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Differential cognitive, neurophysiological, and stress responses to acute cycling and stretching in young adults with risky alcohol use

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ABSTRACT

While physical activity has shown beneficial effects on mood, anxiety, and drug-related variables in adults with alcohol use disorder (AUD), its impact on young individuals with risky alcohol use (RAU) remains under-explored. This study examined the effects of an acute, intense exercise session on cognitive and psychophysiological outcomes in young participants with RAU compared to controls (CO). Participants engaging in >150 min/week of moderate-to-vigorous activity were excluded. Based on AUDIT scores (RAU: ♂ ≥ 8, ♀ ≥ 6; CO: ≤3), volunteers (RAU = 47 (14 men and 33 women), CO = 53 (11 men and 42 women)) were assigned to either a 12-min submaximal cycling protocol (RAU = 29, CO = 32) or a stretching session (RAU = 18, CO = 21). The mean age of the sample was 19.54 ± 0.28 years and no differences were observed in waist-to-height ratio with mean values of 0.43 in the CO group and 0.44 in the RAU group. Rate perceived exertion (RPE), lactate levels, heart rate variability (HRV), salivary cortisol (sCORT), and alpha amylase (sAA) were assessed, alongside resting EEG (rsEEG), craving, state anxiety, and neuropsychological performance. Cycling elevated lactate levels and reduced HRV. RAU men showed lower watts compared to the CO men, and this group rated higher RPE than RAU women in both types of exercise. A single short bout of cycling improved phonological fluency in the RAU group and reduced the number of *d*2 test omissions regardless of group and sex. Intense exercise induced changes in sCORT and sAA increased, particularly higher sCORT in RAU men. Unexpectedly, it was the stretching condition that induced greater changes in brain activity, especially in delta and theta bands. Our findings highlight how different types and intensities of exercise can distinctly influence both brain function and cognition, as well as the relevance of designing exercise interventions according to the individual needs and characteristics of vulnerable young populations.

1. Introduction

Alcohol use is a major risk factor for poor health and is responsible for a significant portion of the overall burden of disease and mortality (WHO, 2024). According to the most recent U.S. National Survey on Drug Use and Health, 47.5% of young adults aged 18 to 25 reported consuming alcohol in the past month (Substance Abuse and Mental Health Services Administration (Substance Abuse and Mental Health Services Administration, 2025), while in Spain, the prevalence of alcohol use during the past month among young people aged 15 to 34 years is as high as 63.5% (Encuesta sobre Alcohol y Drogas en España (EDADES, 2024). Notably, young adults are significantly impacted by alcohol, with the highest proportion of alcohol-attributable deaths occurring in the 20–39 age group (WHO, 2024). Young adults are individuals in a transitional phase of life, aged approximately 18 to 25 characterized by significant changes such as forming romantic relationships, establishing careers, and potentially becoming parents, which can challenge their previous sense of stability and self-identity (Cox and Lieberthal, 2005).

Empirical evidence suggests that early substance use is associated with numerous adverse outcomes, including an elevated risk of injuries, accidents leading to disability or death, and poor academic or

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occupational performance, often resulting in school or work dropout (Kearney, 2008). Multiple studies have established links between alcohol consumption and an increased incidence of family violence, antisocial behavior, traumatic experiences, and various psychological disorders, such as anxiety, depression, suicidal ideation, and suicidal behaviors (Fernandes et al., 2020; Ryan et al., 2019).

