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Effects of acute aerobic and resistance exercise on executive function: An ERP study

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ABSTRACT

Objectives: This study addressed the effects of acute, moderate-intensity aerobic and resistance exercise on the shifting aspect of cognition following a 30-min recovery period. It also explored the neuro-electrical activation that underlies the relationship between acute exercise and cognitive function through the examination of P3b and N1 components of event-related potentials.
Design: A counterbalanced, repeated-measures experimental design.
Methods: Thirty-five volunteer young adults completed two experimental sessions (i.e., acute aerobic exercise (AE) and resistance exercise (RE), matched in terms of intensity, and one reading session (control). The AE entailed cycling at 60–70% of maximal heart rate reserve for 30 min. In the RE session, participants performed seven exercises with two sets of 8–12 repetitions at 70% of 10-repetition maximum. Each participant's neuro-electrical activation was recorded 30 min after each session while s/he completed the task-switching test.
Results: After the 30-min recovery period, both AE and RE elicited shorter response times in global switching ($\eta_p^2 = 0.24$) and local switching ($\eta_p^2 = 0.16$) were observed when compared to control. Additionally, larger P3b amplitudes (but not N1 amplitudes) were evident in global switching ($\eta_p^2 = 0.15$) and local switching ($\eta_p^2 = 0.16$), regardless of exercise modality.
Conclusions: The present findings suggest that acute exercise has positive effects on cognitive function. Exercise-induced alterations during the later stages of mental processing might result in superior performance. There were significant selective benefits in terms of brain function regardless of exercise modality.

1. Introduction

A single bout of exercise, known as *acute exercise*, has been shown to elicit benefits for various forms of cognitive task performance post-exercise,[1,2] and such benefits are well supported by a recent meta-analysis.[3] Furthermore, cognitive processes associated with executive function (EF), which concerns a form of higher-level cognition responsible for goal-directed behaviours and regulation of aspects of basic cognition,[4] appear to be enhanced following acute exercise.[5,6] Notably, rather than a unified process, EF has several subcomponents including shifting, inhibition, and updating.[4] To date, while most studies addressing the promising results of acute exercise have focused on inhibition,[3,7] less attention has been devoted to shifting. Etnier and Chang[8] highlighted the necessity to clarify the effects of exercise on specific aspects of EF. Accordingly, examining shifting performance after acute exercise would further elucidate the effects of acute exercise on EF.

Exercise modality is another factor that warrants further consideration to further clarify the influence of acute exercise on EF.[3] While beneficial effects of 30-min acute aerobic exercise (AE) on shifting, inhibition, and updating have been reported across the lifespan,[7,9] the influence of acute resistance exercise (RE) has received much less attention. To date, only a few studies have

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examined the effects of acute RE on EF, and elucidated the beneficial effects on inhibition,[5,10,11] and updating.[12,13] Considering the variability of physiological responses induced by acute AE and RE,[14,15] these two modalities might bear different forms of influence on EF. However, the heterogeneity of experimental designs, types of cognitive tasks used, and participant characteristics, limits the cross-study comparability of acute AE vs. RE on EF. Moreover, few studies examining the influence of both acute AE and RE on EF have suggested that exercise modalities might moderate the relationship between acute exercise and different aspects of EF.[10,12] Specifically, AE has similar effects as RE on inhibition in middle-aged women,[10] young,[16] and older adults,[11] but larger effects than RE on working memory in young adults.[12] Nonetheless, the limited data regarding the effects of AE vs. RE on shifting performance demonstrates a need for further research.

As a useful complement to behavioural measures, event-related potentials (ERPs) can provide insights into distinct stages of mental processes.[17] P3b, a late, endogenous component most prominent at parietal electrode sites (e.g., Pz),[18] is the component most commonly considered in studies that address acute exercise and cognition. Prior ERP studies have demonstrated that AE engenders superior shifting performance as evidenced by outcomes from the task-switching test and larger P3b amplitude in both adults[6,19] and children.[20] Given that the amplitude of the P3b reflects the allocation of attentional resources,[21] it is suggested that acute exercise improves cognitive function by enhancing the allocation of attentional resources.

