Physiology & Behavior 241 (2021) 113588

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

Acute aerobic exercise to recover from mental exhaustion – a randomized controlled trial

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ARTICLE INFO

Keywords:
Cognitive performance
Regeneration
Cognitive flexibility
Subjective well-being
Motivation

ABSTRACT

Purpose: Prolonged periods of intense cognitive activity lead to a state of mental exhaustion. While widespread strategies to recover from mental exhaustion (i.e., watching TV) are non-effective, aerobic exercise seems to be a promising approach. This can be explained by the acute and chronic aerobic exercise-induced benefits on the central nervous system.

Methods: This study investigated the potential of a single bout of moderate aerobic exercise (65–75% of each participants' individual VO2peak) to recover from experimentally induced mental exhaustion. A randomized controlled trial on healthy adults (N = 99) was conducted. They performed 60 min of a cognitively demanding test battery, in order to induce mental exhaustion. Subsequently, they were randomized to one of three treatments: 30 min of moderate aerobic exercise on a cycle ergometer, 30 min of a simple lower body stretching routine (= active control treatment) or watching a popular sitcom (= passive control treatment). Cognitive flexibility performance, mood, tiredness, restlessness, self-perceived cognitive capacity, and motivation were assessed before and after treatment.

Results: The empirical results showed that moderate aerobic exercise led to a better recovery for cognitive flexibility (mean difference divided by pooled standard deviation, Cohen's d= 0.737), mood (d= 0.405), tiredness (d= 0.480), self-perceived cognitive capacity (d= 0.214), and motivation (d= 0.524) compared to active control treatment. Moderate aerobic exercise was also more effective than passive control treatment (d= 0.102 - 0.286) with the exemption of tiredness (d= 0.015) and restlessness (d = -0.473).

Conclusion: In conclusion, this study suggests that a single bout of acute aerobic exercise supports regeneration of cognitive flexibility performance and of subjective well-being. This holds true not just compared to artificial active control treatment but also compared to widespread leisure time activity, namely watching TV.

1. Introduction

Prolonged periods of intense cognitive activity decrease neuronal activation and deteriorate top-down processes from prefrontal cortical areas [1,2]. Consequently, a state of mental exhaustion arises [3], that is characterized by a decline in cognitive performance and deterioration of subjective well-being [4,5] as well as intrinsic motivation [6,7]. In work environments, mental exhaustion negatively impacts productivity [8]. Furthermore, it increases the risk of errors and occupational accidents. In professions, such as surgeons [9,10], air traffic controllers, and pilots [11,12], mental exhaustion can have life-threatening consequences. Moreover, frequent mental exhaustion leads to a lasting psychological state of mental fatigue with permanent alterations in brain structure and function [13]. These include significant volume decreases in white and gray matter [14,15], and changes in EEG activity and cognitive processing [16].

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https://doi.org/10.1016/j.physbeh.2021.113588
Received 8 March 2021; Received in revised form 5 September 2021; Accepted 8 September 2021
Available online 11 September 2021
0031-9384/

Widespread strategies to recover from mental exhaustion, such as watching TV or smoking [17] are not effective and even detrimental [18–20]. Nevertheless, research on healthy and effective ways to recover from mental exhaustion is scarce. A promising approach to this problem is aerobic exercise. Evidence shows that already a single session of aerobic exercise leads to several positive adaptations within the central nervous system (e.g., increases in prefrontal oxygenation [21] and increases in circulating neurotrophins [22]). At the behavioral level, a large number of studies shows that cognitive performance improves following a single bout of aerobic exercise [23]. Interestingly, a plethora of evidence exists for acute aerobic exercise induced benefits of cognitive flexibility deficits [24,25], which seems to be particularly susceptible for mental exhaustion-induced deterioration [26,27]. Concerning subjective well-being, aerobic exercise can improve mood states [28,29], feelings of tiredness [30] and nervousness [31]. Additionally, a single session of exercise is associated with higher levels of motivation

