Research Article

Effects of Exercise-Induced Fatigue on Attention Networks in Active and Inactive Individuals: A Pilot Study

Maryam Kayvani[1], Sana Soltani[2*], Akram Kavyani[3]

1. Department of Cognitive and Behavioral Sciences and Technology in Sports, Faculty of Sports Science and Health, Shahid Beheshti University, Tehran, Iran.
2. Department of Motor Behavior, Faculty of Sports Sciences, Bu-Ali Sina University, Hamadan, Iran.
3. School of Health Science and Social Work, Griffith University, South Port, Australia.

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ABSTRACT

Introduction: Previous research has shown that neural mechanisms contribute to muscle fatigue by reducing neural drive to the muscles. This pilot study aimed to investigate whether exercise-induced fatigue influences cognitive functions, particularly attentional control (i.e. alerting, orienting, and executive function [(EF)]), and to determine whether these effects differ between physically active and inactive individuals.

Materials and Methods: Twenty-four participants were categorized into two subgroups: Active and inactive. Fatigue was induced by performing submaximal aerobic endurance exercise until exhaustion was reached.

Results: Fatiguing exercise improved alertness in both groups. Orientation performance declined in the inactive group but remained unchanged in the active group. EF improved in the active group but showed increased error rates in the inactive group.

Conclusion: The effects of exercise-induced fatigue on attentional networks appear to depend on the physical activity level and specific attention component assessed.

*** Corresponding Author:**
Sana Soltani, Assistant Professor.
Address: *Department of Motor Behavior, Faculty of Sport Sciences, Bu-Ali Sina University, Hamadan, Iran.*
Tel: *+98 (913) 7190757*
E-mail: *sana.soltani@basu.ac.ir*

Introduction

Muscular fatigue is an exercise-induced reduction in muscle ability [1], originating at different levels of the motor pathway, and is typically categorized into peripheral and central components [2]. Peripheral fatigue is caused by changes at or distal to the neuromuscular junction, while central fatigue occurs in the central nervous system (CNS), resulting in a decrease in neural drive to the muscle [1, 3]. The effect of exercise-induced fatigue on cognition and the link between CNS circuits of physical fatigue and cognitive functions have rarely been studied. According to some studies, mental fatigue has different effects on various behavioral, physiological, and psychological outcomes during exercise [4-8]. The most significant contributor to the harmful effects of mental fatigue on endurance performance has been higher perceived exertion [9]. However, no relationship is found between mental and central fatigue [10]. Despite studies on the effect of mental fatigue on physical function, the reciprocal relationship and effect of physical fatigue on mental functioning remain unclear.

Descriptive reviews [11, 12] and meta-analytic studies [13-17] have reported conflicting results regarding the effects of exercise on cognitive functions. Some studies have focused on the short-term effects of exercise on cognitive function. For example, one study assessed the cognitive performance of 15 cyclists immediately after a single training session and found improvements in simple reaction time and executive function (EF), but no changes in selective reaction time or finger-tapping speed. However, a reduction in stimulus classification speed and information processing was observed among young, actively trained male cyclists [18]. Similarly, other investigators examined the effect of 60 minutes of cycling on cognitive functions. They found a subsequent decrease in complex perceptual discrimination and an increase in reaction time on the memory-based vigilance test, while detection and identification did not differ between the exercise and control groups [19]. Wilke et al. concluded that the acute effect of resistance exercise on cognitive function depends on specific cognitive subdomains [16]. Considering task specificity, working memory and attention remained unaffected, whereas inhibitory control and cognitive flexibility were improved after resistance exercise [16, 20].

It is worth noting that most studies explore the effects of exercise on cognitive function rather than the effects of exercise-induced fatigue. The effects of exercise-induced fatigue on cognitive functions may also be task-specific. In addition to the varied effects of exercise on different cognitive tasks, the role of physical fatigue must be considered. Furthermore, evidence on the effects of intense exercise on cognitive control has mostly come from studies using incremental protocols, where the effects of exercise are confounded by those of exhaustion [21, 22]. This study aimed to separate the effects of exercise-induced fatigue from exercise intensity by using a maximal voluntary contraction (MVC) test immediately after exercise and measuring cognitive function thereafter.

