0.001, *partial eta* square = 0.679) significantly affected our outcome measures. Age explained ~76% and group membership explained ~68% of our explained variance.

## Effect of age and group on significant dependent measures

The effect size profile for variance explained by group and age for our significant variables is presented in Figure 2. Effect size weights are shown in exact proportion for easier visualization of the interaction between these measures by predictor. Table 1 presents physiological scores by group. Table 2 presents cognitive scores by group.

### Age

As expected, age had a significant effect on (1) $VO_2$ Max (F(1, 49) = 31.789, p < 0.001, *partial eta* square = 0.393). This suggests age accounted for almost 40% of the variance in $VO_2$ Max scores (48). (2) Age also significantly impacted SwRT (F(1, 49) = 22.249, p < 0.001, *partial eta*

**Table 2** Participant cognitive scores.

| Group | n | SwRT | | SCosts | | P3b Amp | | P3b Lat | |
|---|---|---|---|---|---|---|---|---|---|
| | | M | SD | M | SD | M | SD | M | SD |
| Tai Chi | 10 | 453.94 | 110.84 | 14.13 | 11.97 | 3.94 | 2.43 | 256.40 | 122.48 |
| Meditation | 16 | 477.41 | 188.88 | 401.23 | 122.83 | 4.38 | 1.85 | 264.00 | 72.40 |
| Aerobics | 16 | 489.63 | 96.89 | 400.84 | 53.90 | 3.13 | 1.45 | 269.50 | 82.70 |
| Sedentary | 12 | 654.3 | 154.56 | 654.3 | 154.56 | 2.08 | 0.76 | 203.33 | 42.09 |

SwRT (ms); SCosts, % local switch costs (%); P3b Amp, P3b ERP switch trial amplitude (µV); P3b Lat, P3b ERP switch trial latency (ms). Global ranges: SwRT: 301.88–1104.1; % local switch costs: −0.19–57.87.

square = 0.312). Thus, 31% of the variance in SwRT was accounted for by normal aging. (3) Interestingly, though age significantly impacted percent switch costs ($F(1, 49) = 5.025$, $p = 0.030$, *partial eta* square = 0.093), the effects of aging on percent switch costs was small (9%). (4) Age did not significantly impact P3b switch amplitude ($F(3, 49) = 5.459$, $p = 0.075$, *partial eta* square = 0.063) and contributed only 6% of the variance explained. Age was not significantly different by group ($p = 0.291$).

### Group

Group had a significant effect on (1) $VO_2$ Max ($F(3, 49) = 16.103$, $p < 0.001$, *partial eta* square = 0.496). This suggests almost 50% of the variance in $VO_2$ Max score was due to the effects of group membership (lifestyle). Thus, group membership and aging contributed similarly to this physiological measure. (2) Group effect on SwRT was significant ($F(3, 49) = 8.528$, $p < 0.001$, *partial eta* square = 0.343). This indicates 34% of the variance in SwRT could be attributed to group membership. Again, this is similar to the amount of variance explained by normal aging. (3) Group effect on percent local switch cost was significant ($F(3, 49) = 6.399$, $p = 0.001$, *partial eta* square = 0.282). This suggests 28% of the variance in percent switch costs was due to group membership. Recall, the age covariate explained 9% of the variance on this measure, while group explained 28%. (4) P3b switch amplitude was also significantly affected by group ($F(3, 49) = 5.459$, $p = 0.003$, *partial eta* square = 0.250). Group membership explained 25% of the variance in P3b switch amplitude while the age covariate did not significantly affect this executive proxy.

Neither age nor group significantly affected P3b switch latency.

## Post hoc comparisons

### Self-reported lifetime hours of aerobic practice

Aerobic fitness practitioners reported significantly more hours of aerobic practice than sedentary controls ($p = 0.021$). Meditators and Tai Chi practitioners did not differ from sedentary controls on self-reported lifetime hours of aerobic exercise ($p = 0.670$ and $p = 0.401$, respectively).

Physiological measures (see Figure 3 and Table 1).

