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EEG changes from long-term physical exercise

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Abstract

Electrophysiologic effects of physical exercise were investigated by comparing groups of individuals who engage in regular intensive physical exercise (12+ h/week) to control subjects (2+ h/week). Electroencephalographic (EEG) activity was recorded under eyes open/closed conditions to assess baseline differences between these groups. Spectral power was less for the exercise compared to the control group in the delta band, but greater in all other bands. Mean band frequency was higher for the exercise compared to controls in the delta, theta, and beta bands. Some differences in scalp distribution for power and frequency between the exercise and control groups also were found. The findings suggest that physical exercise substantially affects resting EEG. Theoretical mechanisms for these effects are discussed.

Keywords: Electroencephalogram (EEG); Spectral analysis; Exercise; Cognitive function

1. Introduction

Several reports have suggested that frequent physical exercise may have facilitating effects on general cognitive function (Bashore & Goddard, 1993; Tomporowski

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& Ellis, 1986) and affective state (Boutcher & Landers, 1988; Petruzzello & Landers, 1994; Youngstedt et al., 1993). For example, age-related differences in performance on some cognitive tasks are attenuated in subjects with high- compared to low-physical exercise (Dustman et al., 1984; Spirduso, 1980; Baylor & Spirduso, 1988), although strong effects are not always obtained (cf. Blumenthal & Madden, 1988; Dustman et al., 1994). Despite the implication of these findings that exercise can contribute to intellectual performance and that such activities affect cognitive capability, the basis for these effects is not well understood (Dustman et al., 1994; Hatfield & Landers, 1987). However, a generally positive relationship of exercise on event-related potential (ERP) and neuropsychological measures of mental processing speed has been reported (cf. Bashore, 1989; Dustman et al., 1990a; Geisler & Squires, 1992; Lijzenga et al., 1994). When such findings are considered in the context of the association between background electroencephalographic (EEG) activity and ERPs (Basar & Stampfer, 1985; Basar et al., 1984; Pritchard et al., 1985), it is not unreasonable to suppose that rigorous physical exercise could affect EEG activity and, therefore, cognitive function.

In particular, because inter-subject variability of alpha-activity is related to individual variation in the P300 ERP component (Jasiukaitis & Hakerem, 1988; Intriligator & Polich, 1994, 1995; Mecklinger et al., 1992; Polich, 1996; Polich & Luckritz, 1995), changes in background EEG activity may directly affect ERP variation. Some support for this hypothesis has been obtained. Assessment of subjects before and after exercise appears to produce an increase in alpha power across studies that employed widely different electrophysiological methodologies (Boutcher & Landers, 1988; Farmer et al., 1978; Hatfield et al., 1984; Kamp & Troost, 1978; Wiese et al., 1983; for a review, see Hatfield & Landers, 1987). The underlying causes of these effects are not clear, however, because little control has been implemented over the possible influence of baseline EEG values with respect to the long-term changes that may result from physical exercise. This is a fundamental point to establish, so that the effects of exercise can be evaluated by comparing EEG results between the active and passive or baseline values.

Surprisingly, few studies have employed cross-sectional designs to determine how individual levels of exercise might contribute to baseline EEG differences between groups. Dustman et al. (1990b) assessed the interaction between exercise and age by comparing groups of healthy young and older men such that half of the subjects in each group were in good aerobic condition, and half were in poor aerobic condition. Relative to low-fit men, high-fit subjects had better neurocognitive functioning and significantly greater amounts of alpha activity (8–10 Hz) regardless of age — findings that again imply that exercise contributes to CNS function and superior cognitive performance (Dustman et al., 1994; Dustman et al., 1993). Results of a similar previous report from the same laboratory support this view (Dustman et al., 1985).

The present study was designed to directly examine this issue by comparing young adult exercisers who have engaged in high levels of physical exercise to control subjects who perform comparatively little exercise. Subjects were measured in a rested state that occurred during the course of their normal weekly schedule so

that baseline EEG activity could be obtained, with both spectral power and mean frequency measures assessed. If exercise does affect EEG at baseline levels, the exercise and control subjects should demonstrate different electrophysiological patterns. ERP data also were collected from most of the subjects, but these results will be described elsewhere because of design differences with respect to the present study.