Given the importance of task type in research on exercise-induced fatigue, and the fundamental role of attention in most cognitive and motor tasks, it is essential to evaluate the effects of attentional tasks. The term EFs refers to a wide range of top-down mental processes required for the cognitive control of behavior. Inhibitory control of attention, a core EF, enables us to selectively attend to stimuli by suppressing irrelevant inputs, based on intention [23]. Selective attention initiates many cognitive processes, including alerting and orienting, and involves executive control networks in the brain (i.e. attention networks [ANs]) [24]. The orienting network shifts attention to specific spatial locations or prioritizes certain sensory inputs for processing [24, 25]. The executive control network detects conflicts and inhibits interference during top-down processing [26, 27]. The AN test (ANT) is used to measure the functioning of ANs [28, 29]. Executive control, a function of ANs and essential in sports, enables planning, decision-making, error detection, generating new responses, and overriding habitual actions.

To understand inconsistencies in prior research regarding the relationship between exercise-induced fatigue and cognitive functioning, we must consider limitations such as the failure to accurately measure fatigue in fatigue-inducing protocols, variations in cognitive tasks and their scheduling, and differences in participants' physical activity levels. Variations in physical fitness have been shown to affect cognitive function [30], especially EFs [31, 32], and may also lead to different physiological responses to fatigue and variations in fatigue perception. However, few studies have assessed the exact extent of fatigue in both active and inactive participants.

Studying this relationship is crucial because inactive individuals may be more vulnerable to fatigue due to lower physical conditioning. A well-established relationship exists between physical activity and cognitive function, with regular physical activity consistently enhancing cognitive performance [11, 33].

In summary, the relationship between fatigue, ANs, and physical activity level can be summarized as follows: Mental fatigue impairs performance in the executive control network. Exercise-induced fatigue also reduces cognitive function, particularly EF. However, a history of physical activity enhances cognitive performance, such that active individuals outperform inactive individuals. Therefore, the question arises: Can a history of physical activity moderate the negative effects of exercise-induced fatigue on cognitive performance? That is, does the cognitive performance of active individuals deteriorate less after exercise-induced fatigue than that of inactive individuals?

In the present study, we investigated the effects of exercise-induced fatigue on AN function in active and inactive young adults. The fatigue-inducing protocol was designed individually for each participant according to their baseline physical activity level. To confirm fatigue induction, we measured MVCs before and after the intervention. After establishing performance decline in both groups, we examined the effects of fatigue on AN function using the ANT.

Materials and Methods

Twenty-four healthy young adults (19 females, five males) voluntarily participated in this study after providing informed consent. Before participation, the study protocol was thoroughly explained to each participant.

Participants were randomly assigned to either an active or inactive group based on their responses to the international physical activity questionnaire–long form (IPAQ) [34]. According to IPAQ classification, physical activity levels are categorized as: (1) low/inactive, (2) minimally active, and (3) health-enhancing physical activity, a highly active group.

During the initial screening, participants were asked about their lower extremity health to exclude those with a history of injuries, surgeries, congenital abnormalities, or neurological conditions, such as stroke, affecting the knees, ankles, or associated musculature. Participants were instructed to maintain consistent eating and sleeping routines for at least two days before the sessions, ensure adequate hydration, and refrain from consuming alcohol, caffeinated beverages, psychotropic medications, or antidepressants within 24 hours of testing.

Instruments

The assessment tools included the IPAQ [34] for physical activity evaluation, the mini-mental state examination (MMSE) for cognitive screening [35], and a Biodex System 4 Pro isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) to measure maximal muscle strength. Additional equipment included a Monark 894E peak bike (Monark Exercise AB, Sweden) for aerobic testing, a Borg CR-10 scale for rating perceived exertion, and an ANT [36] for attentional assessment. Standard anthropometric measurements were obtained using a calibrated scale and measuring tape, visual acuity was assessed using a Snellen chart, and all cognitive tasks were presented on a 14-inch laptop computer.

