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Acute Aerobic Exercise and Creative Thinking: Comparison of Transient Hypofrontality State and Strength Model of Self-Controls' Theoretical Predictions

Ejercicio aeróbico agudo y pensamiento creativo: comparación del estado de hipofrontalidad transitoria y el modelo de fuerza de las predicciones teóricas de los autocontroles

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Abstract. Creativity is a high-level cognitive activity that can" be affected by acute aerobic exercise. This paper aims to determine how acute aerobic exercise intensities may influence aspects of divergent and convergent creative thinking. In this regard, to give an insight into the results, the predictions of the transient hypofrontality thesis and the strength model of self-control have been taken into consideration. Ninety-three healthy male college students (age = 21.18 ±1.73 years) were randomly assigned to anaerobic threshold intensity (%85 HR_{max}, n = 31), low intensity (%60 HR_{max}, n = 31), and control (n = 31) groups. Participants performed divergent (Alternate Uses Task) and convergent (Raven's Advanced Progressive Matrices Test) creative thinking tasks before, during, and after cessation of two anaerobic thresholds and low intensities and control conditions. For the divergent creative thinking, flexibility and fluency performances during and after cessation of exercise in anaerobic threshold and low-intensity groups were improved in comparison to the control group. These results were consistent with the transient hypofrontality thesis and inconsistent with the strength model of self-control predictions. In contrast, the performance of convergent creative thinking was relatively stable during and after cessation of exercise in anaerobic threshold and low-intensity groups which was inconsistent with both the transient hypofrontality thesis and the strength model of self-control predictions. The findings suggest that theoretical predictions of transient hypofrontality thesis are more adaptable with literature than the strength model of self-control to consider the exercise-creative processes relationship and further study of the issue would be of interest.
Key words: Cognition, Convergent, Creativity, Divergent, Self-depletion, Physical Activity

Resumen. La creatividad es una actividad cognitiva de alto nivel que puede ser afectada por el ejercicio aeróbico agudo. Este estudio tiene como objetivo determinar cómo las intensidades de ejercicio aeróbico agudo pueden influir en los aspectos del pensamiento creativo divergente y convergente. En este sentido, para dar una visión de los resultados, se han tenido en cuenta las predicciones de la tesis de hipofrontalidad transitoria y el modelo de fuerza del autocontrol. Noventa y tres estudiantes universitarios sanos (edad = 21.18 ±1.73 años) fueron asignados al azar a grupos de intensidad umbral anaeróbica (%85 HRmax, n = 31), baja intensidad (%60 HRmax, n = 31), y control (n = 31). Los participantes realizaron tareas de pensamiento creativo divergente (Tarea de Usos Alternativos) y convergente (Pruebas Progresivas Avanzadas de Raven) antes, durante y después de la cesación de dos intensidades umbral anaeróbicas, baja intensidad y condiciones de control. Para el pensamiento creativo divergente, el rendimiento en flexibilidad y fluidez durante y después de la cesación del ejercicio en los grupos de intensidad umbral anaeróbica y baja intensidad mejoró en comparación con el grupo de control. Estos resultados fueron consistentes con la tesis de hipofrontalidad transitoria e inconsistentes con las predicciones del modelo de fuerza del autocontrol. En contraste, el rendimiento del pensamiento creativo convergente fue relativamente estable durante y después de la cesación del ejercicio en los grupos de intensidad umbral anaeróbica y baja intensidad, lo que fue inconsistente con las predicciones tanto de la tesis de hipofrontalidad transitoria como del modelo de fuerza del autocontrol. Los hallazgos sugieren que las predicciones teóricas de la tesis de hipofrontalidad transitoria se adaptan mejor a la literatura que el modelo de fuerza del autocontrol para considerar la relación entre el ejercicio y los procesos creativos, y el estudio adicional del tema sería de interés.
Palabras clave: Cognición, Convergente, Creatividad, Divergente, Autoagotamiento, Actividad Fisica)

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Introduction

Among the considerable attention that has been paid to research the impact of an acute bout of exercise on cognitive functions (Cantelon & Giles, 2021), the effects of aerobic acute exercise on creative thinking remains under-investigated. Creativity as the generation process of new and useful original ideas or solutions has generally been divided into divergent thinking (DT) and convergent thinking (CT) modes (Cortes et al., 2019). DT is a process in which many ideas or alternative answers are generated on a particular topic or problem from available information (Guilford, 1967). Regarding the use of the majority of available resources to find several solutions to a question, this process needs a weaker top-down control. Indeed, the unconscious thought caused by the diminished prefrontal activity might be related to a type of spontaneous creative output and increased generation of novel ideas (Heilman et al., 2003). CT, as a high-level cognitive activity, is the process of selecting the most appropriate solutions and strategies from known information through step-wise analytical search (Frith et al., 2020; Kounios & Beeman, 2014) for a particular problem based on conscious effort. Because CT is linked to knowledge, an idea would be produced through the manipulation of experience (de Rooij & Vromans, 2020). Then, this process entails more top-down cognitive control and increases the activity of the administrative areas in the brain (Dietrich, 2003) for a rational solution to a given problem. Given that the thinking processes use the attentional capabilities of the prefrontal area differently, changes in prefrontal activity may lead to different results for these types of creative thinking. The intensity of aerobic exercise has an essential role in the cognitive function-acute exercise relationship (Tomporowski, 2003). Since the brain codes the activity intensity based on neural firing, it has been shown to cause temporary changes in cognitive functioning (Salmon, 2001). In low-intensity exercise the brain does not require to shift the metabolic resources from the related to the unrelated areas to the task (Globus et al., 1983). Conversely, in maximal-intensity exercise, the limited blood flow and oxygen uptake make it impossible to continue the activities further to allocate the brain's energy resources, resulting in exhaustion and exercise cessation. Nevertheless, at moderate to high intensity, the brain controls and maintains the activity of the neural motor areas by temporarily down-regulating the prefrontal cortex's metabolic activity, and rapid changes occur in the activity of the neuronal populations. Then, metabolic resource allocation inside the brain will change and lead to transient hypofrontality. This is an altered state of consciousness, in which brain activity decreases in the prefrontal cortex, leading to a decrease in some higher executive functions (Dietrich, 2003).