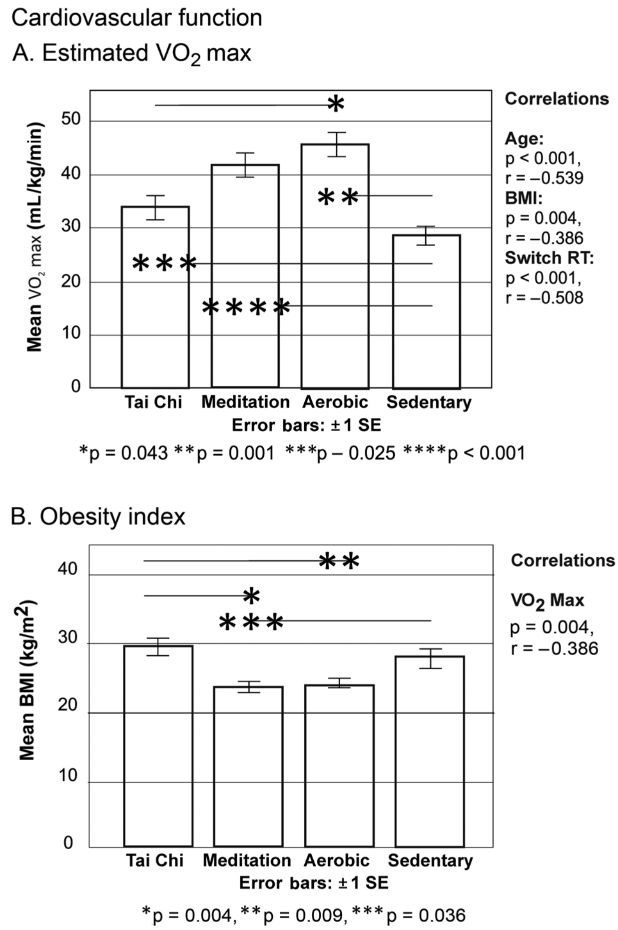


**Figure 3** (A) Estimated $VO_2$ Max (mL $O_2$/kg/min) and (B) BMI (kg/$m^2$) group means (±1 SE).
Groups: Tai Chi, meditation + exercise, aerobic exercise, and sedentary.

### $VO_2$ Max (see Figure 3A)

Aerobic fitness practitioners outperformed Tai Chi practitioners ($p = 0.043$) and sedentary controls ($p < 0.001$) on aerobic capacity. Meditators ($p < 0.001$) and Tai Chi practitioners ($p = 0.025$) also outperformed sedentary controls (see Figure 3). This is to be expected, as Tai Chi requires moderate aerobic exertion and our meditators self-reported aerobic activity.

### Body mass index (see Figure 3B)

BMI was significantly different between groups ($p = 0.002$). Both Tai Chi and sedentary control BMI was significantly higher compared to meditators ($p = 0.004$ and $p = 0.036$ respectively). Tai Chi participant BMI was significantly higher than aerobic fitness practitioners ($p = 0.009$). Aerobic fitness practitioners and sedentary controls were not significantly different on BMI.

Cognitive measures (see Figure 4 and Table 2)