In this context, risky alcohol use (RAU), understood as six or more points for women and eight or more for men on the Alcohol Use Disorder Identification Test (AUDIT, Spanish adaptation: Contel Guillamon et al., 1999) (EDADES, 2024), is a pattern of alcohol consumption frequently observed among young people and has been associated to emotional, cognitive and brain alterations (de Goede et al., 2021; Sampedro-Piquero et al., 2024). For instance, RAU has been linked to poorer performance in attention, executive functioning such as inhibitory control, or psychomotor speed, and learning/memory domains (Antón-Toro et al., 2021; Avdija, 2022; Blume et al., 2000; Kang and Kim, 2022; Sampedro-Piquero et al., 2024). Nonetheless, some studies have found no significant cognitive deficits, which may be attributed to methodological differences, including sample characteristics, assessment tools, patterns of alcohol intake, or even sex-related variations (Flores-Bonilla and Richardson, 2020). In this regard, sex-related differences must be considered when studying the effects of alcohol. Thus, some studies have found that compared to men, who usually drink for positive reinforcement, women are more likely to drink to regulate negative affect and stress reactivity (Stoica et al., 2021). Besides, the association between alcohol consumption and the development of anxiety or depressive symptoms appears to be stronger in women than in men (Peltier et al., 2019; Torres et al., 2023). Moreover, the impact of RAU on resting brain activity in young individuals remains insufficiently explored, with some studies suggesting similar neural alterations to those observed in adults. Specifically, studies indicate an increase in theta (4–8 Hz) and/or beta (13–21 Hz) power (Herrera-Díaz et al., 2016; López-Caneda et al., 2017; Mumtaz et al., 2017). A previous study conducted by our group with young participants aged 18 to 25 found that men in the RAU group displayed a higher theta/beta ratio, which is related to poorer cognitive control and higher impulsivity, compared to RAU women (Sampedro-Piquero et al., 2024).

Taking all this into account, attractive and non-stigmatizing interventions for young adults with RAU are needed, focusing on improving their physical, social, and mental health symptoms (Simonton et al., 2018). There are several treatment approaches targeting problematic substance use in young people, such as family-based treatments, motivational enhancement therapy, pharmacological treatments, cognitive behavioral therapy, or 12-step programs, but they have shown limited efficacy and seem to be not appropriate for young people who have not identified their drug use as problematic (Hofmann et al., 2012; Stockings et al., 2016). In this context, exercise-based interventions appear to be a feasible alternative. A meta-analysis by Lardier et al. (2021) showed that exercise interventions can reduce alcohol consumption in adults with alcohol use disorder (AUD). Moreover, this might constitute a promising complementary approach by reducing anxiety and depression and improving quality of life (Gür and Can Gür, 2020; Hallgren et al., 2017; Martínez-Calderon et al., 2023). Engaging young adults in an exercise protocol could represent a dual-benefit strategy by reducing anxiety induced by stressful events and, consequently, preventing substance use (Broman-Fulks et al., 2004).

Nevertheless, studies conducted in this population have shown mixed results, with some findings supporting aerobic exercise as effective in reducing drug use and substance-related measures such as craving (Gawor et al., 2021), while others have found no significant changes in levels of depression, anxiety, self-efficacy, or alcohol consumption (Gür and Can Gür, 2020). Moreover, there are also several studies that have found a positive association between exercise practice and alcohol intake (Bardo and Compton, 2015; Dodge et al., 2017; Leasure et al., 2015). This relationship has been observed in both college students and the general population and across multiple indicators of alcohol use and physical activity (Moore and Werch, 2008; Musselman and Rutledge, 2010). While this association is often attributed to social dynamics related to team sports, evidence indicates that it also applies to non-athletes and individuals outside the college context (Conroy et al., 2015). Longitudinal and large-scale survey studies further support this link, showing that individuals tend to consume more alcohol on days when they are more physically active, with stronger associations among younger adults, men, and those engaging in vigorous exercise (Lisha et al., 2011; Piazza-Gardner and Barry, 2012). Given that exercise is being explored as a potential intervention for problematic alcohol use, a clearer understanding of this relationship is needed.

On the other hand, several factors appear to contribute to the discontinuation of regular exercise among young adults engaged in RAU, including their potentially poor physical condition, low mood, low self-esteem, low motivation, and low perceived self-efficacy (Horenstein et al., 2021; Welford et al., 2023). Additionally, a lack of time due to social, work, and/or educational commitments may also hinder the maintenance of regular exercise at these ages. Hence, short bouts of high-intensity exercise could be an unexplored avenue to induce psychological and cognitive benefits in this population and engage them in exercise practice. Previous studies performed with university students have revealed that an acute bout of moderate exercise significantly reduced alcohol craving and increased mood and positive affect, whereas anxiety and negative affect decreased from pre- to post-intervention (Gawor et al., 2021; Herbert et al., 2020). Interestingly, in a recent systematic review by Klamert et al. (2023), more than two-thirds of acute exercise studies conducted among young people reported significant benefits for substance use outcomes, compared to just over half of the long-term studies. Similar results have also been found in adults with AUD (Brown et al., 2016; Hallgren et al., 2021a). Despite this evidence, there is a scarcity of results regarding the acute exercise-cognition relationship, as well as its underlying brain and psychophysiological activity changes in young people with RAU. This is likely due to the complexity of the phenomenon, which is influenced by a range of factors such as the modality, intensity, and duration of the exercise bout, as well as age, sex, physical fitness, and the level of alcohol use.