It is noteworthy that other ERP components, such as N1, can also provide relevant insights that complement those provided by P3b. N1 is an early component most prominent at frontal electrode sites (e.g., Fz), and thus reflects the initial extraction of sensory information.[18] To date, very few studies have investigated the effects of acute exercise on cognition with due consideration of N1; those that have, found them to be negligible in nature.[1] However, such studies were confounded by an overt focus on the influence of AE on the inhibition aspect of EF, and research has yet to address whether acute RE might influence the early stages of sensory information processing.

Therefore, the aim of the present study was to use ERPs in tandem with behavioural measures to examine the effects of different modalities of acute exercise (i.e., AE and RE), matched in terms of intensity, on a single aspect of EF. Specifically, we assessed the individual effects of AE and RE on the shifting aspect of EF using the task-switching test. Moreover, N1 and P3b of participants' ERPs were recorded. Two research hypotheses were tested: both exercise modalities would result in superior shifting performance compared to the control condition (H_1); and both modalities would increase P3b amplitudes but have limited effects on N1 amplitudes (H_2).

2. Methods

Thirty-five participants aged 18–22 y were recruited for the present study. The minimum sample size was estimated from an a priori power analysis using G*Power[22] (power = 0.80, alpha = 0.05, $\eta_p^2 = 0.27$).[16] All participants met five inclusion criteria: (1) no psychiatric or neurological disorders, (2) normal or corrected-to-normal vision, (3) no cardiorespiratory diseases, (4) no neuromuscular disorders, and (5) were right-hand dominant.

The shifting aspect of EF was assessed by means of a computer version of the task-switching test[23] using STIM 2.0 software (Neurosoft Labs Inc., Sterling, VA, USA). In brief, each participant was presented with six blocks of 64 trials. For the first block, the participant was required to identify whether the stimulus (i.e., digits 1–9, without digit 5) within the solid-line square was greater/less than the digit 5 (i.e., AAAA...). For the second block, the participant identified whether the stimulus within the dotted-line square was even/odd (i.e., BBBB...). The blocks 3–6 consisted of an equal number of stimuli from the first and second blocks forming an alternating-runs paradigm (i.e., AABBAA...). Mean response times (RTs) for the correct responses and accuracies for the following conditions were then computed to facilitate statistical analysis: (1) homogeneous condition (i.e., AAAA or BBBB); (2) heterogeneous condition (i.e., AABBAA...); and (3) switch (i.e., AB or BA in the heterogeneous condition), and (4) non-switch (i.e., AA or BB in the heterogeneous condition).

Table 1
Summary of characteristics of participants (mean ± SD).

Variable	Male	Female	Overall
Sample size (n)	17	13	30
Age (years)	21.35 ± 1.41	20.92 ± 1.18	21.17 ± 1.32
Education (years)	16.29 ± 0.72	16.14 ± 0.54	16.23 ± 0.65
Height (cm)	172.00 ± 6.46	158.77 ± 3.86	166.27 ± 8.58
Weight (kg)	66.71 ± 9.57	51.38 ± 2.69	60.07 ± 10.64
BMI (kg/m^2)	22.52 ± 2.81	20.41 ± 1.26	21.60 ± 2.48
Digit span			
Forward	14.76 ± 1.09	14.62 ± 1.26	14.70 ± 1.15
Backward	10.41 ± 3.54	10.62 ± 2.50	10.50 ± 3.08
$\dot{V}O_{2\,max}$ (mL kg^{-1} min^{-1})	50.98 ± 11.54	38.44 ± 6.69	45.54 ± 11.48

BMI: body mass index.

In a repeated-measures (RM) design, participants were required to visit the laboratory on four occasions (i.e., one familiarisation and three experimental sessions) with at least 48 h between visits. Participants were instructed to avoid exercise, caffeine,[24] and alcoholic drinks in the 12 h prior to each visit. Each participant received $25 as compensation following each visit. Ethical approval was granted by the Institutional Review Board of Fu Jen Catholic University.

During the first visit (i.e., the familiarisation session), each participant was administered an informed consent form, completed a demographic questionnaire and the Digit Span Forward and Backward test[25] (Table 1). Additionally, her/his cardiorespiratory fitness ($\dot{V}O_{2\,max}$) and absolute strength were assessed following the procedures described previously.[1,5] Briefly, $\dot{V}O_{2\,max}$ was estimated using the submaximal YMCA Ergometer Test[26] with a cycle ergometer (Ergoselect 200 P, Ergoline, Germany), and absolute strength was assessed following 10-repetition maximum (RM) guidelines[27] for leg press, leg extension, chest press, chest fly, lateral pull down, right bicep curl, and left bicep curl. Notably, practice task-switching trials were also administered until correct responses reached the 80% level; this ensured sufficient test familiarisation.[23] Full details of the test protocol can be found in Supplementary File 1.