2. Methods

2.1. Subjects

Exercise subjects were recruited through personal contact and advertisements in local fitness centers. This subject group was defined by their life-long commitment to athletic endeavors via their participation in Olympic-caliber events (i.e., training for Olympic or similar competitions in triathalon, bike racing, tennis, etc. events), excelling at high-school or college level sports (i.e., playing at the varsity level for at least three or more years basketball, baseball, etc.), or having at least a three-year history of performing vigorous, acrobic physical exercise (i.e., individuals who provided strong evidence of their personal committment to consistent aerobic physical exercise). The control group was defined by the absence of any previous participation in high level sports activity and engagement in relatively minimal aerobic activities. It should be noted expressly, however, that the control subjects did engage in some exercise, although much less than the exercise group (see Table 1 and below). This was deemed as a desirable quality for the control group to preclude the possibility that any obtained effects could be attributed to just the difference between exercise and none, so that we can be considered as evaluating the high and low ends of the exercise continuum, rather than high vs. 'none'. All subjects completed an exercise survey, laboratory questionnaire, reported being free of neurological or psychiatric disorders, and provided informed written consent.

Subject group characteristics are summarized in Table 1. Individuals from each group were well matched on age, educational level, and sex (12 M, 6 F in each group) to minimize general neurocognitive variation (Polich & Kok, 1995). However, the subject groups differed appreciably in the time spent engaged in vigorous physical exercise — a factor that produced strong differences in resting heart rate (assessed at manually at the wrist) and body temperature (assessed at the ear canal with a Termoscan Pro-1 thermometer). The scattergram between exercise amount and heart rate is portrayed in Fig. 1 and illustrates that the athletic subjects demonstrated consistent slowing of heart rate relative to the controls (a similar association was observed between exercise and body temperature). Subjects also self-rated their physical and mental states at the time they were tested. They were asked simply to indicate how they felt as the electrodes were being affixed. This procedure was adopted to assess for possible group differences with respect to overall physical/mental state at the time of testing. It has proven quite useful in

previous studies to detect subjects who may be excessively fatigued for reasons unrelated to the experimental protocol.

2.2. Recording conditions and procedure

EEG activity was recorded using gold-plated electrodes affixed with electrode paste and tape. The EEG data were obtained from monopolar recordings at the Fz, Cz, and Pz electrode placements, referred to linked ears, with and bandpass of 0.25–70 Hz, and a digitization rate of 125 Hz. EOG was recorded bipolarly with electrodes placed below and at the outer canthus of the left eye. Impedance for all recording sites was 10 Kohms or less.

EEG was recorded for 3 min while eyes were open and 3 min while eyes were closed. A total of 80 s of artifact-free EEG data for each eyes open/closed condition was selected by visual inspection from each subject and spectral analysis performed to extract power and mean frequency in six bands using a Hanning smoothing algorithm: delta (0.25–4 Hz), theta (4–8 Hz), alpha-1 (7.5–9.5 Hz), alpha-2 (9.5–12.5 Hz), beta-1 (12–20 Hz), and beta-2 (20–70 Hz). The overall or global (0.25–70 Hz) EEG power and mean frequency also were computed. The theta and alpha-1 bands overlap by 0.5 Hz has no consequences for the subsequent results.

Table 1
Summary statistics for the exercise and control subject groups

	Exercise (n = 18)	Control (n = 18)	Probability[a]
Age (years)			
Mean	31.44	31.89	—
S.D.	5.83	6.94	
Education (years)			
Mean	15.72	15.11	—
S.D.	2.47	2.40	
Exercise (h/week)			
Mean	12.56	2.50	***
S.D.	11.17	1.58	
Heart rate (beats/min)			
Mean	58.39	70.78	***
S.D.	9.90	7.13	
Temperature (°F)			
Mean	97.97	98.40	**
S.D.	0.52	0.42	
Self-rating[b]: physical			
Mean	7.94	8.50	—
S.D.	1.17	1.20	
Self-rating: mental			
Mean	8.00	8.44	—
S.D.	1.61	1.25	

[a]***$P < 0.01$, ***$P < 0.001$, (—)non-significant.
[b]Subjects rated their physical and mental states at the time of testing by circling a single number in the series from 1 to 10, which were described as 'low' and 'high', respectively.