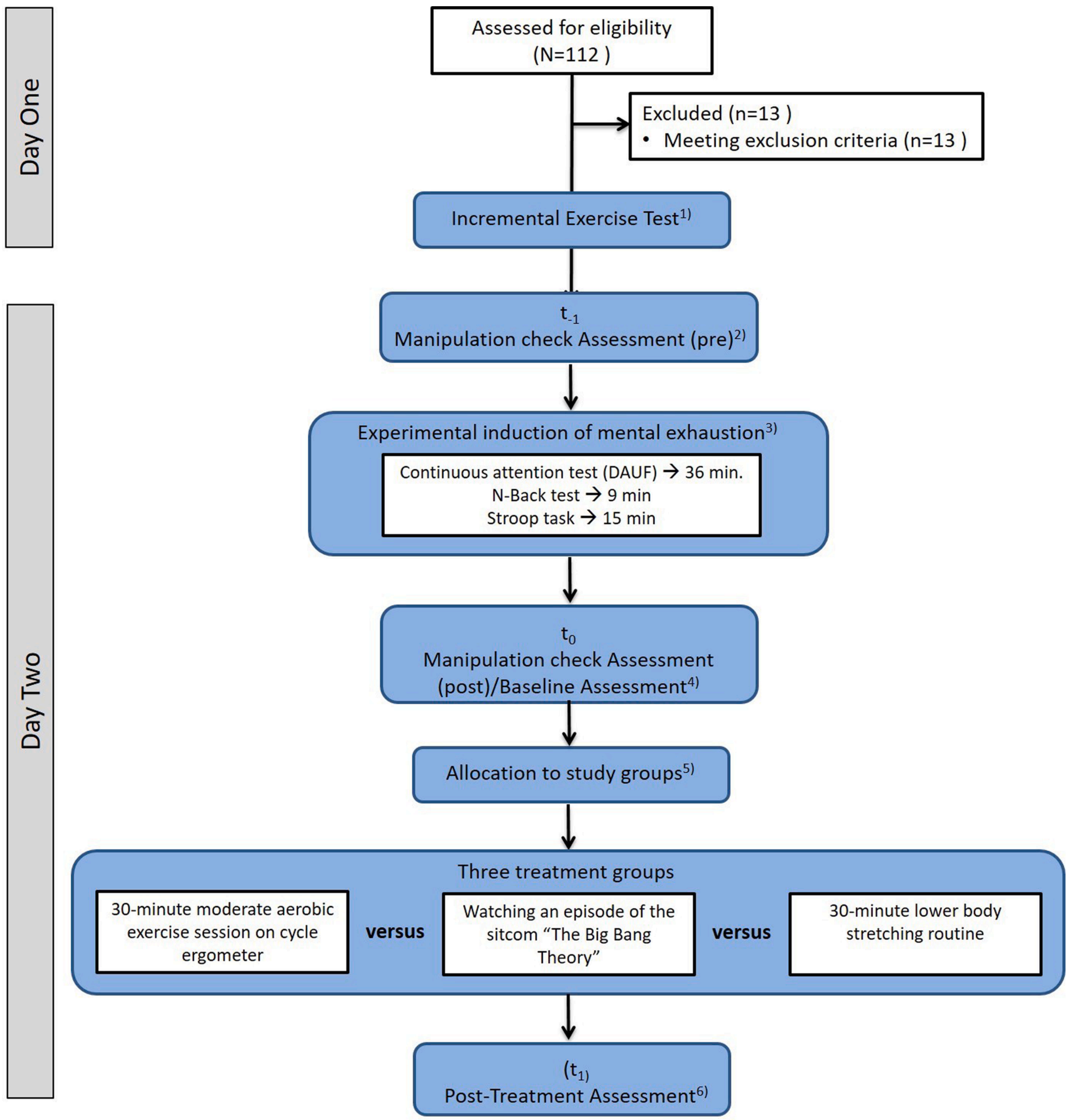

Fig. 1. (Note: 2 columns width; colored) Flowchart of the study. (1) Incremental Exercise Test was used to control training load in exercise group. Details of the Incremental Exercise Test protocol are described in the Supplementary Material to this article; (2) To control for success of manipulation of mental exhaustion, prior to and after mental exhaustion induction, study outcomes were captured. These comprised of cognitive flexibility measurement (Trail Making Test part B), measurement of mood, mental alertness, restlessness (via Multidimensional Mood State questionnaire), as well as self-perceived cognitive performance capacity and motivation (visual analogue scales) (3) Participants worked for 60 min on a demanding cognitive test battery, which comprised of a continuous attention test (DAUF), a N-Back test, and a Stroop task (4) The manipulation check post-Assessment was equal to the Baseline Assessment (t0) of the study and comprised the study outcomes (5) A randomization with balanced allocation 1:1:1 was conducted (6) Post-Assessment (t1) was conducted immediately after cessation of treatment and comprised of the study outcomes.

for subsequent tasks [32,33].

In this randomized controlled trial, we investigated the potential of a single bout of moderate aerobic exercise to recover from experimentally induced mental exhaustion. We examined the effects of exercise on the regeneration of cognitive flexibility performance, as well as on subjective well-being; namely, on mood, mental alertness, nervousness, self-perceived cognitive performance capacity, and motivation for cognitively demanding tasks after reaching mental exhaustion. The recovery potential of aerobic exercise was compared to the recovery potential of watching TV and to a lower body stretching routine. In conclusion, the primary aim of this study was to test the hypothesis that 30 min of moderate aerobic exercise improves the recovery of cognitive flexibility performance after cognitive exhaustion significantly more than active and passive control treatments. A secondary aim was to test the hypothesis that 30 min of moderate aerobic exercise improves the recovery of subjective well-being, after cognitive exhaustion has occurred, significantly more than active and passive control treatments. A detailed overview (Table 1) on tested hypotheses can be found in the Supplementary Material of this article.