To the authors´ knowledge, the effect of acute aerobic exercise on creative thinking has been scarcely investigated from the theoretical point of view of Transient Hypofrontality Thesis (THT) and Strength Model of Self-Control (SMSC) models. THT predicts that when the brain is under pressure, it starts reducing the activity of the specific brain regions from top to down. Therefore, the brain's limited metabolic resources are saved for current functions that are more important. This reduction starts with the areas supporting higher executive functions and moves to the fundamental cognitive areas (Kemppainen et al., 2005). Thus, the prefrontal cortex, as the highest structure in the hierarchy, becomes the first region subject to down-regulation (Dietrich, 2003). Information processing in the brain relies on competitive interaction among neurons and limited energy resources (Miller & Cohen, 2001). Then, when put under pressure by short acute aerobic exercise intensity around the anaerobic threshold, the brain allocates the resources from higher cognitive structures. A short delay after exercise cessation, the body's metabolism is gradually returned, and the arousal levels are also increased (Audiffren et al., 2008). Consequently, normalization of the neural activation patterns and improvement of cognitive processing will occur (Dietrich, 2003). Besides, studies showed that prefrontal activity might be influenced by acute exercise at moderate intensity through increasing prefrontal cortex oxygenation and positively influencing activation changes of the dorsal and lateral prefrontal cortex (Kujach et al., 2018) during and after exercise cessation (Pires et al., 2018). Since acute aerobic exercise may affect neural circuit stimulation (Dietrich, 2004), it is expected that the cognitive processes involved in creativity are also impacted by short-term aerobic exercise with moderate to high intensities.

Creativity, and in particular DT, is related to lower prefrontal activity and the altered transient cerebral state indicates a potential role of transient hypofrontality in producing creative thinking (Heilman et al., 2003). Hence, it is not surprising to claim that acute exercise affects creative thinking. On the one hand, the improvement of DT resulting from light to high intensities of acute aerobic exercise confirms this claim (Aga et al., 2021; Blanchette et al., 2005; Zhao et al., 2022). On the other hand, based on the presumptive hypothesis that executive functions change during physical exercise (Cantelon & Giles, 2021), several authors have demonstrated that divergent and convergent processes could differently be affected by the intensities of acute aerobic exercise (Aga et al., 2021; Colzato et al., 2013; Matsumoto et al., 2022; Oppezzo & Schwartz, 2014; Zhao et al., 2022). Colzato et al. (2013) investigated whether two creative thinking modes in athletes and non-athlete individuals are influenced by moderate and severe intensities of acute exercise and rest conditions. They found that moderate and intense exercise resulted in a drop in DT in both athletic and non-athletic participants and improved the CT in athletes, and a reduction in non-athlete individuals. Also, the moments of test administration did not significantly affect the results. Although according to the THT, the temporarily changes in the prefrontal cortex's metabolic activity are attributed to the intensity of acute exercise, Colzato et al. (2013) stated that resource allocation relies not only on the intensity of acute exercise but also on the type of creativity task and skill level of the participant. Prolonged and intense (70-80% heart rate maximum (HR_{max})) exercises are prerequisites for a steady-state protocol and provide a state of transient hypofrontality (Tomporowski, 2003). Lack of enough time to reach the mentioned state was probably the reason that DT dropped during and after exercise, as well as the little temporal overlap between exercise and creative thinking tasks. Then, an individual's creative thinking, regardless of the level of fitness, would probably benefit from oxygenation of acute exercise with moderate intensity (Colzato et al., 2013). Oppezzo and Schwartz (2014) measured changes in divergent and convergent processes during 4-minute self-selected walking conditions on a treadmill or outdoors as very-light to light intensity through alternate uses test (AUT) and compound remote-association test (CRA) tasks, respectively. Results demonstrated that the originality subscale of divergent thinking increased, while convergent thinking was impaired compared to sitting.

In the last few years, much more information on the acute exercise–creative thinking relationship has become available to researchers. Investigating the effect of an acute bout of aerobic exercise on divergent and convergent thinking with the regulating role of mood, Aga et al (2021) asked subjects to conduct AUT and insight problem-solving (matchstick arithmetic problems) tasks measuring divergent and convergent thinking, before and after a 15-minute exercise (light to vigorous intensities) or control interventions. They found that exercise enhanced divergent thinking, especially in the flexibility and fluency subscales, independent of subjects' mood after exercise. In contrast, the effect on convergent thinking depended on subjects' mood after exercise. Subjects reporting high vigor tended to solve more insight problems and vice versa. In Matsumoto et al. (2022) it was also shown that creative thinking modes are differently influenced by physical activity. In their experimental intervention, subjects were asked to walk downstairs from the fourth to the first floor and back at their usual pace in the light intensity equal to 55% maximum heart rate. Then, changes in divergent and convergent thinking were evaluated through AUT and matchstick arithmetic problem tasks, respectively. They found that, compared to using the elevator, stair-climbing enhanced just subjects' originality subscale of divergent thinking but did not affect convergent thinking. In a recent paper to investigating the effects of short-term aerobic exercise on creativity, Zhao et al. (2022) asked undergraduate students to complete Chinese compound remote associate problems and alternates using tasks as convergent and divergent creativity tests, before, after 25 minutes of short-term aerobic exercise, as well as, 30 minutes after finishing. The exercise included a series of aerobic movements with high frequency, more jumps, and 70-79% maximal heart rate intensity in a short period. They found that short-term aerobic exercise immediately improved convergent creativity and divergent creativity but not after a 30-minute delay. The evidence from the literature intimates that rapid changes in neural population activity can lead to change creative thinking modes like other execution functions.