A growing body of research sought to elucidate the effects of a single bout of exercise on cognitive performance (Chang et al., 2012). This research was based on the premise that the physiological responses elicited by exercise influenced cognitive functioning, which could be assessed using behavioral measures. Key physiological responses implicated in the cognitive literature included changes in heart rate (HR) (Murray and Russoniello, 2012), levels of the brain-derived neurotrophic factor (BDNF) (Bekkos et al., 2025; Venezia et al., 2017), and alterations in plasma catecholamines (Kliszczewicz et al., 2018). Concerning this issue, Lambourne and Tomporowski (2010) conducted a meta-analytic review of 40 studies examining acute exercise in healthy young adults. Cognitive performance was assessed either during exercise or following exercise. Their results indicated a small detrimental effect of acute exercise on cognitive performance during exercise ($d = -0.14$), whereas post-exercise assessments revealed a modest improvement ($d = 0.20$). Moderator variables, including exercise intensity and duration, timing of cognitive task administration, exercise modality, cognitive task type, and study design, were identified as influencing these outcomes. The effects of acute exercise on cognition also appeared to depend on the nature of the cognitive task, prompting increased research on executive functions and frontal-lobe dependent measures (Sibley and Beilock, 2007; Tomporowski and Ganio, 2006). This trend aligned with interest in the transient *hypofrontality hypothesis* (Dietrich, 2006) and meta-analytic evidence suggesting task-specific moderation of exercise effects (Lambourne and Tomporowski, 2010). Neuroimaging studies partially supported the transient *hypofrontality hypothesis* and indicated additional physiological mechanisms. Near-infrared spectroscopy (NIRS) studies consistently reported decreased prefrontal oxygenation during intense exercise (Bhambhani et al., 2007; Ekkekakis, 2009). Furthermore, neuroendocrinological changes contributed to the effects of acute cardiovascular exercise on cognition through catecholamines (dopamine, noradrenaline, and adrenaline) and cortisol. High-intensity exercise-induced cortisol elevation increased arousal, potentially impairing cognitive performance. Concurrently, catecholamines preferentially activated the limbic system over the prefrontal cortex, diminishing executive function performance (McMorris et al., 2009). Conversely, even brief exercise bouts (10–40 min) were associated with improvements in executive functions, likely due to transient increases in prefrontal blood flow and oxygenation (Verburgh et al., 2014). Some studies suggest that exercise may exert a beneficial effect on inhibitory control, a highly relevant finding considering the essential role of this function in regulating behavior in response to negative emotions (Verburgh et al., 2014; Zhang et al., 2020). Interestingly, this improvement in inhibitory control was related to an enhancement in oscillatory brain activity during and following an acute bout of exercise (Ciria et al., 2018).

Collectively, these findings suggested that exercise-induced physiological responses, including HR, BDNF, endorphins, serotonin, and catecholamines, could predict the impact of acute exercise on cognition (Labelle et al., 2013). Lower-intensity exercise optimized physiological activation immediately post-exercise, whereas higher-intensity exercise maximized cognitive benefits when assessments were delayed. Consistent with this, cognitive tests administered approximately 11–20 min after exercise typically demonstrated the largest effects. Beyond executive functions, acute exercise was reported to modulate attentional and vigilance performance in an intensity-dependent manner (Sanchis-Navarro et al., 2024). Specifically, light-intensity exercise enhanced accuracy in attentional network tasks without accelerating reaction time, whereas vigorous-intensity exercise improved vigilance by reducing response latency. Phasic alertness improved following exercise, while orienting and cognitive control networks remained unaffected.