2. Methods

2.1. Trial design

A randomized controlled study with three different treatment groups was conducted (balanced allocation ratio, 1:1:1). Randomization was implemented based on sealed, opaque envelopes provided by a co-worker who was not further involved in the study. The randomization sequence was generated using SPSS Statistics software (random number seed). The study groups comprised of a single bout of 30 min moderate aerobic exercise on a cycle ergometer, watching an episode of a popular sitcom (= passive control treatment), and a simple lower body stretching routine (= active control treatment) (refer to 2.4. Treatments). All treatments were administered after an experimental induction of mental exhaustion through 60 min of a cognitively demanding test battery. The study flow-chart is depicted in Fig. 1. The study protocol was approved by the Ethics Committee of the German Sport University (Germany) and registered at the German Clinical Trial registry (DRKS00014746). Participants were included in the study only after they gave written informed consent. The study conformed to the Declaration of Helsinki.

2.2. Participants

Participants were young healthy adults, who were students from the German Sport University Cologne. Participants were blinded to the research hypothesis in order to avoid biases due to expectations. Participants were not aware that the first part of the cognitive test battery aimed to mentally fatigue them (see details in 2.3. Procedures). The only inclusion criterion was to be 18 years of age or older. Exclusion criteria comprised of acute infections, any history of or acute cardiopulmonary, metabolic, neurological or psychiatric diseases, any limitation in the ability to exercise or complete the cognitive testing procedures, any consumption of legal psychoactive substances (including caffeine and nicotine) prior to testing, and any consumption of illegal or prescription medication during the previous month. The total number of participants was $N = 99$ with 47 females and 52 males enrolled in the study.

2.3. Procedures

This study was conducted at the Institute for Cardiology and Sports Medicine of the German Sport University (Cologne, Germany) on two non-consecutive days. On the first day of their visit, participants gave demographic/anthropometric data and completed an incremental exercise test to determine their peak oxygen uptake (VO_2peak). The detailed protocol of the incremental exercise test can be found in the Supplementary Material to this article.

Intelligence is closely associated with cognitive performances [34–37]. Sleep quality and caffeine use can alter cognitive performances [38–40]. To avoid confounding of these variables participants' intelligence was captured using the Multiple-Choice Vocabulary Intelligence Test [41]. Sleep quality was captured using the Pittsburgh Sleep Quality Index [42]. Moreover, participants were instructed to refrain from caffeine prior to testing. All tests were performed only on weekdays between 9:00 a.m. and 1:00 p.m.

On day two, participants worked for 60 min on a demanding cognitive test battery to induce a state of mental exhaustion. The procedure was similar to the one used by Tanaka and colleagues [43]. The cognitive test battery comprised of a continuous attention test, an N-Back test, and a Stroop-task. All tests were computerized and operated via the 'Wiener Test-System' (Schuhfried, Vienna, Austria) (further details on the test battery are described in the Supplementary Material to this article). Participants were not aware that this cognitive testing was not an actual study endpoint but only used to mentally exhaust them. Thus, participants were more likely to stay motivated and to work focused during the mental exhaustion manipulation. To control for success of mental exhaustion manipulation, study outcomes (see details in 2.4. Treatments) were captured prior to (t_{-1}) and after mental exhaustion manipulation (t_0). Subsequently, participants were randomly assigned to one of the three study groups and allocated treatment was carried out. Immediately after cessation of treatment, post-treatment assessment (t_1) was carried out, which comprised of the below described study outcomes.

2.3.1. Treatments

Aerobic exercise group: Thirty minutes exercise on a cycle ergometer (Lode Excalibur Sport, Groningen, Netherlands) at an intensity corresponding to 65–75% of the participants' individual VO_2peak (as measured during incremental exercise test). The intensity was controlled using heart rate, which was measured with a Polar 92053123T31 Chest belt by Polar Electro Oy (Kempele, Finland). If heart rate would decrease under the heart rate corresponding to 65–75% of the participants' individual VO_2peak workload was increased automatically. If heart rate would increase over that boundary workload was decreased.

Passive control group = Sitcom watching group: Watching an episode of the sitcom "The Big Bang Theory" (Episode 1, Season 4) on a laptop computer while sitting at a desk.