Procedure

The study was conducted over two sessions, each lasting approximately 90 minutes.

Session 1 (baseline assessment)

Baseline physiological and cognitive assessments were performed during the first session. Upon arrival at the laboratory, participants first completed the MMSE to assess cognitive status. This was followed by the ANT, administered under non-fatigued conditions for approximately 20 minutes to establish baseline cognitive performance. Finally, participants performed MVC of the knee flexor (hamstring) and extensor (quadriceps) muscles at a 90-degree knee angle using an isokinetic dynamometer. The initial MVC assessment familiarized participants with the strength testing protocol.

Session 2 (fatigue and post-fatigue testing)

The second session was conducted 1-3 days after the first. The participants were instructed to avoid strenuous physical or mental activity and maintain their regular routines between sessions.

At the beginning of the second session, all participants performed the MVC test again to obtain pre-fatigue muscle strength levels. Subsequently, they completed a fatigue-inducing exercise protocol using a stationary ergometer. Post-exercise fatigue was quantified using MVC measurements obtained with an isokinetic dynamometer. Immediately afterward, both the ANT and MVC tests were re-administered to assess changes in cognitive performance and muscle strength resulting from the induced fatigue. Figure 1 shows an overview of the study protocol.

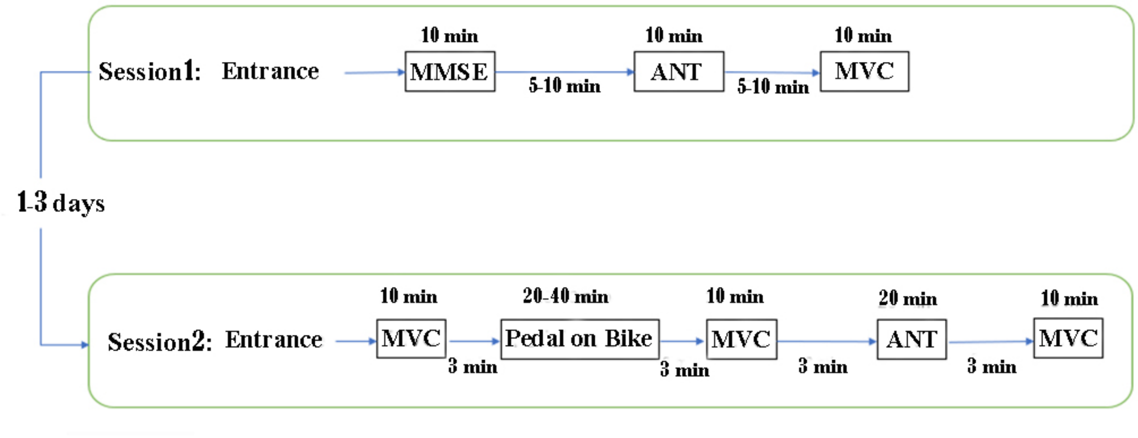

Figure 1. Overview of experimental protocol

MVC

The maximal isometric strength of the knee flexors (hamstrings) and extensors (quadriceps) was assessed using an isokinetic dynamometer before and after the fatigue protocol. Participants were seated in an adjustable chair with their hips and knees positioned at 90 degrees, ankles in a neutral position, and pelvis and chest secured with straps to minimize compensatory movements. A monitor positioned 50 cm in front of the participants displayed real-time visual feedback of the contraction force to promote maximal effort.

The participants were instructed to perform three MVCs for each muscle group, holding each contraction for 5 s, with 2 minutes of rest between trials. Strong verbal encouragement was provided during each effort to ensure maximum performance. In the first session, par-