In addition, improvements in mental health also mediated the effects of exercise on cognition. Animal studies have indicated that exercise alleviated stress-induced depressive symptoms, accompanied by alterations in regional homogeneity and functional connectivity in brain regions critical for cognition, including the hippocampus and prefrontal cortex (Dong et al., 2020). These findings suggested that exercise-induced mental health improvements supported neurofunctional adaptations underlying cognitive processes. The model proposed by Stillman et al. (2016) posited a bidirectional relationship among physical activity, cognition, and mental health, wherein psychological well-being both influenced and was influenced by cognitive functioning. In summary, the effects of acute aerobic exercise on cognitive performance in healthy adults depended on exercise-related factors (e.g., intensity and duration), cognitive variables (e.g., task type and cognitive domain), and individual characteristics such as habitual physical activity (Herbert, 2025).

Based on previous evidence, this study aimed to examine the effects of a short session of intense aerobic exercise, compared to a stretching protocol used as an active control, on cognitive and psychophysiological variables in young individuals with RAU and a control group (CO). Stretching, as a form of mind-body exercise, may influence the neuroendocrine, autonomic, and central nervous systems, all of which play a role in emotional regulation (Chen et al., 2025). This type of exercise can promote parasympathetic activation, leading to increased vagal tone and improved heart rate variability (HRV), a key indicator of emotional resilience and stress recovery (Weber et al., 2010; Wu et al., 2024). Additionally, stretching emphasizes body awareness, which enhances interoceptive accuracy and has been linked to more adaptive emotion regulation and reduced anxiety levels (Pinna and Edwards, 2020).

All things considered, we hypothesized that cycling would lead to greater improvements in executive function and attentional performance compared to stretching. Additionally, we expected cycling to elicit larger reductions in HRV and more pronounced increases in salivary cortisol (sCORT) and salivary alpha-amylase (sAA). Finally, we anticipated that EEG oscillatory power would shift toward patterns indicative of heightened arousal or enhanced cognitive control following cycling.

2. Material and methods

2.1. Participants

A total of 100 college students aged between 18 and 25 years were recruited through verbal disclosure, e-mails, and notice boards at the Autonomous University of Madrid (Caucasian, 25 men and 75 women, aged 19.54 ± 0.20 and matched for education level). We would like to note that this imbalance between male and female participants represents an important limitation of our study. All the volunteers included in the study signed an informed consent, and they created an alphanumeric code to guarantee privacy during the data processing and analysis phases. Information regarding their substance use, anxiety trait, emotional regulation and impulsivity was collected using several on-line standardized questionnaires via the Qualtrics® platform: Alcohol Use Disorder Identification Test (AUDIT, Spanish adaptation: Contel-Guillamón et al., 1999); the Cannabis Abuse Screening Test (CAST, Spanish adaptation: Cuenca-Royo et al., 2012; Legleye et al., 2007); State-Trait Anxiety Inventory (STAI-t, Spielberger et al., 1970; Spanish adaptation: Buela-Casal et al., 1986); the Difficulties in Emotion Regulation Scale (DERS, Spanish adaptation: Hervas and Jodar, 2008), Rosenberg self-esteem scale (RSE, Spanish adaptation: Atienza et al., 2000) and the Impulsive Behavior Scale (UPPS-P, Spanish adaptation: Cándido et al., 2012). Risky alcohol use was determined using the AUDIT questionnaire (women ≥6; men ≥8 points) and the CO group scored ≤3 points (EDADES) 1995–2024). All volunteers with an AUDIT score above 19 points were excluded as they were considered to have an addiction and not risky consumption. The AUDIT questionnaire was developed by the World Health Organization (WHO) as a simple method of screening for alcohol abuse and to assist in brief assessment (Saunders et al., 1993). Once the AUDIT had been published, many studies have been conducted to evaluate its validity and reliability in different clinical and community samples throughout the world (Allen et al., 1997; Berner et al., 2007; Nadkarni et al., 2019). Generally, total scores of 8 or more are recommended as indicators of hazardous and harmful alcohol use. Hence, improvements in detection have been achieved in some cases by lowering or raising the cut-off score by one or two points, depending on the population and the purpose of the screening program (Conigrave et al., 1995; von der Pahlen et al., 2008). Participants were divided into 2 groups: CO, $n = 53$ (11 men) and RAU, $n = 47$ (14 men). RAU volunteers were not treatment-seeking.