Active control group: Thirty minutes of simple lower body stretching routine were supposed not to induce cardiovascular arousal. A similar routine was applied in a former study [44] and it consisted of lower body stretches using basic foam roller exercises for the quadriceps femoris muscle, calf muscles, hamstrings, iliotibial band and gluteal region. Each exercise was performed for 30 s in two sets. In addition, a one-minute break was taken between each exercise. For further details on the stretching exercises refer to Junger and Stöggl [44].

The time spent on interventions was the same for each group.

2.4. Outcomes

Cognitive flexibility performance, mood, tiredness, nervousness, self-perceived cognitive performance capacity, and motivation for cognitively demanding tasks subjective symptoms were measured prior to (t_{-1}) and after mental exhaustion manipulation (t_0), as well as directly following allocated treatment (t_1).

2.4.1. Cognitive flexibility performance measures

Cognitive flexibility is the ability to adapt cognitive processing strategies to face new and unexpected conditions in the environment. It is a core domain of executive functions [45]. In the present study, cognitive flexibility performance was measured using part B of the Trail Making Test [46], which has been used before in studies as a tool to measure mental fatigue [26, 47,48]. The test was computerized and operated via the testing platform 'Wiener Testsystem' (Schuhfried, Vienna, Austria [49]). In this test, participants are supposed to connect the numbers "1" – "13" and the letters "A" – "L" alternating in ascending order ("1" – "A" – "2" – "B" etc.) as fast as possible. The time to complete part B represents cognitive flexibility performance [46] and was therefore used in this study as an outcome measure. A smaller value reflects a better cognitive flexibility performance. Retest reliability of TMT B was stated as r= 0.86 - 0.94 [50].

2.4.2. Subjective well-being scales

Mood, tiredness, and restlessness were measured using the Multidimensional Mood State Questionnaire [51]. This questionnaire contains 24 items. Each item represents two contradicting states (e.g., unhappy vs. happy) and is ranked using a Likert scale ranging from 1 = "not at all" – 5 = "extremely". Eight items each sum up to a score on a superordinate bipolar dimension, namely "bad mood vs. good mood", "tiredness vs. wakefulness", and "restlessness vs. calmness". The score on each dimension ranges from eight to 40 with lower scores representing a state of decreased subjective well-being and higher scores representing a state of increased well-being [52]. Cronbach's alpha of MDBF was reported as α = 0.66 - 0.92 [51].

Participants self-perceived cognitive performance capacity and their motivation to work on cognitively demanding tasks were measured additionally using separate visual analogue scales [53]. Each scale was exactly 100 mm wide with extreme points labelled. The left endpoint always represented the low extreme (e.g., extremely low self-perceived cognitive performance capacity/ extremely low motivation for cognitively demanding tasks), the right endpoint the high extreme (e.g., extremely high self-perceived cognitive performance capacity/ extremely high motivation for cognitively demanding tasks). The number of millimeters between the low endpoint and participants' marking on each scale was used as measure for further analyses.

2.5. Sample size

Sample size calculation was done for the main hypothesis using G*Power 3.1.9.2 software [54]. As relevant effect size, a moderate effect (d= 0.50) was defined. Alpha was set at 5%. Test power (1-β) was set at 80%. Participants' baseline values were included in the model as covariate. Required sample size in such an analysis of covariance model can be calculated as $(1-\rho^2)$*n, with ρ representing the correlation between participants' baseline and post-treatment outcome-scores, and n representing the sample size that would have been required if a t-test of post-treatment outcome-scores was applied [55]. We estimated the correlation between patients' baseline and at post-treatment values with ρ = 0.70. Under the presuppositions made, sample size calculation showed that 33 participants would be required in each group leading to a total sample size of N = 99.

2.6. Statistical methods

To check if mental exhaustion manipulation was successful, cognitive performance and subjective well-being were analyzed prior to and after manipulation attempt using dependent t-tests. As criterion for successful manipulation of mental exhaustion, a significant deterioration was defined a-priori. The main hypothesis was analyzed using one-factor analyses of covariance. The time to complete TMT part B at post-treatment assessment was defined as dependent variable in this analysis. "Treatment group" (acute moderate aerobic exercise group vs. active control group) was defined as between-subjects factor and time to complete TMT part B at baseline as covariate. The secondary hypotheses were also analyzed using one-factor analyses of covariance.

Dependent variables were mood, tiredness, and restlessness scores in the Multidimensional Mood State Questionnaire, as well as participants self-perceived cognitive performance capacity and their motivation to work on cognitively demanding tasks measured on visual analogue scales at post-treatment assessment. "Treatment group" (acute moderate aerobic exercise group vs. passive control group vs. active control group) was defined as between-subjects factor and scores in the Multidimensional Mood State Questionnaire/visual analogue scales of the variables concerned at baseline as covariate. Pairwise comparisons of estimated marginal means of intervention groups were carried out using least significant difference. Analysis of covariance assumptions were examined and in case of violation corrections were carried out or non-parametric procedures were applied. Cohen's d values were calculated as effect size measures for group comparisons. Statistical analyses were conducted using SPSS 25® (IBM®, Armonk, NY, USA). A result was considered significant at a p-value equal to or less than 5%.