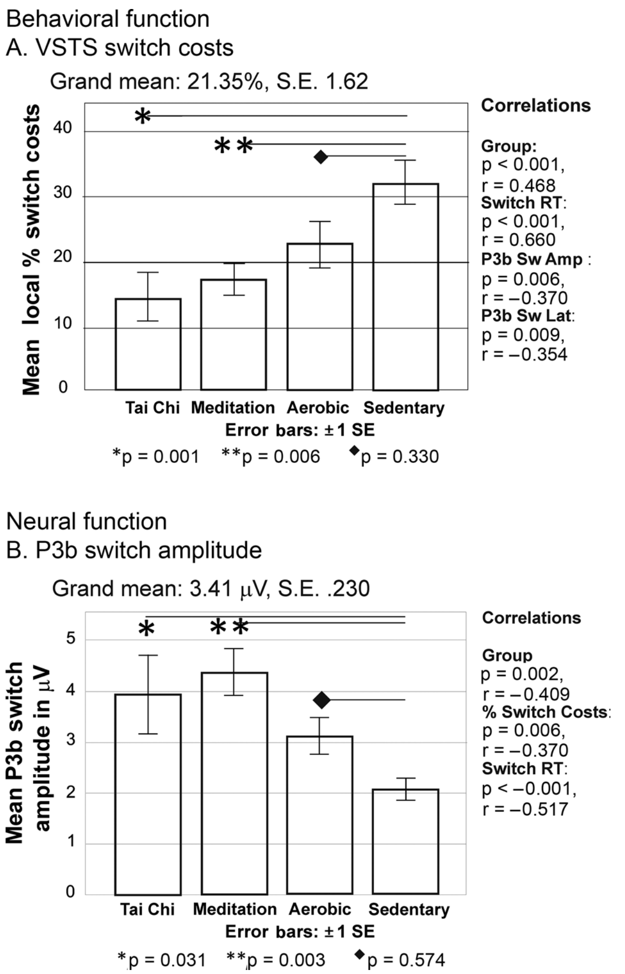


**Figure 4** (A) Percent local switch costs and (B) P3b switch trial amplitude (μV) group means.
Groups: Tai Chi, meditation + exercise, aerobic exercise, and sedentary (±1 SE).

**Switch reaction time**

Tai Chi ($p<0.001$), meditation ($p=0.001$), and aerobic fitness practitioners ($p=0.014$) showed significantly shorter SwRTs than sedentary controls. There were no significant differences between training groups on SwRT.

**Percent local switch costs (see Figure 4A)**

Tai Chi ($p=0.001$) and meditation practitioners ($p=0.006$) showed significantly lower local percent switch costs than sedentary controls. Importantly, aerobic fitness practitioners did not differ significantly on percent local switch costs compared to all other groups.

**P3b switch amplitude (see Figure 4B)**

Similar to local switch cost results, Tai Chi ($p=0.031$) and meditation plus exercise practitioners ($p=0.003$) showed significantly larger P3b switch amplitudes than sedentary controls. Again, aerobic fitness practitioners and sedentary controls did not differ significantly on this key executive function measure.

**P3b switch latency**

There were no significant differences between groups, though P3b switch latency was significantly and negatively correlated with percent local switch costs ($p=0.009$, $r=-0.354$), suggesting lower switch costs were associated with longer P3b switch latencies.

**Correlations (see Table 3)**

Correlations supply evidence that significant patterns of association are present in a data set. To control for multiple tests of significance, only correlations significant at the $p<0.0125$ level are reported in Table 3. Group membership was significantly and positively correlated with SwRT ($p=0.003$, $r=0.400$) and switch costs ($p<0.001$,

**Table 3** Pearson's correlations between key measures.

| | Group | Age | VO2 | BMI | SwRT | SCosts | P3b Amp | P3b Lat |
|---|---|---|---|---|---|---|---|---|
| Group | | −0.206 | −0.142 | −0.037 | 0.400[a] | 0.468[a] | −0.409[a] | −0.194 |
| Age | | | −0.539[b] | 0.003 | 0.433[a] | 0.181 | −0.156 | 0.143 |
| $VO_2$ | | | | −0.386[a] | −0.508[b] | −0.289 | 0.324[a] | 0.077 |
| BMI | | | | | 0.144 | −0.010 | −0.201 | −0.198 |
| SwRT | | | | | | 0.660[b] | −0.517[b] | −0.289 |
| SCosts | | | | | | | −0.370[a] | −354[a] |
| P3b Amp | | | | | | | | 0.214 |
| P3b Lat | | | | | | | | |

[a]$p<0.0125$, [b]$p<0.001$. Group (Tai Chi = 1, Meditation = 2, Aerobic = 3, Sedentary = 4); age (years); estimated $VO_2$ Max (mL $O_2$/kg/min); BMI (kg/$m^2$); SwRT (ms); Scosts, % local switch costs (SwRT – no-SwRT/no-SwRT); P3b Amp, P3b ERP switch trial amplitude (μV); P3b Lat, P3b ERP switch trial latency (ms).

$r = 0.468$), and negatively correlated with P3b switch amplitude ($p = 0.002$, $r = -0.409$). Though age did not differ significantly between our groups ($p = 0.291$), SwRT was significantly and positively correlated with age ($p = 0.001$, $r = 0.433$; greater age was correlated with longer SwRTs) and switch costs ($p < 0.001$, $r = 0.660$; lower switch costs were correlated with shorter SwRTs). SwRT was significantly and negatively correlated with $VO_2$ Max ($p < 0.001$, $r = -0.508$; greater aerobic capacity was correlated with shorter SwRTs) and P3b switch amplitude ($p < 0.001$, $r = -0.517$; shorter reaction times were correlated with larger P3b switch amplitudes).