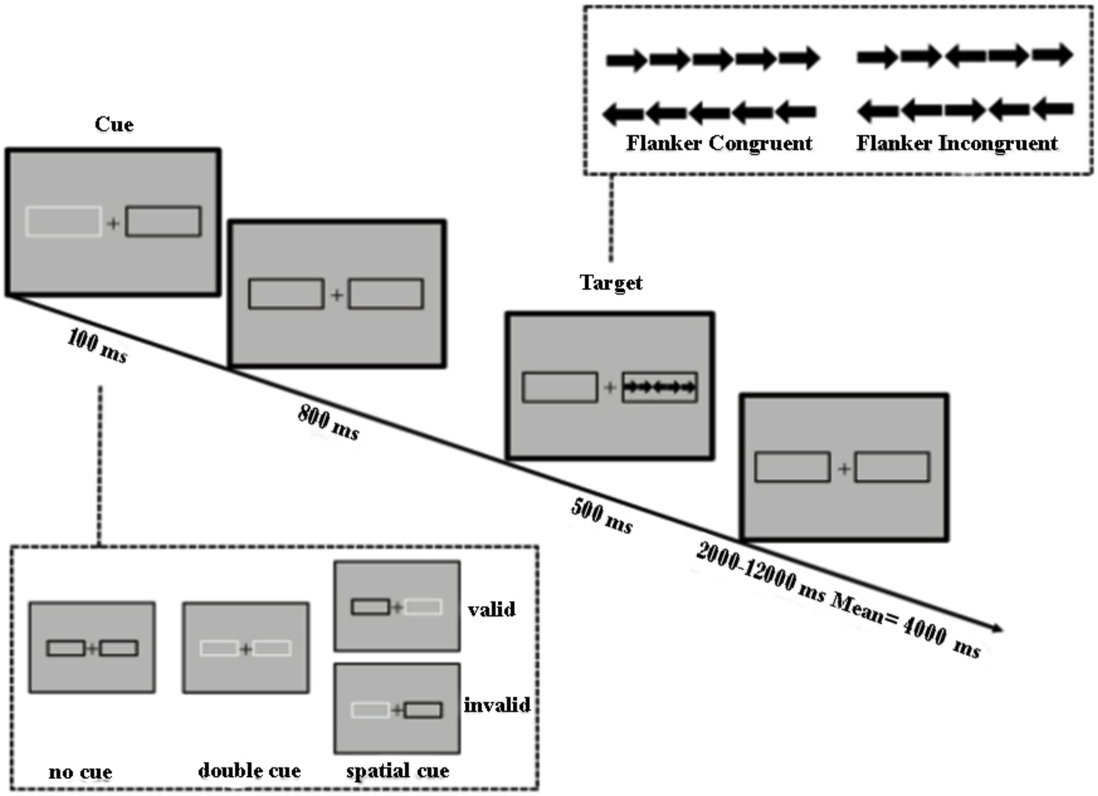

Figure 2. The ANT experimental procedure

ticipants also completed three familiarization trials for both flexors and extensors to learn the testing procedure and reduce the learning effect.

Fatiguing exercise

To induce global fatigue, the participants performed dynamic endurance exercise on a Monark ergometer using a progressive protocol designed to ensure comparable levels of exhaustion across both active and inactive individuals, accounting for differences in VO_2Max. The saddle and handlebars were individually adjusted for each participant, who began with a 10-minute warm-up at their preferred speed. The exercise then continued using a ramp protocol, starting at an initial workload of 25 W with 5 W increments every 5 minutes. Visual feedback helped participants maintain a pedaling cadence of 50–60 rpm, and they were verbally encouraged to sustain maximal effort. The session concluded when participants either chose to stop or were unable to maintain a cadence above 50 rpm for more than 10 seconds, despite strong verbal encouragement, with perceived exertion ratings reaching 19–20, indicating voluntary exhaustion.

ANT protocol

The ANT was conducted using a standard 20-minute version developed by Fan et al. (2009) and presented and recorded using the Psychtoolbox software [36]. As illustrated in Figure 2, each trial began with a central fixation point, followed by one of three cue conditions: No-cue, double-cue, or spatial-cue. After a 400 ms interval following cue offset, the target display appeared, presenting either a congruent or an incongruent condition. Figure 2 shows the timing details for cue presentation, target display, and inter-stimulus intervals. To assess the three components of attention, alerting, orienting, and EF, an equal number of trials for each condition was randomly distributed across blocks. The participants were instructed to prioritize both speed and accuracy. The session began with a 24-trial practice block, followed by a test phase consisting of 288 trials divided into three blocks of 96 trials. The reaction time and accuracy data were automatically recorded throughout the test.