3. Results

All randomized participants received treatment and were included into analysis. Table 2 provides descriptive and anthropometric data of the tested sample.

3.1. Success of mental exhaustion manipulation

Participants' empirical data concerning cognitive flexibility performance, as well as subjective well-being before and after the mental exhaustion manipulation are presented in Table 3. The criterion for successful mental exhaustion manipulation was fulfilled for subjective well-being. Participants showed significantly worse mood (d = −0.57, t= 6.15, p < 0.001), significantly more tiredness (d = −1.20, t= 7.27, p < 0.001), significantly more restlessness (d = −0.59, t= 2.52, p < 0.001), significantly less self-perceived cognitive capacity (d = −2.02, t= 13.55, p < 0.001), and significantly less motivation for a cognitively demanding task (d = −0.93, t= 8.16, p < 0.001) after the mental exhaustion manipulation. However, the mental exhaustion manipulation applied in this study did not lead to a significant deterioration of cognitive flexibility performance. Participants' cognitive flexibility measured as performance in the TMT part B improved from before to after the mental exhaustion manipulation (see Table 3).

Table 2
Descriptive and anthropometric data of the tested sample (mean ± standard deviation).

	Aerobic exercise group(n = 34)	Active control group(n = 32)	Passive control group(n = 33)	Total(N = 99)	p-value*
Sex	♀ = 17/ ♂ = 17	♀ = 15/ ♂ = 17	♀ = 15/ ♂ = 18	♀ = 47/ ♂ = 52	0.93
Age (yr)	22.00 ± 3.47	21.00 ± 2.39	21.03 ± 4.59	21.61 ± 3.60	0.56
Height (m)	1.75 ± 0.09	1.75 ± 0.08	1.76 ± 0.08	1.76 ± 0.09	0.86
Weight (kg)	68.67 ± 10.97	69.12 ± 11.58	69.54 ± 10.76	69.83 ± 10.93	0.94
BMI (kg/ m^2)	22.30 ± 2.16	22.52 ± 2.39	22.27 ± 2.24	22.46 ± 2.18	0.86
Heart rate (bpm)	66.81 ± 8.92	69.30 ± 10.78	71.44 ± 10.02	69.43 ± 10.05	0.22
VO_2peak (mL min^{-1})	49.92 ± 8.98	46.63 ± 9.23	48.25 ± 11.8	48.81 ± 7.26	0.26
MWT-B Score	29.24 ± 3.01	28.78 ± 2.38	28.39 ± 3.02	28.71 ± 2.90	0.52
PSQI Score	4.64 ± 2.70	4.28 ± 1.76	5.61 ± 3.12	4.83 ± 2.63	0.72

BMI = Body Mass Index; MWT-*B* = Multiple Choice Vocabulary Test; PSQI = Pittsburgh Sleep Quality Index; ♀ = Female; ♂ = Male.
p-values indicate significance of empirical differences between treatment groups for descriptive and anthropometric data.

Table 3
Empirical data of the tested sample ($N = 99$) before and after mental exhaustion (mean ± standard deviation).

	Prior to mental exhaustion manipulation	After mental exhaustion manipulation	p-value of dependent t-test	Cohen's d
Cognitive flexibility	20.36 ± 5.49	18.44 ± 4.65	$p < 0.001$	−0.38
Tiredness vs. wakefulness	28.12 ± 6.78	19.47 ± 7.53	$p < 0.001$	−1.33
Bad mood vs. good mood	33.76 ± 5.52	30.28 ± 6.61	$p < 0.001$	−0.69
Restlessness vs. calmness	31.62 ± 5.22	27.87 ± 7.08	$p < 0.001$	−0.75
Cognitive capacity	7.04 ± 1.54	4.48 ± 2.04	$p < 0.001$	−1.62
Motivation	6.93 ± 1.83	5.53 ± 2.23	$p < 0.001$	−0.93

p = statistical p-value.

3.2. Success of exercise manipulation

At the end of t_1, participants in the exercise group showed on average a heart rate of 149.67 bpm ± 20.53. The participants in the passive control group and active control group on average reached a heart rate at t_1 of 60.67 bpm ± 9.07 and 76.15 bpm ± 13.55, respectively. The increase in heart rate in the exercise group was significantly larger compared to the active (d= 5.21, t= 18.29, $p < 0.001$) and to the passive control group (d= 4.30, t= 15.49, $p < 0.001$). All participants in the exercise group were able to follow the protocol and stayed within the heart rate corresponding to 65–75% of the participants' individual VO_2 peak.