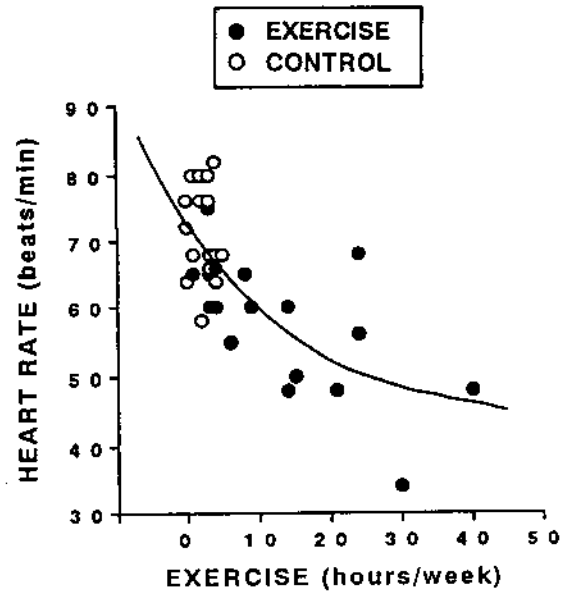

Fig. 1. Scattergram and regression line for exercise and heart rates from exercise and control subjects (n = 18/group). The fitted curve is a third-order polynomial: $r = 0.716$, $P < 0.001$.

However, the high end of the beta-2 band may reflect aliasing, so that these results should be viewed with caution.

3. Results

Greenhouse-Geisser corrections were applied to all analyses of variance with repeated measures factors. Only the probability values from the corrected df will be reported. The spectral power data (μV^2) were subjected to a $\log_{10}$ transformation prior to statistical analysis (Pollock et al., 1990; Pollock et al., 1992), with the mean band frequency data (Hz) assessed directly since no transformation was required.

The mean spectral power values (± 1 S.D.) for each EEG band from the Pz electrode site, for each subject group, and for the eyes open closed conditions are presented at the top of Fig. 2. Data from only this one electrode site are presented because they are illustrative of the major effects. The mean band frequency (± 1 S.D.) for each subject group, EEG band, and eyes open closed conditions are presented at the bottom of Fig. 2. A three-factor (2 exercise groups $\times$ 2 eye conditions $\times$ 3 electrodes) analysis of variance was applied to the transformed spectral power and mean band frequency data within each band. The results of these analyses are summarized in Table 2. Note that although the overall effects of the eyes open/closed factor were generally additive, interactions between the eyes and any other independent variable occurred because of the increase in spectral

power when eyes were closed. Subject group interacted with recording electrode position for several analyses. These findings are illustrated in Fig. 3, which plots the global (0.25–70 Hz) band's mean (± 1 S.E.) spectral power and mean frequency data as a function of midline electrode site (see below).

3.1. Spectral power

The major effects for the spectral power data were: (1) exercise subjects had less delta and more theta, alpha-1, alpha-2, beta-1, and beta-2 power compared to the control subjects; (2) more EEG power was produced when eyes were closed compared to open, with the beta-2 band yielding an interaction between subject