The inclusion criteria were: 1) aged 18–25 years; 2) an absence of diagnosis of substance use disorder; 3) an absence of comorbid disease, such as anxiety-related disorders, depression, psychotic disorder or attention-deficit/hyperactivity disorder (ADHD); 4) alcohol as the predominant substance of consumption and non-problematic consumption of other drugs, specifically cannabis and tobacco. Exclusion criteria included consumption of recreational drugs (besides alcohol, cannabis and nicotine); a score of ≥4 in CAST, indicative of problematic cannabis use; a regular performance of ≥150 min of moderate/vigorous physical activity per week assessed by the International Physical Activity Questionnaire short form (IPAQ-SF, Craig et al., 2003) and not using a bicycle in their daily routines; the consumption of prescription drugs that could affect their performance, such as anxiolytics, antidepressants and oral contraceptives; or blood pressure before exercise session (≥ 140/90 mmHg).

The study received approval from the Ethics Committee of the Autonomous University of Madrid (code: CEI-122-2490) in accordance with the Ethical Principles for Medical Research Involving Human Subjects adopted in the Declaration of Helsinki by the World Medical Association (64th WMA General Assembly, Fortaleza, Brazil, October 2013), Recommendation No. R (97) 5 of the Committee of Ministers to

Member States on the Protection of Medical Data (1997), and the Spanish Data Protection Act (Ley Orgánica 15/1999 de Protección de Datos, LOPD). All the participants were informed about the study prior to their inclusion in the study and had provided their written informed consent.

2.2. Assessment protocol

Once participants were included based on their answers on the online questionnaires, a laboratory session was scheduled with them. During the two-hour session we conducted pre-and-post-exercise assessments regarding cognition, anxiety state and psychophysiological variables. Details of these measurements and the study schedule will be displayed in the following sections. Participants were randomly assigned to each exercise condition, either intense on a cycle ergometer (RAU = 29, CO = 32) or an active control condition of stretching (RAU = 18, CO = 21). For this purpose, we used a computer-generated list (https://www.random.org/lists/) and we checked group/sex balance afterwards. In each group, there were no differences between participants in their educational level and weekly physical activity (details are displayed in Table 1).

2.2.1. Pre-exercise assessment

Upon arrival, informed consent was collected, and anthropometric measurements such as arterial tension, height, weight, hip and waist circumferences were taken. HR was monitored throughout the entirety of the laboratory session (before, during and after exercise session) by a Polar H10 device connected to the Polar Sensor Recorder mobile app (Polar H10®). Firstly, resting state electroencephalography (rsEEG) was carried out using Bitbrain's Versatile cap (model E32.A1). Twenty-two electrodes (Fp1, Fpz, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, O1, O2) placed according to the international 10–20 system were selected, processed and analyzed. The sampling rate was 256 Hz. A reference channel was placed on the left earlobe, and ground was localized in AFz. Participants were seated in a comfortable chair during the EEG set-up, where the experimenter fitted the EEG cap and ensured that all electrode impedances were kept below 5 kΩ. After this, participants sat still while the EEG recording was ongoing. The participants alternated twice between sitting with their eyes closed for five minutes (Eyes Closed/EC condition) and sitting with their eyes open for five minutes while staring at a fixation dot painted on the wall 90 cm away from them (Eyes Open/EO condition). This resulted in a total of 10 min of rsEEG recording per condition and participant. The conditions were counterbalanced.

Afterwards, psychological and neuropsychological tests were administered to the volunteers: Desire for Alcohol Questionnaire (DAQ, Love et al., 1998) to measure their alcohol craving; STAI-state (Spielberger et al., 1970) measured their current anxiety state; d2 test (Brickenkamp and Cubero, 2002) was used to assess their sustained attention, paths 3 and 4 of *Test de los Senderos* (TESEN) (Portellano and Martínez Arias, 2014), which measure visual motor planning skills; Letters and Numbers Sequencing test from WMS-IV (Wechsler, 2008) to measure attention, working memory, processing speed, and cognitive flexibility, Five Digits Test (FDT, Sedó, 2007), which assesses cognitive flexibility, inhibitory control, and information processing speed, and FAS / PMR Word Fluency (Buriel et al., 2004). Upon completion of these tests, saliva samples were collected (10:00 a.m. to 5:30 p.m.) through salivettes (Salivette®, Sarstedt, S.A., Barcelona, Spain) to analyze cortisol and alpha amylase response before the start of the exercise. Although this time window has been used in previous studies (Moreno-Fernández et al., 2023; Moreno-Fernández et al., 2024), we would like to clarify that, to avoid the influence of diurnal variations in cortisol levels, the assessment sessions were balanced across groups. Furthermore, we verified that the time of day at which the sample was collected (morning

Table 1
Online questionnaires results and anthropometric variables for each group.