3.3. Recovery from mental exhaustion

Recovery from mental exhaustion was investigated in 99 participants (aerobic exercise group: $n = 34$, active control group: n= 32, passive control group: n= 33). Empirical data on how cognitive performance and subjective well-being changed from before to after treatments is summarized in Table 4. The table shows that cognitive flexibility performance, as well as the measures of subjective well-being improved from t_0 to t_1 in each treatment group. Fig. 2 shows the estimated marginal means (represented by the bars) and standard deviations (represented by the vertical line over each bar) of each treatment group and for each outcome. Effect sizes of pairwise comparisons, Cohen's d values, as well as the results of post hoc testing are also depicted in Fig. 2. The pairwise comparisons of the estimated marginal means of intervention groups depicted in Fig. 2 showed that, on average, the exercise group reported better cognitive flexibility performance, better mood, less tiredness, more motivation for cognitively demanding tasks, and more self-perceived cognitive performance capacity than the active control group. The exemption was restlessness, for which exercise group recovered slightly worse than active control group. On average, the exercise group also recovered better if compared to the passive control group. The only exemptions were tiredness, in which exercise group and passive control group showed almost identical recovery and restlessness, in which the passive control group recovered better. However, overall testing of between-subjects factor "treatment group" on different outcomes did not reach significance for mood ($F(2, 95) = 1.47$, $p = 0.23$, $eta^2 = 0.03$), restlessness ($F(2, 95) = 1.92$, $p = 0.15$, $eta^2 = 0.04$), self-perceived cognitive performance capacity ($F(2, 95) = 0.55$, $p = 0.58$, $eta^2 = 0.01$), or for motivation for a cognitively demanding task ($F(2, 95) = 2.30$, $p = 0.11$, $eta^2 = 0.05$).

A small to moderate effect size was revealed for tiredness. This difference between did reach statistical significance ($F(2, 95) = 2.61$, $p = 0.08$, $eta^2 = 0.05$) and a statistically significant moderate effect of between-subjects factor "treatment group" was revealed on cognitive flexibility performance ($F(2, 76) = 3.81$, $p = 0.03$, $eta^2 = 0.09$). Pairwise comparisons revealed significant difference between exercise group and active control group ($p = 0.01$) for cognitive flexibility recovery. The difference between exercise group and passive control group ($p = 0.21$), as well as the difference between passive control group and active control group ($p = 0.12$) did not reach statistical significance for cognitive flexibility recovery.

Table 4
Empirical data of the tested sample before and after respective treatment (mean ± standard deviation).

	Aerobic exercise group($n = 34$)		Active control group($n = 32$)		Passive control group($n = 33$)	
	t_0	t_1	t_0	t_1	t_0	t_1
Cognitive flexibility	18.50 ± 4.91	16.16 ± 2.88	19.70 ± 6.03	17.26 ± 3.13	18.16 ± 3.68	18.12 ± 4.40
Tiredness vs. wakefulness	19.06 ± 6.52	26.21 ± 6.12	19.59 ± 8.37	26.56 ± 5.98	19.79 ± 7.85	24.18 ± 7.01
Bad mood vs. good mood	30.09 ± 6.29	33.88 ± 4.72	31.09 ± 6.97	34.19 ± 5.78	29.70 ± 6.69	32.21 ± 6.18
Restlessness vs. calmness	28.35 ± 5.61	31.38 ± 4.49	27.88 ± 8.40	32.81 ± 5.50	27.36 ± 7.22	31.33 ± 6.57
Cognitive capacity	4.25 ± 1.86	6.26 ± 1.73	4.45 ± 2.06	5.99 ± 2.15	4.73 ± 2.13	6.16 ± 1.90
Motivation	5.47 ± 2.33	6.91 ± 1.88	5.44 ± 2.39	6.45 ± 2.24	5.67 ± 2.01	6.24 ± 2.27

t_0 = prior to treatment; t_1 = immediately following treatment.

4. Discussion

The aim of the present study was to investigate the potential of a single bout of moderate aerobic exercise to recover from experimentally induced mental exhaustion. We examined the recovery effect of acute moderate aerobic exercise on cognitive flexibility performance, shown through the results of TMT part B. Moreover, we investigated the recovery effects of acute moderate aerobic exercise on aspects of subjective well-being, namely on mood, mental alertness, calmness, self-perceived cognitive capacity, and motivation for a cognitively demanding task. The effect of exercise was compared to watching an episode of a popular sitcom (= passive control group treatment) and to active control group treatment.