Statistical analysis

Descriptive statistics, including frequency, Mean±SD, were used to summarize the data. The Shapiro-Wilk test confirmed normal distribution, and Levene's test verified homogeneity of variances. A two-way (group×condition) analysis of variance (2×2 ANOVA) was conducted to examine the main effects and interactions. An a priori power analysis, based on Moore et al. [19], estimated an effect size of 0.14—reflecting the smallest significant effect observed for changes in simple and complex perceptual tasks following fatigue. With α=0.05 and power=0.95, the required sample size was calculated to be 24 participants for a within-between ANOVA with two measurements and two groups, using G*Power 3.1. Thus, the sample size in this study met the requirements for detecting the hypothesized effects. All outcome measures demonstrated acceptable internal consistency, with inter-rater reliability coefficients ranging from 0.65 to 0.87. Statistical analyses were performed using SPSS software,version 20.0 and G*Power software, version 3.1.

Results

Table 1 presents the descriptive data on age, height, weight, MMSE score, IPAQ score, Borg rating score, and the pre-fatigue to post-fatigue MVC ratio for the groups. According to the table, the reduction in maximal contraction force of both groups was 25%, indicating the effectiveness of the fatigue protocol.

Table 2 and Figure 3 illustrate the Mean±SD of the ANT reaction time and error of the active and inactive groups under pre-and post-fatigue conditions. The efficiency of alerting was calculated using reaction times (RTs) with no cue minus RTs with double cues, orienting was RTs with central cues minus RTs with spatial cues, and EF was RTs of incongruent flankers minus RTs of congruent flankers.

Alerting

Alerting performance was analyzed using a 2×2 ANOVA with group (active vs inactive) and condition (before vs after fatigue) as factors, examining both reaction time and error scores. For reaction time, there were no significant main effects of group ($F_{1,22}$=1.59, P=0.22, η^2=0.06) or condition ($F_{1, 22}$=1.36, P=0.26, η^2=0.05), and no significant interaction between group and condition ($F_{1, 22}$=0.03, P=0.86, η^2=0.001). In contrast, error scores showed a significant main effect of group ($F_{1, 22}$=5.38, P=0.03, η^2=0.31), indicating that the inactive group made more errors than the active group. A significant main effect of condition was found ($F_{1, 22}$=10.50, P=0.007, η^2=0.46), with higher error rates observed after fatigue. However, the interaction between group and condition for error scores was not significant ($F_{1, 22}$=0.90, P=0.25, η^2=0.07).

Table 1. Group comparisons of demographic, cognitive, and physiological characteristics

Variables	Mean±SD		T	P
	Active Group	Inactive Group		
Age (y)	23.3±4.45	22.2±3.95	0.80	0.430
Height (cm)	160.16±10.41	156.56±8.01	1.62	0.110
Weight (kg)	64.56±5.65	61.16±7.34	3.57	0.001
MMSE score	28.33±1.23	26.91±1.78	1.78	0.080
IPAQ score	196.3±22.61	132.41±13.45	5.78	0.001
Borg RPE score	17.16±1.24	17.08±1.45	0.50	0.760
MVC ratio	0.8±0.07	0.72±0.1	1.54	0.100

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Abbreviations: MMSE: Mini-mental state examination; IPAQ: International physical activity questionnaire; MVC: Maximal voluntary contraction; RPE: Rating of perceived exertion.

Orienting

For the orienting network, a 2×2 ANOVA revealed no significant main effect of group ($F_{1, 22}$=0.15, P=0.69, η^2=0.007) or condition ($F_{1, 22}$=1.40, P=0.24, η^2=0.06) on reaction time; however, the interaction between group and condition was significant ($F_{1, 2}$=4.27, P=0.05, η^2=0.16). A follow-up paired t-test indicated that, within the inactive group, reaction time significantly increased after fatigue compared to the pre-fatigue condition (t=2.37, df=11, P=0.03, MD=25.28). Regarding error scores, a significant main effect of group was found ($F_{1, 22}$=4.67, P=0.05, η^2=0.01), with the inactive group exhibiting more errors than the active group. However, the interaction between group and condition for error scores was not significant ($F_{1, 22}$=0.06, P=0.79, η^2=0.006).