During experimental sessions 2–4, two exercise sessions (i.e., AE and RE sessions) matched by intensity and a control session (reading) were presented in a counterbalanced order. The intensities chosen for AE and RE have been associated with beneficial effects on EF.[1,13] The detailed protocols for AE[1], RE[13] and the control[13] sessions have been published. Briefly, the AE session entailed cycle ergometry for 30 min; specifically, a 5-min warm-up, 20 min of moderate-intensity exercise [i.e., 60–70% of maximal heart rate (HR) reserve), and a 5-min cooldown. For the RE session, the participant had a 5-min warm-up and then performed two sets of 8–12 repetitions at a moderate intensity (i.e.,70% of their 10 RM) for approximately 20 min with the aforementioned exercises. For the control session, participants were instructed to sit quietly and read exercise-related materials for 30 min. HR was taken at three time points: resting (i.e., measured pre-trial), in-task (i.e., measured during the trial), and post-task (i.e., measured 30 min after cessation of the session).

Thirty minutes after the cessation of experimental sessions, participants were fitted with an electrode cap (NeuroScan Quick-Cap; Neuro, Inc., Charlote, NC) with 32 Ag/AgCI electrodes, in line with the International 10–20 System, for electroencephalographic (EEG) recordings. Electrodes impedance was kept below 10 kΩ. Offline EEG processing and analysis included eye-blink correction, epoching (−100–600 ms relative to the stimuli onset), baseline correction (−100–0 ms relative to the stimuli onset), artificial rejection (signals > ±100 μV), and low-pass filtering (20 Hz, 24 dB/octave). The time-windows for P3b and N1 were estimated from the grand-averaged waveforms (i.e., 300–550 ms and 50–150 ms for P3b and N1, respectively). The mean amplitudes of P3b and N1 were derived from the mean amplitude values within the corresponding time windows.[28] The detailed EEG recording and offline analysis procedures have been documented elsewhere[1,20] and can be found in Supplementary File 2.

The statistical analysis was performed using SPSS (SPSS v. 20, Chicago, IL) with alpha set at $p < 0.05$. Initial data screening for univariate outliers ($z > 3$ *SD*) and Kolmogorov–Smirnov tests for normality ($p < 0.05$) were conducted. HR was analysed using a 3 (session: AE vs. RE vs. control) × 3 (time point: resting HR vs. in-task HR, vs. post-task HR) repeated-measures (RM) ANOVA. A 3 (session) × 2 (global switch: homogeneous vs. heterogeneous) RM ANOVA, as well as a 3 (session) × 2 (local switch: switch vs. non-switch) RM ANOVA, were applied for the RT and accuracy data. Mean amplitudes of P3b and N1 were analysed separately using a 3 (session) × 2 (global switch) × 3 (site: Fz vs. Cz vs. Pz) RM ANOVA as well as a 3 (session) × 2 (local switch) × 3 (site) RM ANOVA. The Greenhouse–Geisser correction was applied where sphericity was violated and follow-up comparisons were conducted using Bonferroni-adjusted multiple comparisons. Estimated effect sizes were reported using partial eta squared (η_p^2). Mean and standard errors were presented.

3. Results

Data from five participants were excluded due to poor EEG signal quality. Accordingly, reported "participant characteristics" and data analyses were predicated on the remaining 30 participants (see Table 1), and only significant interactions or main effects are presented herein; detailed results can be viewed in Supplementary File 3.

With regard to HR, a significant session × time point interaction ($F_{4,116} = 98.92$, $p < 0.001$, $\eta_p^2 = 0.77$) emerged. Follow-up comparisons indicated that the mean in-task HR assessed during the AE session was the highest (142.30 ± 1.82 bpm), followed by RE (107.67 ± 2.77 bpm), and control (67.93 ± 3.41 bpm). Two-way ANOVA indicated a significant main effect of session ($F_{2,58} = 149.22$, $p < 0.001$, $\eta_p^2 = 0.84$) and time point ($F_{2,58} = 917.71$, $p < 0.001$, $\eta_p^2 = 0.97$).