The single bout of aerobic exercise applied in this study led to better recovery of participants' cognitive flexibility performance than active control treatment after mental exhaustion. The acute exercise treatment showed advantageous recovery effects also on subjective well-being compared to active control group treatment after mental exhaustion. Empirical data showed a uniform pattern with beneficial effects of exercise treatment on cognitive flexibility performance, mood, mental alertness, self-perceived cognitive capacity, and motivation for cognitively demanding tasks after mental exhaustion induction compared to active control group treatment (compare Fig. 2). The effect on cognitive flexibility performance was most pronounced reaching an almost large degree (d= 0.737) following Cohen's classification [56]. Concerning aspects of subjective well-being small to moderate effects were shown (d= 0.149 - 0.524). This is surprising - in participants who are not mentally exhausted, the effects of acute moderate aerobic exercise on subjective well-being were reported higher [28–33] than the effects on cognitive flexibility performance [23,24]. The described phenomenon that individuals with lower cognitive baseline levels benefit most from acute exercise [57–59] seems to hold true also for the transient cognitive decline with mental exhaustion. At the same time, this seems to be not the case for the examined aspects of subjective well-being.

In this study, potential of acute moderate aerobic exercise to recover from mental exhaustion was not only compared to active control

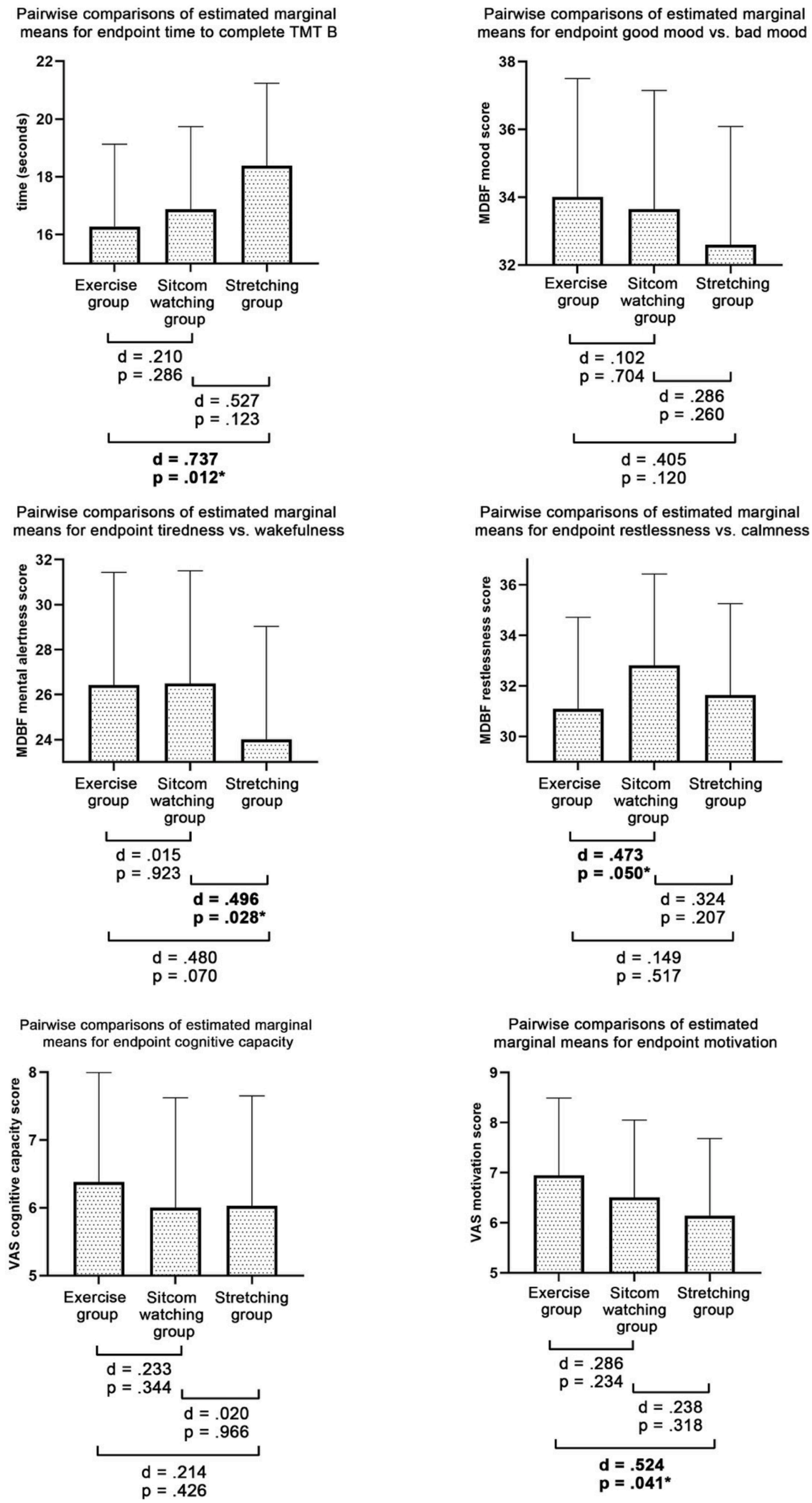

Fig. 2. (Note: 2 columns width) Pairwise comparisons of estimated marginal means for each group and for each outcome (mean ± standard deviation). TMT = trail making test; MDBF = multidimensional mood state questionnaire; VAS = visual analog scale; *d* = Cohen's effect size; *p* = statistical *p*-value.