	CO		RAU		p values	η_p^2
	Men	Women	Men	Women		
Age	20.54 ± 0.69	18.84 ± 0.17	20.35 ± 0.74	19.33 ± 0.34	$p = 0.12$	–
Years of study	12.32 ± 0.10	12.17 ± 0.04	12.47 ± 0.13	12.16 ± 0.06	$p = 0.69$	–
Exercise per week (min)	59.98 ± 0.34	54.01 ± 0.07	61.45 ± 1.23	57.87 ± 0.32	$p = 0.73$	–
VPA (min/week)	49.61 ± 25.69	41.17 ± 21.29	92.73 ± 38.05	70.30 ± 31.29	$p = 0.70$	–
MPA (min/week)	26.15 ± 12.48	33.72 ± 10.62	32.73 ± 22.32	38.78 ± 8.33	$p = 0.96$	–
TOTAL PA (METs – min/week)	995.88 ± 179.6	1391.55 ± 156.01	2042 ± 633.76	1558.16 ± 164.24	$p = 0.11$	–
Waist-to-hip ratio	0.90 ± 0.01	0.87 ± 0.008	0.89 ± 0.02	0.85 + 0.01	&$p = 0.02$	0.06
Waist-to-height ratio	0.44 ± 0.01	0.43 ± 0.005	0.44 ± 0.01	0.43 ± 0.007	$p = 0.90$	–
Onset age (alcohol)	14.73 ± 1.52	14.49 ± 0.70	14.86 ± 0.42	14.30 ± 0.25	$p = 0.93$	–
AUDIT	1.10 ± 0.37	1.36 ± 0.18	10 ± 0.78	9.10 ± 0.59	*$p = 0.001$	0.7
AUDIT-C	0.08 ± 0.08	0.02 ± 0.02	2.45 ± 0.16	2.06 ± 0.14	++$p = 0.001$	0.06
CAST	0.10 ± 0.10	0.07 ± 0.05	3.28 ± 1.44	1.15 ± 0.38	*$p = 0.001$	0.13
Tobacco cigarettes/day	0	0.09 ± 0.09	3.43 ± 1.71	1.12 ± 0.43	*$p = 0.002$	0.10
STAI trait	23.10 ± 2.77	25.57 ± 1.48	22.92 ± 2.41	28.88 ± 1.70	$p = 0.44$	–
DERS	58.10 ± 6.80	61.64 ± 2.48	59.64 ± 4.40	68.12 ± 2.90	$p = 0.27$	–
Emotional neglect	10.45 ± 0.95	10.50 ± 0.61	12.86 ± 1.30	10.52 ± 0.59	$p = 0.12$	–
Emotional confusion	5.36 ± 0.74	6.21 ± 0.44	6.5 ± 0.67	6.39 ± 0.31	$p = 0.24$	–
Emotional interference	11.64 ± 1.50	11.12 ± 0.62	8.86 ± 1.24	12.64 ± 0.70	#$p = 0.04$	0.05
Emotional dysregulation	16.27 ± 2.21	17.79 ± 0.81	17.26 ± 1.86	21 ± 1.33	$p = 0.14$	–
Emotional rejection	14.36 ± 2.20	16.02 ± 0.89	14.14 ± 1.27	17.58 ± 1.27	$p = 0.60$	–
UPPS-P	42.00 ± 2.46	41.36 ± 1.17	45.43 ± 1.93	47.18 ± 1.19	*$p = 0.006$	0.08
Negative urgency	8.18 ± 0.78	8.83 ± 0.46	8 ± 0.58	9.70 ± 0.51	$p = 0.47$	–
Lack of perseverance	7.64 ± 0.72	6.57 ± 0.31	8.10 ± 0.76	8.10 ± 0.41	*$p = 0.04$	0.05
Lack of premeditation	6.64 ± 0.45	6.45 ± 0.29	7.43 ± 0.42	7.91 ± 0.34	*$p = 0.01$	0.07
Sensation seeking	10.00 ± 0.93	10.24 ± 0.49	11.43 ± 0.81	10.94 ± 0.55	$p = 0.21$	–
Positive urgency	9.55 ± 0.80	9.26 ± 0.35	10.50 ± 0.58	10.54 ± 0.39	*$p = 0.03$	0.05
EAR	31.00 ± 1.63	29.86 ± 0.66	30.71 ± 1.17	28 ± 0.77	$p = 0.36$	–