EF

For the EF network, analysis of variance revealed significant main effects of group ($F_{1, 22}$=4.74, P=0.04, η^2=0.18) and condition ($F_{1, 22}$=8.92, P=0.007, η^2=0.28) on reaction time, indicating that both physical activity status and fatigue influenced performance. However, the

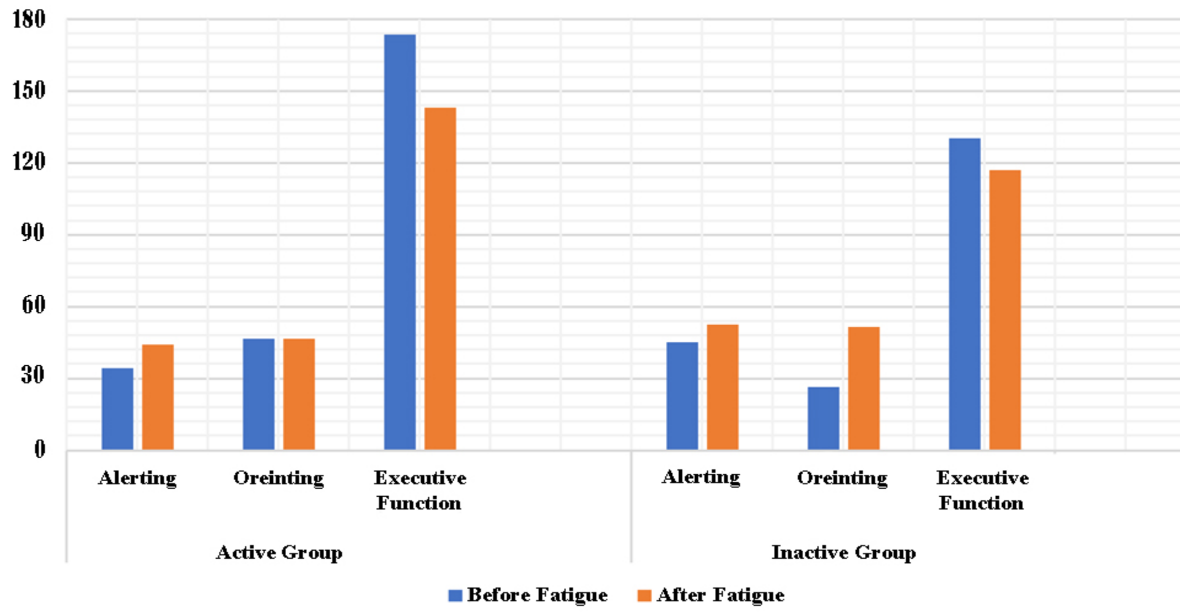

Figure 3. ANT RT performance before and after fatigue induction in active versus inactive groups

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Table 2. AN performance: Reaction times (ms) and error rates (%) before and after fatigue induction

Group		Mean±SD					
		Alerting RT	Orienting RT	Executive RT	Alerting Errors	Orienting Errors	Executive Errors
Active	Pre	34.04±27.73*	46.68±30.03	173.67±38.77*	6.28±4.19	5.42±4.39	11.14±7.37
	Post	43.85±24.01*	29.82±26.55	142.97±36.08*	4.57±4.11	6.42±4.9	8.71±9.3
Inactive	Pre	45.23±27.64*	26.21±40.89*	130.31±51.13	10.71±1.9	10.45±1.91	17.83±5.07*
	Post	52.6±26.42*	51.49±34.08*	117.1±39.64	7.57±1.9	8.42±3.59	19.14±9.88*

RT: Reaction time.

*P<0.05 for pre- vs post-fatigue comparisons.