treatment but also to a widespread strategy to recover from mental exhaustion, namely watching a sitcom (= passive control treatment) [17]. Acute aerobic exercise remained advantageous if compared to watching an episode of a sitcom. However, it is quite surprising that the recovery effects of acute exercise were smaller if compared to watching a sitcom than if compared to active control treatment for cognitive flexibility, mood, and motivation for a cognitively demanding task. In this study, watching a sitcom was more beneficial on the increase of calmness than exercise. Former research described watching TV as non-effective strategy to recover from mental exhaustion [17]. In addition, our findings show that 30 min of sitting while watching TV increase wakefulness. Former findings, which indicate that prolonged sitting while watching TV causes tiredness [60], were not replicated. However, existing studies that showed an increase in tiredness while sitting usually induce several hours of sitting.

The results presented here must be interpreted against the background of limitations. The participants of the present study were students at the German Sport University Cologne. This population can be described as physically fit and very active as practical exercise is part of their studies. If compared to the general population, the participants of the present study seem to be less prone to physical exhaustion. Experimental induction of mental exhaustion was successful concerning subjective well-being. However, the applied cognitive testing battery to induce mental exhaustion in participants did not deteriorate participants' time to complete TMT part B. This clearly is a limitation of the present study because transient decline in cognitive performance has been repeatedly described for mental exhaustion [4,5]. Therefore, our study did not confirm former evidence that showed that cognitive flexibility was particularly deteriorated by mental exhaustion [26]. Future trials may need to apply a larger amount of cognitive work load over a longer period of time to induce mental exhaustion [2, 26]. Potentially, in our study an actual deterioration of cognitive flexibility performance after mental exhaustion manipulation was superimposed by learning effects in TMT handling, even though parallel forms were used. Learning effects are a common problem in cognitive testing [61, 62]. Individual results of cognitive tests significantly improve when exposed to the same stimuli more than once, furthermore, such effects occur particularly between the first and second trial of a cognitive test [63]. Future studies should give the participants more time to practice the test procedure before the actual experiment starts [64]. The fact that acute moderate aerobic exercise had a large positive effect on participants' time to complete TMT part B compared to active control group (d= 0.737) supports the assumption that actual cognitive decline was superimposed by learning effects. Still, the present study was designed to rule out such learning effects by using different trials for cognitive testing, as recommended by other researchers [65]. The benefits of a single bout of aerobic exercise on following cognitive flexibility performance in participants that had not been mentally exhausted were reported to be small [24]. The present study gives no hint on what mediates the recovery effect of acute moderate exercise on mental exhaustion. There are several factors that are less likely to have significant effects in both control groups than in the aerobic group. First, the increase of cerebral blood flow and tissue oxygenation through exercise [66]. Second, the impact of glucocorticoids, released through exercise [67–69], on cognition, attention, and vigilance [70,71]. In addition, dopamine and other monoamines, which are also partly regulated through exercise [72], also benefit motivation [73]. Furthermore, physiological correlates like cardiovascular fitness and its connection to cognitive testing should be examined. Future trials should investigate these physiological and psychological mediators more closely. The present study was only powered for at least moderate effects and the minimum sample size in each group of 33 slightly fell below that ($n = 32$ in active control group). However, some effects of exercise for aspects of subjective well-being in this study were only small to moderate. To provide more generalizable data future studies should power for small effects. Moreover, future studies should try to apply acute exercise as strategy to recover from mental exhaustion in applied contexts – this could be, e.g., aviation, surgeons or the academic field. Future studies could consider other populations (students in school/different educational fields) and even clinical populations that include patients suffering from anxiety [74], depression [75,76] and addiction [77,78] and examine benefits of acute aerobic exercise after mental exhaustion on these groups.

Acknowledgments

We would like to thank all participants for the time and effort they put into our study. All authors contributed to the study concept and design, data acquisition and data analysis. All authors critically revised and approved the final manuscript. The authors have no conflicts-of-interest to declare. The authors have no professional relationships with companies or manufacturers who will benefit from the results of the present study. This research did not receive any specific grant from funding agencies in the public, commercial, or non-for-profit sectors. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.physbeh.2021.113588.

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