Values are means ± SEM. VPA: vigorous physical activity; MPA: moderate physical activity; METs: metabolic equivalent task; PA: physical activity; min: minutes.
*Asterisk represents significant differences between the CO and the RAU groups ($p \leq 0.05$).
& represents significant differences between men and women ($p \leq 0.05$).
# represents significant differences between the men and the women within the RAU group ($p \leq 0.05$).
++ represents significant interaction GROUP X SEX ($p \leq 0.05$).

or afternoon) did not significantly affect cortisol levels (*Time x Group*: $F_{(1,90)} = 1.83$, $p = 0.18$). Finally, we also recorded the participants' waist-to-hip ratio and their waist-to-height ratio before they began the exercise protocol corresponding to the experimental group to which they belonged (cycle ergometer/stretching). Both exercise protocols lasted 12 min. Waist circumference was measured in all participants using a measuring tape, with the last rib taken as the anatomical reference, and hip circumference was measured at the level of the hip bone. Regarding the waist-to-height ratio, it was calculated as the ratio of waist circumference to height, both measured in centimeters. These measurements were consistently performed by two members of the research team. Volunteers were required to refrain from consuming alcohol for at least 72 h prior to attending the laboratory, as well as coffee or tea for at least 12 h before the saliva sample collection.

2.2.2. Exercise session

Participants were asked to refrain from eating for the last 2 h prior to this session and to refrain from heavy exercise during the previous 24 h. As an objective index of physical effort, we analyzed lactate levels pre- and post- exercise in all participants. A small blood capillary sample (0.3 μL) was collected from the fingertip using fine lancets (Romed Holland, Van Oostveen Medical B.V.) through a lancing device (Nesira, Acofar). Next, a strip for lactate detection (Lactate Pro 2, TECIL) was prepared on the lactate analyzer (Lactate Pro 2 LT-1730, ARKRAY Factory Inc., Shiga, Japan). The analysis time was around 15 s and the measurement range 0.5–25 mmol/L.

In the sub-maximal exercise condition, participants cycled on a calibrated mechanically braked cycle ergometer (Model Cardio Fit E35 Tunturi, Spain) for a total of 12 min without stopping between increments. As previous research suggests, acute exercise sessions may need to exceed 10 min to have significant effects on alcohol craving (Ussher et al., 2004). The exercise protocol was a direct replication of the procedure described by Hallgren et al. (2021b). After standard adjustment of the seat and handlebars, the 12-min protocol of progressive intensity was divided into a 4-min warm-up with low-intensity cycling at a sustained power output of 30–35 watts. Following this, resistance was increased, marking the beginning of the remaining 8 min of high intensity cycling, where a minimum output of 60 rpm had to be maintained while obtaining the maximum possible watts. Participants were asked about their perceived effort based on the Rating of Perceived Exertion scale (RPE, Borg et al., 1987) at 3:30 min, 4:00 min, 8:30 min, 9:00 min, and 12:00 min. The RPE is a visually presented, single-item scale ranging from 6 (not strenuous at all) to 20 (maximally strenuous) that enables participants to rate how strenuous they perceive the exercise session (Hallgren et al., 2021b). The final 8 min of the cycling protocol were intended to reach vigorous-intensity exercise according to the American College of Sports Medicine guidelines (≥60% HRR) (ACSM) (Garber et al., 2011). No fixed HR or power output target was imposed; HR was continuously recorded to characterize the physiological response to the exercise stimulus and power output was also recorded after 8 and 12 min. After minute 12, a 1-min cool-down was performed at 30 W when we collected the second lactate sample.