Besides THT, it would be of interest to consider short-term changes in creative thinking processes resulting from acute aerobic exercises using other explanations of the rapid changes in the activity of the execution functions. The SMSC (Baumeister et al., 1998) has been presented as an alternative and plausible mechanism for the explanation of the causal relationship between exercise and cognitive processes (Audiffren & Andre, 2015). Based on this model, tasks such as persistence, emotion regulation, etc., that require self-control are supported by limited physiological and psychological resources, the so-called single global strength. According to this model, while implementing two simultaneous tasks, the mentioned resources do not shift rapidly, but they are gradually depleted to run the second task. Self-control can be described as the capacity of individuals to exert control and alter their behavioral tendencies to gain a specific goal through self-regulatory processes (Sniehotta et al., 2005). Because these processes are conscious, intentional, and goal-directed they must be fed by self-control resources (Baumeister & Vohs, 2007). When persons are carrying out two or more self-regulation tasks simultaneously, they should divide the limited self-control resources among them (Audiffren & Andre, 2015). In these conditions, physical endurance and mental processes such as response inhibition depend on limited and depletable resources (Hagger et al., 2010) including subjective perceptions (Clarkson et al., 2010). SMSC predicts that exercise cessation leads to the recovery and replenishment of self-control resources (Tyler & Burns, 2008). Furthermore, the durability of the decrease in the performance of self-regulation tasks, duo to acute exercise, depends on the level of self-control resources necessary to maintain the intensity of the exercise. In the current study, acute aerobic exercise with a specific intensity is considered as a self-regulation task. Given that acute aerobic exercise and cognitive functions use a single global strength, the self-control resources to carry out the next attention-demanding task will probably be depleted due to the implementation of acute exercise (Audiffren & Andre, 2015).

In relation to gender differences in creative thinking, the greater male variability hypothesis assumes that men have more interindividual variability than women in both physical and psychological attributes (Ellis, 1894/1934). He and Wong (2021) in examination of divergent and convergent creativity in men and women provided evidence for this hypothesis. They attributed this, on one hand, to greater inter-hemispheric connections in women's brain (Abraham, 2016), and on the other, to higher levels of self-efficacy in the analytical and problem-solving creativity of men (Karwowski, et al., 2016). Thus, in the present study, experiments were only carried out on male students and no gender comparison was made. Acute aerobic exercise leads to changes in cognitive functions (Lambourne & Tomporowski, 2010; Tomporowski, 2003) which might be explained by the THT and SMSC. Since acute exercise increases the use of metabolic control resources, it is assumed that during and immediately after exercise cessation, more control-demanding tasks may be influenced more intensely than the less control-demanding tasks. Thus, the present study aimed to investigate how acute aerobic exercises with low and anaerobic threshold intensities affect DT and CT processes. Based on theoretical predictions of THT and SMSC, we hypothesized that aerobic acute exercise at an anaerobic threshold, compared to low-intensity one and no exercise, improves flexibility, fluency, originality, and elaboration subscales of DTs and reduces CT performances during and immediately after exercise. Additionally, we expected, following the mentioned models, no differences between low-intensity exercise and no-exercise conditions.

Materials and Methods

Participants

Via posters placed on campus and department, male students who participated in leisure sports activities were asked to participate in the study. Using self-report assessments and asking the question: "How many times a week do you participate in moderate to vigorous physical activities?", their level of physical activity was considered. Those who had 2-3 times regular exercise sessions were invited to the experiment. After excluding 3 persons due to not meeting the inclusion criteria for, 93 (age_M =21.18 ± 1.73 years) students were recruited. They were randomly assigned into three groups of 31 persons including anaerobic threshold (AT) (85% HR_{max}, age_M = 21.8 ± 2.02), low intensity (LI) (60% HR_{max}, age_M = 20.55 ± 1.59), and control groups

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(age$_M$ = 21.2 ± 1.6). The randomization was done through a dice method by rolling 1 or 2, subjects are assigned to an AT group, 3 or 4 to an LI group, and 5 or 6 to a control group. All selected participants had normal vision and had no history of mental illness other diseases unsuitable for exercise. After explaining the test procedure, freely-given, informed consent was obtained from all participants included in the study. This study was performed in accordance with the ethical standards as laid down in the Declaration of Helsinki and the experiment protocol was also approved by the local Ethics Committee (Figure 1, CONSORT).

A priori power analysis was performed for sample size estimation. According to the estimated effect sizes in a range of 0.35 to 0.38 based on literature (Colzato et al., 2013; Davranche et al., 2015; Del Giorno et al., 2010), α= 0.05 and power = 0.95, the estimated sample sizes needed with this range of medium effect sizes (G*Power 3.1.9.7 software) were approximately n = 84 to 99. Thus, the proposed sample size of this study, n=93, was more than adequate for the evaluation of the objectives and control of the possible mediating factors.

Measures

An electronic ergometer model Tuntory E980, Finland, was used to administer the exercise manipulation. A polar heart rate belt (PHRB) was used to continuously measure heart rate during riding to control the intensity of exercise. A printed version of Raven's Advanced Progressive Matrices Test (RAPMT) and an Alternate Use Task (AUT) were also employed to evaluate CT and DT processes, respectively.