JMR

interaction between group and condition was not significant ($F_{1, 22}$=1.52, P=0.23, η^2=0.06). Overall, reaction times decreased following fatigue in both groups. For error scores, a significant main effect of group was found ($F_{1, 22}$=6.19, P=0.02, η^2=0.34), with the inactive group making more errors than the active group. Neither the main effect of condition ($F_{1, 22}$=0.28, P=0.60, η^2=0.02) nor the interaction effect ($F_{1, 22}$=0.22, P=0.64, η^2=0.01) was significant. These results suggest that, under fatigue, the inactive group responded faster but at the cost of reduced accuracy.

Discussion

This study aimed to determine whether exercise-induced fatigue affecting the CNS can alter cognitive functions, specifically alertness, orientation, and EFs involved in selective attention in active and inactive individuals.

The active and inactive groups did not show different reaction times for alerting under pre- and post-fatigue conditions. Inactive individuals made more errors (lower accuracy) compared to active individuals in both the pre- and post-fatigue conditions, and their post-fatigue alerting errors were reduced, indicating that they were more accurate after fatigue. Regarding orientation, the reaction time of the inactive group in the fatigue condition was significantly increased. Regarding the EFs network, both groups responded faster under the fatigue condition; however, the inactive group made more errors, indicating lower accuracy than the active group. Thus, physical activity, accompanied by subsequent fatigue, improved alertness in both groups, reduced the orienting performance of the inactive group, and did not affect orientation speed in the active group. The executive control network improved in active individuals (η^2=0.18), but the error rate of the executive control network increased in inactive individuals after fatigue (η^2=0.34).

This study had unique characteristics that set it apart from other similar studies. First, we examined the effects of endurance exercise-induced fatigue on cognitive function, particularly ANs. Previous research has investigated the effect of short-term and long-term exercise, regardless of the effects of physical fatigue on the AN. Second, the MVC test was used to objectively measure post-exercise fatigue. However, the degree of physical fatigue has not been objectively measured in studies examining the effects of fatigue on cognitive function. In this study, MVC was reduced by approximately 25% after engaging in physical activity. Finally, this study examined how regular exercise adaptation impacted the effect of exercise-induced fatigue on the cognitive function of active and inactive groups. In previous studies [37-39], the effect of exercise-induced fatigue on cognitive functions was examined only in active and professional individuals. This is important because exercise has been proven to stimulate the brain to maintain functions and structures involved in EFs [2, 40, 41]. This benefit is achieved through relatively long-lasting physiological changes in executive control structures.

Our results replicated the general facilitating effect of exercise on the alerting network, as evidenced by an improvement in the overall state of tonic vigilance and preparedness. No significant differences were observed between the active and inactive groups in the alerting network. These results may be explained by the theory of arousal and exercise-induced increases in adrenaline and noradrenaline secretion. These results are partially consistent with the findings of a recent meta-analysis [42], which showed that the performance of tasks involving quick decisions and automated behaviors improves with exercise-induced arousal.

These results were consistent with those of Huertas et al. and Hogervorst et al., who examined the effects of exercise sessions with different intensities on the cognitive performance of professional cyclists. They concluded that short-term exercise reduced the alerting effect, but other AN functions, such as orientation and EF, were unaffected. According to the authors, short-term exercise may have altered phasic alertness by increasing tonic vigilance. In the present study, alerting accuracy scores improved after physical activity. Unlike Huertas et al., the present study found that fatiguing physical activity disrupted the orientation network in inactive individuals and improved EFs, especially in active individuals. This difference is likely due to variations in fitness levels and the intensity of physical activity [43, 44].

Regarding the effect of exercise-induced fatigue on the orienting network, our results showed that the level of physical activity modulates this function, inducing a decrease in visuospatial attention in inactive individuals. We argue that normal exogenous attentional function was affected by exercise-induced fatigue, which had a greater impact on inactive than active participants. Consequently, target processing was prioritized over irrelevant stimuli. Similar to the study conducted by Moore et al., the effect of orientation decreased in this study. These researchers also showed a decrease in complex perceptual differentiation tasks after 60 minutes of cycling. Unlike the present study, they found an increase in reaction time during the memory-dependent vigilance test [19]. Therefore, the effect of exercise-induced fatigue may be task-specific and have a more significant impact on perceptual tasks, which require relatively automated processing compared to effort-based memory tasks. However, in line with previous studies [39, 43], the present results did not show changes in the orienting speed of active individuals after exercise or subsequent fatigue.