With regard to RT of the global switch, two-way ANOVA indicated a significant main effect of session ($F_{2,58} = 8.98$, $p < 0.001$, $\eta_p^2 = 0.24$), with shorter mean RTs for both the AE and RE sessions (631.75 ± 20.66 ms and 622.24 ± 22.30 ms, respectively) relative to the control session (688.77 ± 24.26 ms). There was also a significant main effect of global switch ($F_{1,29} = 268.14$, $p < 0.001$, $\eta_p^2 = 0.90$), with a longer mean RT for the heterogeneous (765.32 ± 26.20 ms) compared to the homogeneous condition (529.85 ± 15.27 ms; see Fig. 1a).

With regard to accuracy of the global switch, a significant main effect of session ($F_{2,58} = 4.38$, $p = 0.020$, $\eta_p^2 = 0.13$) was observed, with greater mean accuracy levels for the AE session (93.15 ± 0.52%) than the RE session (90.67 ± 1.05%). There was also a main effect of global switch ($F_{1,29} = 13.85$, $p = 0.001$, $\eta_p^2 = 0.32$), with a lower mean accuracy level for the heterogeneous (91.37 ± 0.70%) relative to the homogeneous condition (93.04 ± 0.72%).

For RT of the local switch, a main effect of session ($F_{2,58} = 5.61$, $p = 0.006$, $\eta_p^2 = 0.16$) was observed, with shorter mean RTs for both the AE (745.90 ± 27.21 ms) and RE (738.61 ± 31.52 ms) sessions relative to the control session (818.56 ± 33.65 ms). Additionally, a main effect of local switch ($F_{1,29} = 53.66$, $p < 0.001$, $\eta_p^2 = 0.65$) was observed, with a longer mean RT evident for the switch (807.47 ± 30.46 ms) relative to the non-switch condition (727.91 ± 24.05 ms; see Fig. 1b).

For accuracy of the local switch, there was a main effect of session ($F_{2,58} = 6.24$, $p = 0.005$, $\eta_p^2 = 0.18$), with greater mean accuracy levels for both the AE and control sessions (92.33 ± 0.59% and 92.11 ± 0.82%, respectively) than for the RE session (89.66 ± 1.08%). There was also a main effect of local switch ($F_{1,29} = 12.85$, $p = 0.001$, $\eta_p^2 = 0.31$), with a greater mean accuracy level for the non-switch (92.07 ± 0.70%) relative to the switch condition (90.67 ± 0.77%).

Fig. 2 illustrates the grand-averaged waveform of the ERPs for global switch (Fig. 2a and b) and local switch (Fig. 2c and d). For P3b amplitudes of the global switch, a two-way, global switch–site interaction ($F_{2,58} = 25.56$, $p < 0.001$, $\eta_p^2 = 0.47$) was observed, associated with a large effect size. There was a main effect of session ($F_{2,58} = 5.18$, $p = 0.010$, $\eta_p^2 = 0.15$), with larger mean P3b amplitudes for both the AE (5.53 ± 0.68 μV) and RE sessions (5.92 ± 0.60 μV) relative to control (4.54 ± 0.64 μV). There was also a main effect of global switch ($F_{1,29} = 19.91$, $p < 0.001$, $\eta_p^2 = 0.41$), with a larger mean P3b amplitude for the homogeneous (6.05 ± 0.64 μV) than the heterogeneous (4.61 ± 0.58 μV) conditions. Likewise, a main effect of site emerged ($F_{2,58} = 103.67$, $p < 0.001$, $\eta_p^2 = 0.78$), with the largest mean amplitude at Pz (8.01 ± 0.64 μV), followed by Cz (5.79 ± 0.70 μV) and then Fz (2.20 ± 0.54 μV). For N1 amplitudes of the global switch, there was a significant session–site interaction ($F_{4,116} = 4.95$, $p = 0.008$, $\eta_p^2 = 0.15$), associated with a large effect size. Three-way ANOVA indicated a main effect of global switch ($F_{1,29} = 16.66$, $p < 0.001$, $\eta_p^2 = 0.37$), with a larger mean N1 amplitude for the homogeneous (1.20 ± 0.33 μV) than the heterogeneous condition (0.60 ± 0.29 μV).