Convergent thinking task

The RAPMT was used to evaluate CT capability. RAPMT as one of the insight problem-solving tasks correlates with a convergent production sub-score of the creative reasoning test (CRT) (Jaarsveld et al., 2012). Having three levels of simple, medium, and difficult has made this test appropriate to evaluate convergent thinking in the laboratory (Aga et al., 2021). This task was language-independent and consisted of a series of homogeneous, progressively more difficult items requiring the participant to choose which shape (from eight options) is the best selection to complete a pattern series presented across three rows of designs. Forty-five items, including three 15-item parallel versions, were prepared, matched and approved by three professionally trained psychology lecturers. Each version consisted of simple, medium, and challenging items. Versions 1, 2, and 3 were implemented before, during, and after acute aerobic exercise cessation, respectively, in random order to follow counter-balance conditions. In this way, 10 first, 10 second, and 11 third subjects performed in the order of 1-2-3, 2-3-1, and 3-1-2 versions, respectively.

Divergent thinking task

AUT as a valid test to evaluate DT (Aga et al., 2021; Matsumoto et al., 2022) was used in the present study. In this task, several everyday objects' names were provided to participants. They were asked to express as many as possible new and different uses and applications of these tools. Referring to the method of balancing AUT proposed in the literature to ensure that the sets of AUT tasks are balanced in difficulty (Fink et al., 2020), 3 items consisting of the brick, newspaper, and pencil terms that are common in everyday life and familiar to the participants were selected. Same as convergent task condition, in order to follow counter-balance conditions, 10 first, 10 second, and 11 third subjects performed the order of B-N-P, N-P-B and P-B-N terms, respectively, before, during, and after exercise cessation. In this study, four scores were examined: flexibility, the number of different categories used; originality, each response was compared to total responses from all participants. Those responses that comprised 5% and 1% of all responses were considered unusual (one score) and unique (two scores), respectively; fluency, a total of all answers; and elaboration, the number of response details (Akbari Chermahini & Hommel, 2010). All responses were analyzed for each criterion by two different raters. The inter-rater agreements (Cohen's κ) between raters were 0.79, 0.77, 0.98, and 0.79 for flexibility, originality, fluency, and elaboration, respectively.

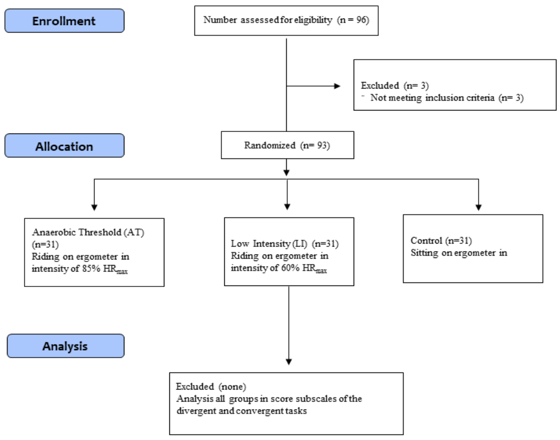

Figure 1. CONSORT diagram of experiment.

Procedure

The within-between pretest-posttest comparison design was used for this study. After entering the laboratory, informed consent was obtained from each participant. After the PHRB was fastened on their chest, they were seated on the bike ergometer and given instructions. In both experimental groups, participants performed a 5-minute warm-up, consisting of two minutes riding with a 1 KJ/Kcal and three minutes riding with a 2 KJ/Kcal workload. Then, they were instructed to maintain a consistent speed within the range of 50-60 rounds per minute. Power output was different for each participant, determined based on their estimated HR_{max} and group assignments. HR_{max} as a common method for prescribing and monitoring intensity during aerobic exercise (American College of Sports Medicine, 2018; Cantelon & Giles, 2021) was assessed using the 208-(age×0.7) formula (Tanaka et al., 2001). In the AT group, the acute exercise began with a 3.0-Watt workload, and 0.5-Watt was added to the workload per minute (Audiffren et al., 2008) until the exercise intensity reached the anaerobic threshold of 85% of HR_{max} (Pinto et al., 2016). Then, they continued pedaling for 15 minutes at a constant intensity of 85% of HR_{max} (Del Giorno et al., 2010), because exercising longer than 20 minutes leads to dehydration or fatigue in high-intensity exercise protocols and causes a decrease in cognitive functions (Benton, 2011). In the LI group, the same protocol was implemented until the exercise intensity reached 60% of HR_{max}, but they continued pedaling for 25 minutes at a constant intensity of 60% of HR_{max} (Lambourne et al., 2010). Cognitive engagement control, a valid approach in the literature (Pontifex et al., 2019), was adopted to manage the control condition. To make the condition closer to the AT group's condition, the control group was allowed to sit on the ergometer, and they were free for 15 minutes to study the sports journals.

All groups performed three versions of RAPMT and AUT tasks before, during, and after exercise cessation. Two tasks were performed at a 1-minute interval between each other and in the counterbalance order (Corgnet et al., 2016). Before acute exercise, participants performed one of the versions of RAPMT as CT for 4 minutes, along with one of the mentioned terms of AUT as DT for 3 minutes. The second batch of tests for the AT group was performed 5th minute after the beginning of exercise at 85% HR_{max} and lasted until the 13th minute. Similarly, the LI group was tested from the 10th minute to the 18th minute. Following acute exercise cessation, both groups rested for 1 minute, and then the last version of RAPMT was implemented in 4 minutes. The third term of the AUT task also lasted for 3 minutes. Before and after acute exercise cessation, their responses were recorded by themselves, but during the exercise, the participants saw the items, answered verbally, and an examiner recorded their responses. The control group performed the first version of RAPMT and AUT before studying the journals, followed by the second version from the 5th to13th minute after the start of the protocol (sitting on the ergometer without pedalling), and the last version was performed one minute after sitting on the ergometer for 15 minutes. For all groups, the number of correct answers was recorded as a result of RAMPT performance (Figure 2).