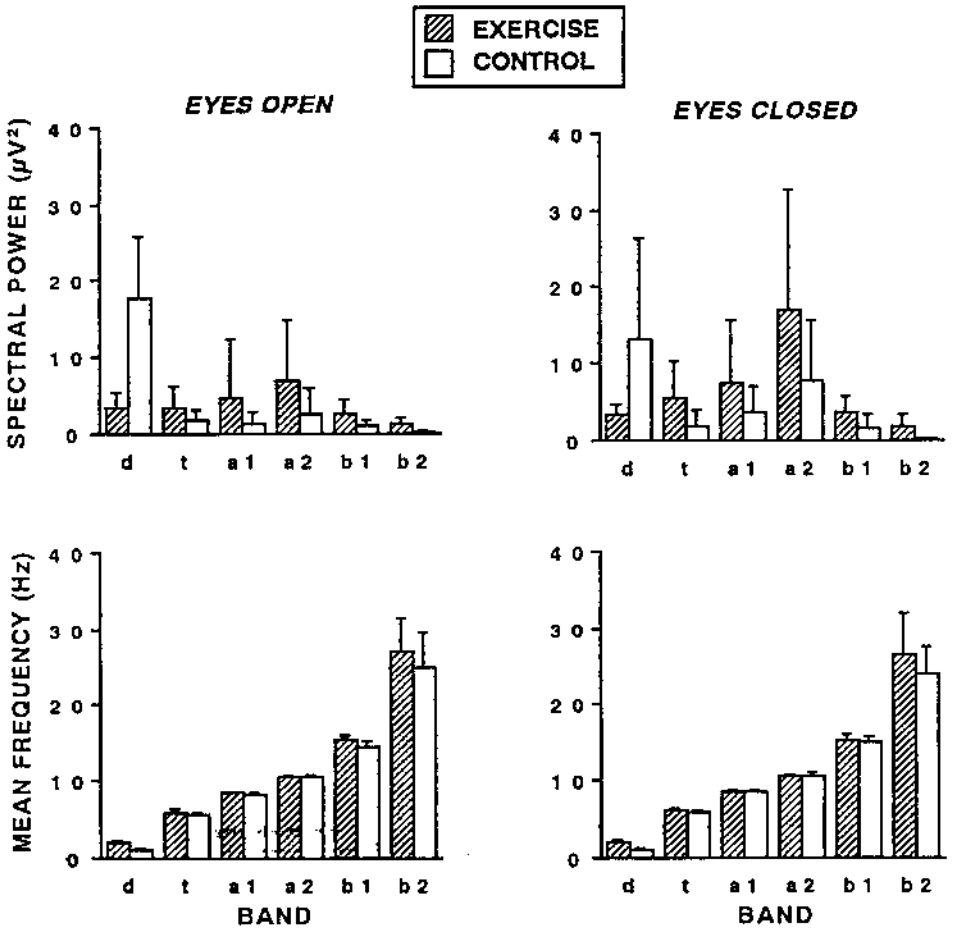

Fig. 2. Mean spectral power (μV^2) and mean band frequency (Hz) ± 1 standard deviation from the Pz electrode site for each EEG band, subject group, and eyes open/closed condition.

Table 2
Summary (*F*-ratios) of analyses of variance (2 groups × 2 eyes open/closed × 3 electrode channels) performed on the spectral power (top) and mean frequency (bottom) EEG data

Factor (df)	d	t	a1	a2	b1	b2	Global
Spectral power							
Group (1,34)	191.2***	6.2*	8.2**	8.8**	24.6*	131.8***	4.8*
Eyes (1,34)	4.5*	23.5***	61.1***	53.7***	27.2***	—	61.3***
Channel (2,68)	4.0*	15.9***	—	54.8***	19.7***	3.7*	8.3**
G × E (1,34)	—	—	—	—	—	6.1*	4.2*
G × C (2,68)	4.0*	4.9*	—	—	—	—	6.5**
E × C (2,68)	—	10.0***	—	—	—	3.8*	—
G × E × C (2,68)	—	—	—	—	—	—	—
Mean frequency							
Group (1,34)	333.6***	8.2**	—	—	17.2***	16.8***	165.5***
Eyes (1,34)	—	12.8***	13.5***	10.7**	—	—	5.8*
Channel (2,68)	6.1**	—	13.3***	12.7***	—	—	8.4***
G × E (1,34)	—	—	—	—	—	—	—
G × C (2,68)	—	—	—	—	—	5.6**	6.3***
E × C (2,68)	11.4***	4.2*	—	3.8*	—	—	—
G × E × C (2,68)	—	—	—	—	4.0*	—	

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, (—) not significant.

group and eyes open/closed; the exercise subjects increased in power more than the controls between the eye conditions; (3) scalp distribution differences between the subject groups were obtained — typically increases in power from the frontal to central/parietal recording sites, with some relatively minor interactions between the electrode and other experimental variables also observed; (4) global spectral power yielded an interaction between subject group and recording channel. As illustrated in the top portion of Fig. 3, exercise subjects increased in power more than controls from the frontal to parietal electrode sites. In general, the major differences between the exercise and control subjects was in spectral power (in the different directions as portrayed in Fig. 2) for the EEG bands.

3.2. Mean frequency

The major effects for the mean frequency data were: (1) exercise subjects produced higher frequencies for the delta, theta, beta-1, and beta-2 bands; (2) eyes open produced slower band frequencies than eyes closed, but no interactions between subject group and the eyes open/closed manipulation were obtained; (3) some scalp distribution effects were observed — typically increases in frequency from the frontal to central/parietal recording sites; (4) global mean frequency yielded an interaction between subject group and recording channel. As illustrated in the lower portion of Fig. 3, exercise subjects increased in frequency somewhat less than the controls from the frontal to parietal electrode sites. In general, the exercise subject group demonstrated higher band frequencies than the control group.

4. Discussion

Young adult exercise subjects produced less baseline delta and more alpha and beta band power than controls. Exercise subjects also evinced higher frequencies for the delta, theta, and beta bands compared to the controls. Similar patterns generally were observed for the eyes open/closed manipulation for both dependent variables across subject groups. These findings are in agreement with and extend previous reports that found increased alpha power for high-fit relative to low-fit subjects (Dustman et al., 1985, 1990b) and studies that assessed EEG activity before and after exercise in a variety of subject sport-populations (Boutcher & Landers, 1988; Farmer et al., 1978; Hatfield et al., 1984; Kamp & Troost, 1978; Petruzzello