With regard to P3b amplitudes of the local switch, a significant local switch–site interaction ($F_{2,58} = 8.54$, $p = 0.003$, $\eta_p^2 = 0.23$) was observed, associated with a large effect size. There was a main effect of session ($F_{2,58} = 5.58$, $p = 0.009$, $\eta_p^2 = 0.16$), with larger mean P3b amplitudes for both the AE (4.87 ± 0.65 μV) and RE sessions (5.14 ± 0.62 μV), when compared with the control session (3.82 ± 0.61 μV). There was also a main effect of site ($F_{2,58} = 128.34$, $p < 0.001$, $\eta_p^2 = 0.82$), with the largest mean P3b amplitude at Pz (7.90 ± 0.63 μV), followed by Cz (4.73 ± 0.68 μV) and Fz (1.21 ± 0.57 μV). For N1 amplitudes of the local switch, no significant interactions or main effects were observed.

4. Discussion

Through an examination of the P3b and N1 of ERPs, the present study aimed to explore the effects of acute AE and RE on the shifting aspect of EF. The hypothesis that acute exercise would facilitate cognitive performance (H_1) was accepted. Specifically, results indicate that acute exercise sessions, regardless of the exercise modality employed, elicited shorter RTs in both global switching (see Fig. 1a) and local switching when compared with control (reading; see Fig. 1b). The hypothesis relating to the neuro-electrical activity (H_2) is also accepted. Specifically, the P3b of the ERP results revealed a pattern that was closely emulated in the behavioural results and larger P3b amplitudes in both the global (see Fig. 2a and b) and local switching (see Fig. 2c and d) conditions were observed following acute AE and RE when compared to the control session. Nonetheless, the acute exercise sessions had a limited effect on N1 amplitudes.

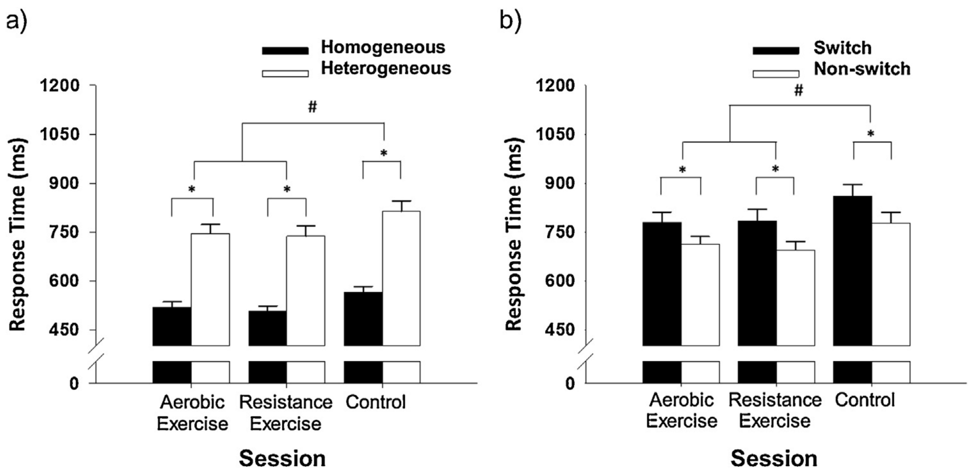

Fig. 1. Response time of (a) global switch (homogeneous vs. heterogeneous) and (b) local switch (switch vs. non-switch) across two exercise sessions and the control session (reading). Error bars represent SE.
*Significant difference between task-switching conditions, $p < 0.05$.
#Significant difference between control and acute exercise sessions, $p < 0.05$.

Concerning the cognitive-behavioural performance, it would seem that shorter RTs following acute AE across all conditions of the task-switching test indicate general facilitation of cognitive function and so H_1 was accepted. Accordingly, the results were in line with previous findings, which indicated that acute exercise elicits similar improvements in both congruent and incongruent conditions during the Stroop task.[1,2,29] Similar general facilitation was observed following RE; a finding that again serves to support the findings of past studies.[13,29]

There is, however, some evidence to suggest that selective cognitive improvements occur following acute exercise, with more sizable benefits occurring for tests that have greater cognitive demands.[5,13] Most related studies were conducted with middle-aged or older adults; in later life, people exhibit reduced cognitive function, with a gradual degradation from ∼20 years.[30] It could be that this gradual cognitive degradation renders older adults more susceptible to changes induced by acute exercise than their younger counterparts, particularly in test conditions that have greater cognitive demands; nonetheless, additional research is required to explore this intriguing possibility.