More importantly, for the current study, our results, similar to others [37], revealed that the level of physical activity moderated the effect of exercise-induced fatigue on EF. Adaptations to physical training improved executive control in fatigued active participants. Conversely, a lack of physical activity induced weaker EF in inactive participants in the fatigued state. EF is necessary to detect the final target, given the limited capacity of the attentional system. Higher levels of physical activity may lead to more efficient focal attention processing and top-down processing, as well as improved self-regulation and inhibitory control in active individuals. These results are inconsistent with those of Hillman et al. as well as Boucard., who showed that long-term regular exercise does not affect inhibitory functions (a subset of EFs) [45, 46]. This difference is likely due to different definitions of active and inactive groups, as well as different measurement indices of EFs across various tasks. Unlike the present study, previous researchers have probably used only the reaction time index, regardless of accuracy. Furthermore, the complicated and multidimensional nature of EFs and the difficulty in operationalizing EFs measurements could also contribute to inconsistencies in the results. The results of the present study also did not agree with those of Tomporowski et al., who found a decline in EFs after exercising in dehydrated conditions [47]. The difference in results can be mainly attributed to the participants' readiness levels, the type of activity that induces fatigue, and the dehydrating conditions.

Even though the independence of AN functions has been established, Xuan et al. pointed out that there may be an interplay among ANs, which means that they are interrelated [48]. Consistent with this idea, our results indicated an interaction effect of executive control on alertness. However, the degree of cognitive adaptation in individuals to physical activity affects this relationship. In other words, the increased sensitivity to exogenous stimuli due to increased arousal after physical activity, which was directly characterized by improved post-fatigue alertness in both groups, is related to the inability to select relevant information in inactive individuals and is therefore associated with reduced EF in these individuals. Rather, improved alertness results in better orientation and prioritization of relevant information in the orienting network, making target detection in the active individuals more efficient. Thus, active individuals had better EF after fatigue. The adaptation created by regular activity may have led to the arousal level of the active group being within the desired range for those individuals. Similar to this study, Hogervorst et al. found that alertness and EFs of trained cyclists were improved after training [44].

Conclusion

The findings of this study demonstrate that exercise-induced fatigue affecting the CNS can influence cognitive functions, specifically alertness, orientation, and EFs involved in selective attention, among both active and inactive individuals. A history of regular physical activity appeared to confer a protective effect, as active participants performed better than inactive participants following fatigue, particularly in tasks involving executive control, with a notable effect size of 34%. However, interpretation of these results is limited by the challenge of disentangling the potential cognitive benefits of acute aerobic exercise from the negative effects of central fatigue. Future research is needed to compare fatiguing versus non-fatiguing aerobic protocols to better isolate these factors. Moreover, assessing EFs during physical exertion rather than after it may yield a clearer understanding of how fatigue impacts cognitive performance in real-time. It is also essential to consider non-physiological factors. For instance, prior evidence suggests that open-skill sports, which demand continuous cognitive engagement, may selectively enhance inhibitory control. In the present study, athletes involved in such sports may have demonstrated superior EF compared to inactive individuals, which could have influenced their post-fatigue performance. Therefore, future studies should further investigate the interaction between exercise-induced fatigue and cognitive function, accounting for the type of sport and the level of cognitive demand (e.g open- vs closed-skill sports).

Ethical Considerations

Compliance with ethical guidelines

This study was approved by the Biological Research Ethics Committee of Shahid Beheshti University, Tehran, Iran (Code: IR.SBU.REC.1397.044).

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Authors' contributions

Study design, experiments, data analysis, writing and final approval: All authors; Conducting the training sessions during the experiment: Maryam Kayvani and Sana Soltani; Supervision: Maryam Kayvani.

Conflict of interest

The authors declared no conflict of interest.

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