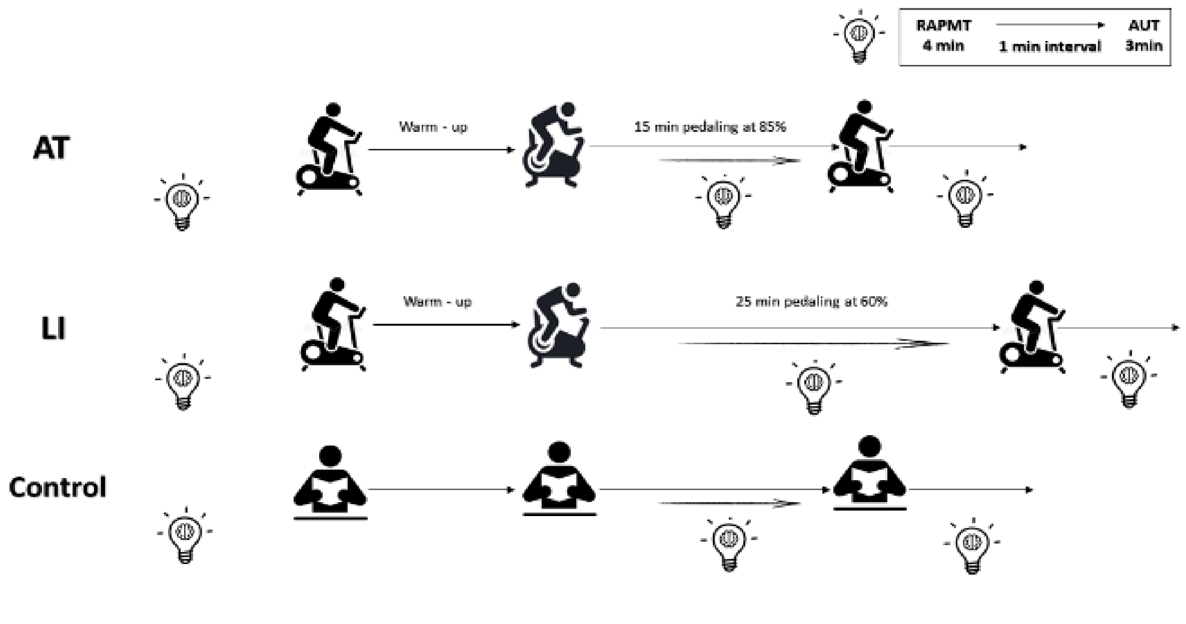

Figure 2. Schematic illustration of the study design

Statistical Methods

The data normality was checked using the Shapiro–Wilk test. 3 (groups) × 3 (times) Mixed ANOVA with Repeated Measures was used for comparing between-group pre-test, during and post-test effects, with groups (AT and LI vs. control) as between-group factor and time (pre-test, during and post-test) as the within-group factors. Due to an RAPMT difference among groups in pre-exercise, RAPMT was included as a covariate in to control the following conditions and univariate ANCOVA was used for analysis of convergent task scores. Effect size (Cohen's d) was calculated and a significance level of $p < 0.05$ was used. The statistical analysis was conducted with IBM SPSS Statistics 23.0.

Results

Descriptive results of the DT and CT tasks showed that acute aerobic exercise influenced innovative thinking (see

Table 1). In a confirmatory analysis plan, the interaction, time, and group effects were analyzed.

Results for Divergent Task

Time and group effects

Results of 3 (groups) × 3 (times) Mixed ANOVA with Repeated Measures showed a significant main effects for time ($F_{(2,90)} = 36.33$, Wilks' Lambda = 0.22, $\eta^2 = 0.78$ $p = 0.00$) and group ($F_{(2,90)} = 4.53$, Wilks' Lambda = 0.67, $\eta^2 = 0.18$, $p = 0.00$), indicating the difference in effect on DT for three groups.

Interaction effect

Results also showed an interaction effect ($F_{(2,90)} = 3.28$, Wilks' Lambda = 0.58, $\eta^2 = 0.24$, $p = 0.00$). Post hoc Bonferroni analysis revealed that exercise in AT intensity led to a reduction in elaboration ($p = 0.01$), as well as improvement of fluency and flexibility ($p = 0.00$, both), no change in originality ($p = 0.32$ and 0.6, respectively) compared to before and after exercise cessation. LI group during compared to before exercise had worse performance in elaboration ($p = 0.00$) and originality ($p = 0.03$), but better in fluency ($p = 0.00$) and flexibility ($p = 0.00$). This group also performed better in originality after exercise cessation compared with before ($p = 0.04$) and during exercise ($p = 0.00$). Besides, their performance in fluency ($p = 0.00$) and flexibility ($p = 0.00$) during exercise was better than after exercise cessation. The control group at the second try performed better in fluency ($p = 0.00$) and flexibility ($p = 0.00$) compared with the first and third tries. Still, they performed similarly in elaboration and originality (see Table 2) (see Fig. 3).

Acute exercise in the anaerobic threshold and the low intensities led to reduction of elaboration ($p = 0.000$, both), but improvement of fluency ($p = 0.00$ and $p = 0.03$, respectively) in comparison to the inactive condition. This effect for the anaerobic threshold group was greater than the low intensity group. Exercise in the low intensity in comparison to the inactive condition led to improvement of flexibility ($p = 0.04$).