The present finding that AE and RE elicited similar improvements in the shifting aspect of EF assessed by the task-switching test, falls in line with the findings of Alves et al.[10] and Wang et al.[16] who reported similar improvements in the inhibition assessed by the Stroop task following acute AE and RE in order and younger adults. By way of contrast, Pontifex et al.[12] found that beneficial effects of acute exercise on updating EF were observed only as a consequence of AE in younger adults. Such inconsistencies relating to the effects of acute exercise on cognition might be attributed to participant characteristics, types of cognitive function assessed and the time, relative to the cessation of the exercise, at which the cognitive task was administered.[3] Investigation of the influence of acute exercise modality on other aspects of cognitive ability (e.g., goal-planning) across the lifespan is clearly a potentially fruitful direction for future research.

Although some previous studies have examined the effects of acute exercise on EF using a neurophysiological approach, either AE or RE was used.[1,13,29] The present results concur with those of previous studies in regard to increased P3b amplitudes following both AE[1,6] and RE.[31] The P3b amplitude is believed to reflect the allocation of attentional resources and associated with greater cognitive function.[21] The present findings suggest that acute exercise may facilitate the allocation of attentional resources, and thus be related to superior EF. Given that no differences in increases to the P3b amplitude across the switch and non-switch conditions were observed (see Fig. 2c and d), it is plausible that changes in the P3b amplitude following acute exercise occur regardless of task complexity. It should be noted, however, that our study is the first to compare different types of exercise modality using ERPs, and found no difference in the level of increase in P3b amplitudes resulting from acute AE and RE. This finding indicates that RE has similarly positive effects as AE on neuro-electrical activation, particularly P3b amplitudes. Specifically, both types of exercise confer benefits in the allocation of attentional resources, leading to our partial acceptance of H_2.

Contrastingly, the N1 amplitudes following the AE, RE, and control sessions showed no significant differences, which confirms our expectations. The N1 is different from the P3b in that it represents the earlier stage of cognitive processing and is associated with the initial extraction of sensory information.[18] Acute exercise had limited influence on the early stage of cognitive processes reflected by the N1 activation during the cognitive tasks associated with the inhibition aspect of the EF.[1] The present findings show that, acute exercise, regardless of whether it is aerobic or anaerobic in nature, has a limited influence on the initial stage of the extraction of sensory information during a task that entails the shifting aspect of the EF.

The present study has some limitations that need to be considered in interpreting the findings. First, while both types of acute exercise improved task-switching performance in terms of global switch RTs, both types of acute exercise did not result in greater levels of global switch accuracy compared to the control session. Rather higher local switch accuracy levels for both AE and control sessions were observed relative to RE. According to the speed-accuracy trade-off, accelerated RTs may be associated with less accuracy, suggesting the positive effect of acute RE on task-switching performance should be interpreted with caution.[32] Nonetheless, the larger P3b amplitudes were also observed following both experimental conditions, indicating that the beneficial effects on EF are not exercise modality-dependent.

Although both of the ERP components (P3b and N1) were selected to further understanding of the neurophysiological mechanisms underlying the relationship between acute exercise and shifting, some other components might offer additional insights. For example, the N4 has been linked to semantic processing,[33] and