Percent local switch costs were significantly and positively correlated with group ($p < 0.001$, $r = 0.468$). Tai Chi and meditation practice were associated with lower percent local switch costs and SwRT ($p < 0.001$, $r = 0.660$; higher switch costs were correlated with longer SwRTs). Percent local switch costs were significantly and negatively correlated with P3b switch amplitude ($p = 0.006$, $r = -0.370$; lower switch costs were correlated with larger P3b switch amplitudes).

Overall, aerobic fitness participants and sedentary controls demonstrated longer SwRTs, larger switch costs, and smaller P3b switch amplitudes compared to Tai Chi and meditation groups.

## Discussion

This cross-sectional, controlled study compared the effects of long-term training in Tai Chi, meditation plus exercise, or aerobic exercise alone to a sedentary lifestyle, on normally aging adult human aerobic capacity and executive function. We utilized an ecologically valid task switch paradigm and dense-array EEG to characterize executive function neural substrates. Only Tai Chi and meditation plus exercise groups demonstrated larger P3b ERP switch trial amplitudes compared to sedentary controls. Interestingly, aerobic fitness practitioners did not differ from any of our other groups on these two measures, suggesting a mid-range of possible practice effects.

Interestingly, Tai Chi practitioners were on average a decade older than aerobic practitioners, yet they outperformed sedentary controls on percent local switch costs and P3b switch amplitudes, while the aerobic fitness group did not. Meditators also outperformed sedentary controls while aerobic fitness practitioners did not. However, the mean age difference between these groups was only ~5 years. This suggests the mental concentration required to perform meditation in combination with chronic aerobic exertion may confer superior executive function benefits compared to exercise alone. Taken together, this convergent evidence suggests Tai Chi benefits executive function in a manner similar to meditation plus exercise, and both Tai Chi and meditation plus exercise may confer superior executive function benefits compared to aerobic exercise alone.

This study has some key limitations: first, its cross-sectional design. Individuals self-selected into their training program. This self-selection may be due to genetic, socio-economic, convenience, or environmental factors which we did not directly assess. Thus, these results may not generalize robustly. Likewise, our sample was drawn from a racially and socio-economically homogenous population. While we can say these results may generalize to similar samples, we cannot speculate on samples from significantly different racial or socio-economic populations.

One could also argue a limitation to the study is that there is no group that practiced mental training in isolation from exercise., Since it is known that mental training benefits executive function, it could be argued that benefits of mental training plus exercise (which was found in this study in the meditation group who also participated in aerobic exercise) do not imply mental training is interacting with exercise, or facilitating the effects of exercise. Instead, each could have its own independent effect on attentional performance. We agree and would simply argue it appears mental training may have added extra benefits to those conferred by aerobic exercise alone. Further controlled studies will need to be done to evaluate these putative effects.

## Conclusions

This study showed long-term practice of Tai Chi benefited a neurophysiological index of executive function. Training groups all outperformed sedentary controls on estimated $VO_2$ Max, suggesting they received expected exercise-related benefits. These results also suggest individuals who engaged in chronic aerobic exercise in combination with mental concentration (Tai Chi and meditation) may have received greater executive function benefits than individuals engaging in aerobic fitness practice alone. Since these three training programs are routinely available in educational, Parks & Recreation, and wellness center settings, they may provide diverse and economical options for health care professionals designing personalized health care protocols to optimize cognitive and cardiovascular capacity in normally aging adults.

On September 4th, 2014 our EEG system manufacture-reer, Electrical Geodesics, Inc. (EGI), made the authors aware of a 36ms temporal offset introduced into the EEG signal by the amplifiers' built in digital filter. While the authors of the paper accounted for the 7ms offset introduced by the latency between the amplifier and the monitor, they were unaware of this additional offset. However, as the results are the product of an intergroup comparison, these offsets have no effect on the final outcome.

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