Results for Convergent Task

Time and group effects

Because of the significant differences in the RAPMT in pre-exercise time among groups (non-homogeneity) ($F_{(2,90)} = 8.54$, $\eta^2 = 0.16$, $p = 0.00$), RAPMT scores were considered as a covariate to control the following conditions. Results of univariate ANCOVA showed no significant difference for RAPMT score during and after exercise cessation, meaning that no main effects were found for time ($F_{(2,30)} = 0.14$, $\eta^2 = 0.00$, $p = 0.71$). Group effect was significant during and exercise cessation ($F_{(2,90)} = 6.51$, $\eta^2 = 0.13$, $p = 0.00$ and $F_{(2,90)} = 7.5$, $\eta^2 = 0.14$, $p = 0.00$, respectively). Indeed, AT group had worse performance than LI ($p = 0.04$) and control group ($p = 0.00$). There was no significant difference between LI and the control group ($p = 0.67$, 0.42, respectively). (see Tables 1 and 2).

Interaction effect

Results revealed no significant interaction effect ($F_{(2,90)} = 0.03$, $\eta^2 = 0.00$, $p = 0.97$).

Table 1.
Mean and standard deviation of Raven's Advanced Progressive Matrix Test (RAPMT) and subscales of Alternative Uses Test (AUT) scores as a function of groups and times.

		RAPMT	AUT-Elaboration	AUT-Fluency	AUT-Originality	AUT-Flexibility	HR
AT	Before	7.5 (3.1)	3.9 (2.8)	5 (2.5)	1 (1.3)	4 (2)	74.2
	During	6.9 (2.6)	2 (1.8)	8.8 (3.3)	0.6 (0.9)	6.3 (2)	163.8
	After	6.9 (2.6)	3 (2.5)	5.9 (3.2)	1 (1.4)	4 (2)	119.4
LI	Before	9.6 (2.6)	3.9 (3.4)	5.9 (3)	1.1 (1.3)	4.9 (2.5)	74.8
	During	9.3 (2.2)	2 (2.2)	8.4 (2)	0.4 (0.9)	6.6 (1.6)	121.1
	After	9.2 (1.9)	2.9 (2.7)	5.1 (2.5)	2.1 (2.2)	4.6 (1.9)	85.5
Control	Before	10.35(2.6)	5 (3.4)	6 (2.6)	0.7 (1)	4.7 (1.8)	75.9
	During	10.32(2.5)	5.4 (3.5)	6.7 (1.9)	0.3 (0.6)	5.5 (1.5)	77.4
	After	10.35(2.5)	4.4 (2.7)	5.2 (1.9)	0.9 (1.3)	4.3 (1.6)	75.1

Table 2.
Bonferroni paired comparisons for Alternative Uses Test (AUT) subscales and Raven's Advanced Progressive Matrix Test (RAPMT) before, during, and after aerobic acute exercise cessation

			Anaerobic Threshold group				Low-Intensity group				Control group			
		Times	Mean Difference	Std. Error	p	d	Mean Difference	Std. Error	p	d	Mean Difference	Std. Error	p	d
AUT	Ela.	Before vs. During	1.87	0.57	0.01*	0.82	1.93	0.51	0.00*	0.67	-0.39	0.68	1	0.11
		Before vs. After	0.774	0.6	0.62	0.34	1.03	0.72	0.49	0.32	0.64	0.54	0.73	0.19
		During vs. After	-1.03	0.51	0.15	0.46	-0.9	0.56	0.35	0.36	1.03	0.49	0.13	0.32
	Flu.	Before vs. During	-3.77	0.47	0.00*	1.31	-2.58	0.58	0.00*	1	0.71	0.42	0.31	0.31
		Before vs. After	-0.87	0.43	0.15	0.31	0.74	0.62	0.72	0.29	0.84	0.45	0.22	0.35
		During vs. After	2.9	0.48	0.00*	0.89	3.32	0.39	0.00*	1.2	1.55	0.3	0.00*	0.79
	Ori.	Before vs. During	0.42	0.25	0.32	0.36	0.67	0.25	0.03*	0.63	0.39	0.2	0.19	0.17
		Before vs. After	0.03	0.34	1	0	-1.06	0.41	0.04*	0.57	-0.26	0.29	1	0.63
		During vs. After	-0.39	0.29	0.6	0.29	-1.74	0.45	0.00*	0.55	-0.64	0.26	0.06	0.50
	Flex.	Before vs. During	-2.29	0.34	0.00*	1.15	-1.67	0.49	0.00*	0.83	-0.81	0.32	0.06	0.48
		Before vs. After	0.06	0.35	1	0	0.32	0.4	1	0.13	0.45	0.33	0.56	0.23
		During vs. After	2.35	0.29	0.00	1.15	2	0.39	0.00	1.14	1.26	0.3	0.00*	0.77

				*				*				
RAPMT	Before vs. During	0.58	0.45	0.63	0.21	0.29	0.46	1	0.12	0.03	0.41	1	0
	Before vs. After	0.58	0.43	0.56	0.21	0.35	0.49	1	0.17	0.00	0.42	1	0
	During vs. After	0.00	0.42	1	0	0.06	0.4	1	0.04	-0.32	0.36	1	0

*p < .05 Ela. = Elaboration, Flex. = Flexibility, Flu. = Fluency, Ori. = Originality. d = Cohen's d