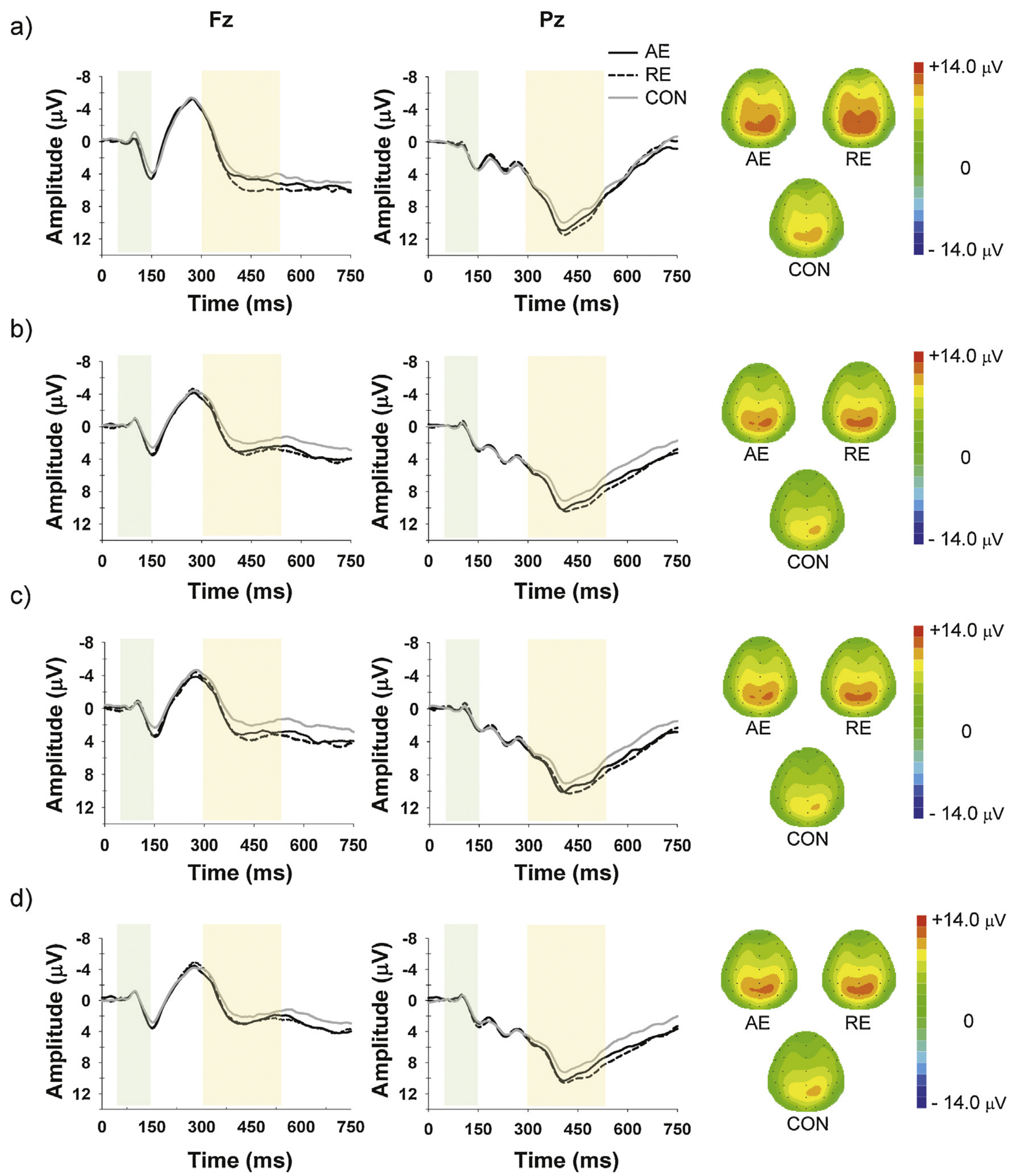

Fig. 2. The effect of experimental sessions on grand-average ERPs recorded at Fz (left panel) and Pz (middle panel), and on the topographic distribution (350–550 ms; right panel) for (a) the homogenous condition of the global switch, (b) the heterogeneous condition of the global switch, (c) switch condition of the local switch and (d) non-switch condition of the local switch.
Note: AE: aerobic exercise; RE: resistance exercise; CON: control. The vertical bars indicate P3b (light yellow) and N1 (light green) components. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

P2 is related to the residual effect of switch cost upon the impending task.[34] Accordingly, the investigation of these other components might be considered in future research.

5. Conclusions

The present results suggest that general improvements in task-switching performance were induced by acute exercise, regardless of whether the exercise modality was aerobic or anaerobic in nature. Given that this improved task-switching performance might be related to an enhanced allocation of attentional resources, the facilitation could be associated with the latter stages of mental processing rather than earlier sensory processing. Nonetheless, further research is needed to identify additional moderators of the effects of acute exercise on EF, as well as to advance understanding of the exercise–cognition relationship.

Practical implications

- Both acute AE and RE improve cognitive performance in young adults.
- Acute AE or RE influence the late, but not the early stages of information processing.
- Exercise-induced benefits for cognitive performance might be partly due to an increase in attentional allocation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jsams.2019.07.009.

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