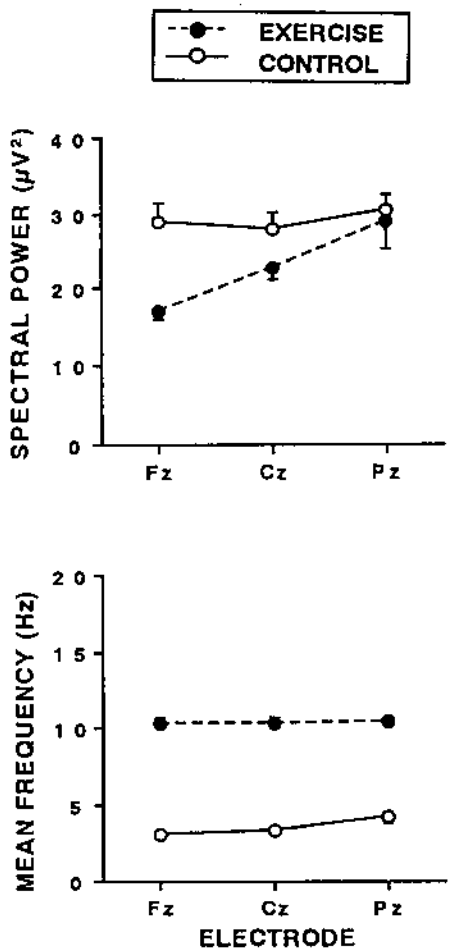

Fig. 3. Mean spectral power (μV^2) and mean band frequency (Hz) ± 1 standard deviation from the global (0.25–70 Hz) band for each subject group as a function of electrode site.

& Landers, 1994; Wiese et al., 1983). Furthermore, given the links between background EEG and cognitive ERPs outlined above (Basar & Stampfer, 1985; Basar et al., 1984, 1989; Jasiukaitis & Hakerem, 1988; Jasiukaitis et al., 1990; Intriligator & Polich, 1994, 1995; Mecklinger et al., 1992; Polich, 1996; Polich & Luckritz, 1995; Pritchard et al., 1985), it is likely that the effects of exercise observed for ERPs would originate from fundamental changes in baseline EEG that are produced by aerobic activity (Bashore, 1989; Bashore & Goddard, 1993; Dustman et al., 1985, 1990b; Geisler & Squires, 1992; Lijzenga et al., 1994). In this view, extended exercise would contribute to increased amounts of alpha-band activity and, therefore, increased P300 amplitude and decreased peak latency (Intriligator & Polich, 1994, 1995; Jasiukaitis & Hakerem, 1988). Thus, both short- and long-term exercise activities demonstrate similar changes in the EEG.

The underlying causes for the influence of physical exercise on the EEG are far from clear, although speculation on the sources of these effects can be made. For example, it is straightforward to assume that physical exercise promotes cerebral blood flow (CBF) that could affect EEG measures (Dustman et al., 1990a; Dustman et al., 1990b), but why such physiologic changes would produce decreases in delta and increases in alpha power is uncertain (cf. Bashore & Goddard, 1993; Dustman et al., 1993). However, when a decrease in CBF occurs because of anoxia or hypoxia, an increase in delta and decrease in alpha and beta activity typically are observed (Chatrian, 1990; Kellaway, 1990; Kraaier et al., 1992; Niedermeyer, 1993). If physical exercise promotes increased CBF, an EEG spectral pattern opposite that of poor CBF might be obtained. The present study's findings, therefore, can be viewed as suggestive support for the hypothesis that increased circulatory capacity contributes to the observed EEG changes.

In a comprehensively elegant review, Dustman et al. (1994) notes that the findings from animal studies 'strongly suggest there is a positive relationship between physical exercise and CNS health' (p. 169), which occurs — at least in part — because of improved neurotransmitter functioning, preservation of dopaminergic cells, increased vascularizaton, and increased cell hypertrophy and complexity. These findings imply that if 'similar kinds of neurobiological changes occur in humans who frequently engage in aerobic exercise, . . . they should outperform infrequent exercisers when compared on a variety of tasks that reflect CNS integrity' (p. 170). Despite these findings in animal subjects, the evidence for humans is not as convincing because other influences may be operative, such as educational level and socioeconomic status. The present study took pains to match the exercise and control subjects on such variables, with only exercise amount and sports accomplishment used to define the groups. Hence, the results reported here may be related not only to the long-term practice of physical exercise but also to athletic talent and achievement. Future studies that use EEG techniques to compare baseline measures for different types of athletes might provide a neurophysiological basis for the identification, evaluation, and prognosis of physical exercise in athletic training.

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