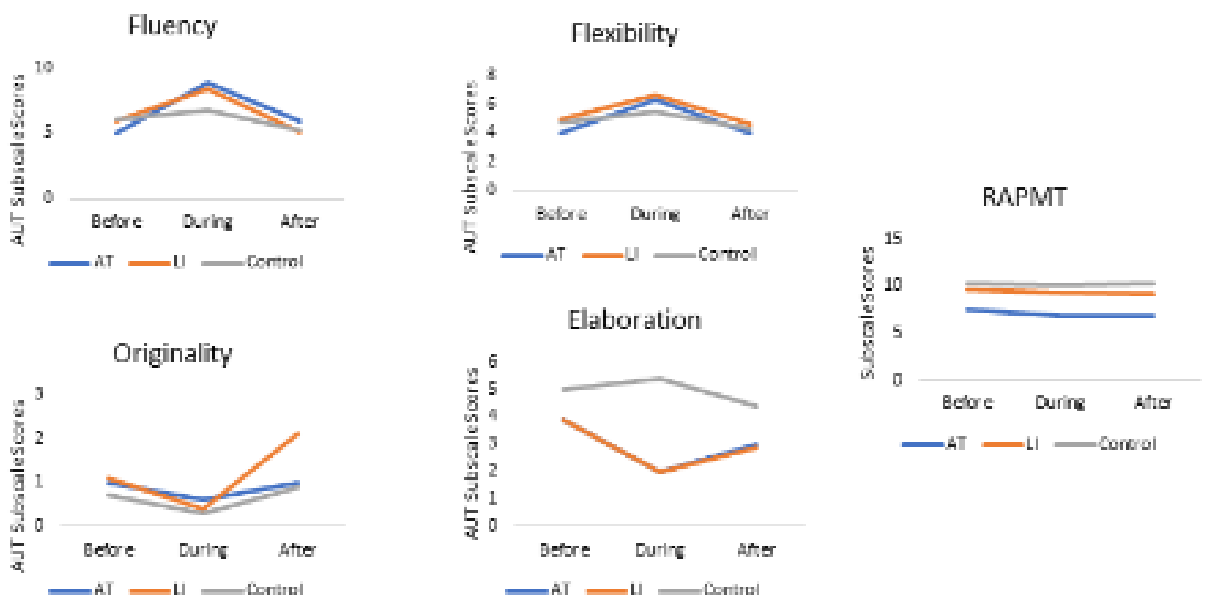

Figure 3. This figure illustrates the variations of AUT's subscales and RAPMT scores in the past, during, and after acute aerobic exercise cessation (AT=Anaerobic threshold group; LI=Low intensity group).

Discussion

In this study, we investigated whether creative DT and CT are influenced by low and anaerobic threshold intensities of acute aerobic exercises. Results showed that, for AT and LI groups, performance on the DT task was better than the control group. It means that DT might be changed through acute aerobic exercise. This effect was greater for the AT than for LI group. Interestingly, on the one hand, for the DT task, improvement in flexibility and fluency during and after exercise in AT and low intensities was consistent with THT and inconsistent with SMSC predictions. On the other hand, relatively stable performance of CT task during and after exercise in AT and low intensities were inconsistent with both THT and SMSC predictions. DT and CT processes were differently influenced by the present study's intervention, and the intensity of acute exercise was found as one of the determinants of the cognitive function-acute exercise relationship (Colzato et al., 2013; Tomporowski, 2003) as specifically demonstrated in this study.

Flexibility and fluency subscales increased during both AT and low intensities and then returned to baseline after exercise cessation. This finding was consistent with THT's predictions, as well as Aga et al. (2021). When comparing effect sizes between the two intensities, it appears that aerobic exercise requirements at the anaerobic threshold could have constrained the brain to allocate the resources from higher cognitive structures to lower ones. Then, inhibition function as one of the fundamental cognitive processes is reduced due to a temporary shift in the activity of neuronal populations (Dietrich, 2003). This transient state led to an increase in two essential aspects of the DT, including fluency and flexibility. However, this finding did not confirm the prediction of SMSC. Therefore, implementing the DT task in the middle of acute aerobic exercise and lack of the complete depletion of the resources may be considered as the reasons for the lack of decrement in fluency and flexibility subscales. Perhaps, lasting acute anaerobic exercise for more than 15 minutes could impair the performance of the mentioned subscales. For further clarification on this probability, it is suggested for future studies to implement the DT task at the beginning, middle, and end of acute aerobic exercise that lasts more than 15 minutes. These findings were also not consistent with fluency and flexibility subscales in Blanchette et al. (2005). The probable cause of this discrepancy can be attributed to differences in the type of creative tasks, which lead to different findings in the acute exercise-cognitive function relationship (Audiffren et al., 2008). In the present study, participants were asked to respond verbally to the DT task, but they responded in a figural manner in Blanchett et al's study. Given the strong effect of verbal training of divergent thinking on subscales including flexibility, fluency, and originality compared to figural training (Fink et al., 2019), DT might be considered as a multidimensional construct, with a distinction between verbal and figural tasks (Clapham, 2003; Cortes et al., 2019). Moreover, in neuroimaging studies, different dimensions of DT require the activation of different hemispheres. Carrying on the figural tasks is associated with greater involvement of right than left parietal activation, whereas it is vice versa for verbal tasks (Foster et al., 2005). Thus, it may be concluded that the interventions can differently influence various modalities for the appraisal of divergent creativity using multiple tasks. Although the neural control had not been considered in the current study, this issue should be regarded in future studies by testing two types of verbal and figural DT tasks during and after acute exercise cessation to more understand the cognition-exercise relationship.

Contrary to fluency and flexibility subscales, the acute exercises caused a reduction in performance of the elaboration subscale that in the AT intensity was more than the low one. This result was not in line with the THTs' predictions. Still, it was in line with the SMSC's forecasts, stating that implementing the acute exercise and creativity task simultaneously leads to depletion of the self-control resources to carry out the next attention-demanding task (Audiffren & Andre, 2015). Indeed, because the elaboration subscale is accompanied by the number of response details, it will make the brain allocate more resources. Also, in the present study, cycling at a constant intensity for a given time was a self-regulating task, since participants had to set their cycling speed in a stable range throughout the test (Schmeichel & Baumeister, 2010). Therefore, it can be concluded that acute cycling exercise, particularly in AT intensity, as a control-demanding task used a common depletable resource in the brain with the cognitive functions to generate the movement and emerge the behavior. This situation led to the depletion of the limited self-control capacity for cognitive-control operations and ego-depletion in participants. Finally, more effort to maintain self-control for carrying out DT tasks failed (Baumeister et al., 1998). The results were also consistent with Colzato et al. (2013). They showed that moderate and intense acute exercises lead to a drop in the creative DT performance, and claimed that the resources allocation during acute exercise might be influenced by the type of the creativity task. Then, given the multidimensionality of the cognitive tasks, acute exercise may impair or improve various aspects of executive function (Cantelon & Giles, 2021; Chang et al., 2012; Lambourne & Tomporowski, 2010), as found in the divergent creative task in our study.

This study showed that although the performance of the originality subscale decreased during low-intensity acute exercise, it improved after exercise cessation. This result was in line with Zhao et al. (2022), as well as THT and SMSC's expectations. THT predicts that neural activation patterns will be normalized after exercise cessation (Dietrich, 2003), and cognitive processing improvement in these conditions can be attributed to the gradual return of body metabolism and increased levels of arousal (Audiffren et al., 2008). SMSC also determines a period after exercise cessation leads to recovery and replenishment of the self-control resources (Tyler & Burns, 2008). Therefore, for coaches and teachers who try to improve the creative processes of individuals through acute exercise administration, it is recommended to use break times to increase cognitive efficiency. Intensity of physical activity is the main stimulation for the entry of Brain-Derived Neurotrophic Factor (BDNF) and endocannabinoids into the process of brain function enhancement (Chen, 2024). In fact, given to influence of acute aerobic exercise with moderate to intense intensity on improvement of students' cognitive function and thinking (Polevoy, 2024), as well as the relationship between motor and cognitive development during growth (Diamond, 2000), it is also recommended to teachers and coaches using these physical activities to improve students' brain function in physical education sessions.

Contrary to THT and SMSCs' predictions, in the present study, the performance of CT throughout exercise in AT and low intensities as well as after exercise cessation was relatively stable. It was expected that cognitive processes with top-down control that are effortful and conscious were impaired more than the unconscious and automatic ones during a high-intensity acute exercise. This result was not consistent with the decline in convergent task performance found in Zhao et al. (2022) and Colzato et al. (2013)' study. Colzato et al. argued that CT requires a more substantial top-down control than DT, as it accompanies by a more constrained search for one or more items. Exercise modality, an important factor, has been shown to differentially impact cognition during exercise (Cantelon & Giles, 2021; Lambourne & Tomporowski, 2010). Performing creative thinking tasks during exercise inherently creates a dual-task environment, but these dual-task effects may be more pronounced depending on the exercise modality. Then, this inconsistency may be attributable to differences in the physical effort required during cycling vs. other aerobic movements. Thus, different effects of simultaneous exercise on creative thinking may be due to the different attentional conflict between coordination of bodily movement and executive control. To the authors' knowledge, the acute exercise-creative thinking relationship has been scarcely investigated from the THT and SMSCs' point of view. However, a difference between experimental intensities and type of task may be possible factors of this inconsistency. It seems that cycling in 85% and 60% HR_{max} intensities have not provided an appropriate opportunity to shift (Dietrich, 2004) or deplete (Baumeister et al., 1998) energy resources to influence CT performance. Further research will be needed to examine THT and SMSCs' predictions on the acute aerobic exercise-CT relationship. Therefore, future studies can be carried out by changing the exercise intensity, exercise type and creative thinking task to explore the exercise pattern that lead to positive effects. In addition, this study only, from the perspective of behavioral data, examined and confirmed the theoretical predictions of THT and SMSC on the impact of acute aerobic exercise on creativity, but the neural mechanism of this effect remains unclear. In the future studies, brain imaging methods such as functional magnetic resonance imaging (fMRI) and event-related potential (ERP) can be consider to explore this problem. It is suggested that in future studies, the effect of non-aerobic exercises such as virtual reality games, that increase the heart rate, on creative thinking should also be investigated. One of the limitations of the present study was the lack of comparison of the sex on the cognition-acute exercise relationship, which is suggested to be considered in future studies. Further studies, which take creative performance of people with different levels of physical activity during an acute aerobic exercise into account, will need to be undertaken.

Conclusion

In the current study, some aspects of creative DT were improved, whereas CT was not notably changed due to the acute aerobic exercise. Our findings suggested that engaging in an acute bout of aerobic exercise enhances divergent thinking. Therefore, aerobic exercise may be considered a beneficial option for improving this cognitive function. For college students, short-term aerobic exercise in moderate to high intensity is a good strategy to improve physical fitness and creative performance, which is of great significance to their study and life. The present research also contributed to a growing body of literature and examined some of theoretical predictions associated with acute exercise and creative processes. This indicated that THT and SMSC differently predict the creative thinking changes during an acute bout of aerobic exercise and further works need to confirm them as the appropriate explanations regarding the cognition-acute exercise relationship.

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Declarations

Ethics Approval

Approval was obtained from the local Ethics Committee of University of Kurdistan. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

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