In the stretching condition, participants stood on a yoga mat (Essentiel Yoga Mat, 170 × 58 × 4 mm) and followed a standardized stretching sequence delivered via a pre-recorded instructional video. A total of nine stretching exercises were performed targeting the gluteals, hamstrings, adductors, latissimus dorsi, pectoralis major, and trapezius muscles, either in isolation or through global stretching positions. All stretches were static in nature and were held for approximately 15 s each. Stretches were performed bilaterally when applicable. During each stretch, participants were instructed to perform two slow and deep breathing cycles (approximately 4 s per inhalation and exhalation). No dynamic or ballistic movements were performed. They were also asked about their perceived effort on RPE scale at the same time points mentioned earlier. Immediately after completing the corresponding exercise condition, a second lactate measurement was taken following the procedure described earlier. We also calculated the maximum HR (Tanaka et al., 2001) and the percentage of effort that each participant had exerted out of the total they could perform (Heart rate reserve (HRRmax (%)): reached HR – resting HR) / (maximum HR – resting HR)). After this, participants were allowed to drink water, dry off, and recover after the exercise. Additionally, following both exercise protocols, we asked the participants about possible discomfort or drowsiness, and none of them reported experiencing these symptoms. The time of day was balanced and controlled across GROUP and SEX conditions, as approximately half of the participants in each group and condition performed the exercise session at the same time of day.

2.2.3. Post-exercise assessment

Following the same procedure described earlier (section 2.2.1), HR was continuously monitored, a second saliva collection swab was taken and lactate levels were registered again. After this, a second rsEEG of the same duration was performed and finally, the STAI-state test, and the DAQ along with the set of neuropsychological tests were administered again (after 10–15 min post exercise). PMR-FAS Fluency test order was counterbalanced to avoid a practice effect. Fig. 1 shows the protocol and time points followed in the experiment design.

2.2.4. Samples and data processing

In the following sections, the method used to register and analyze the different psychophysiological data in our study will be described.

2.2.4.1. EEG and HRV. EEG data preprocessing was done through MATLAB 23.2 (The MathWorks Inc, 2023), and the Fieldtrip toolbox (Oostenveld et al., 2011, 20240307 release). The continuous EEG data was band-pass filtered (0.5–35 Hz), re-referenced to the mean, demeaned and detrended. Eyeblinks, saccadic movements, and other artifacts were removed with Independent Component Analysis (ICA) with the “fast-ica” implementation within Fieldtrip, followed by a visual inspection of the clean data. The continuous signal was then segmented into 2-s length epochs, with a 25% overlap among epochs. For each epoch, the frequency power spectrum was computed using Fast Fourier Transform (FFT) with a Hanning taper. Linear frequencies from 1 Hz to 35 Hz were extracted with a 0.5 Hz resolution using the “nextpow2” zero-padding option. In order to avoid the conflation of aperiodic and oscillatory components of the signal (Donoghue et al., 2020), the Fitting Oscillations and One-Over-F algorithm (FOOOF) was implemented using the “fooof_aperiodic” and “fooof_peaks” options in Fieldtrip. In this way, for each participant, channel, and epoch we obtained the offset and slope of the aperiodic component as well as the power spectrum of the oscillatory component. To determine whether the slope of the aperiodic component was homogeneous across electrodes, a one-way ANOVA was carried out. The analysis revealed significant differences between electrodes both before ($F_{(1,21)} = 4.01$, $p < 0.001$) and after exercise ($F_{(1,21)} = 5.02$, $p < 0.001$). Based on the topographical distribution of the average slope values across electrodes, five regions of interest (ROI) were identified: anterior (Fp1, Fpz, Fp2, AF3, AF4, F3, F4), central (C3, Cz, C4, Fz), posterior (Pz, O1, O2), left lateral (T7, P7, P3, F7), and right lateral (T8, P4, P8, F8). Thus, a mean slope value was obtained for each region of interest and group. To retain only those portions of the data containing oscillatory activity within each frequency band (delta: 1 to 4 Hz, theta: 4 to 8 Hz, alpha: 8 to 13 Hz, and beta: 13 to 30 Hz), power spectrum segments that lacked identifiable peaks within the corresponding frequency ranges were identified and discarded using MATLAB's “findpeaks” function. The remaining power spectra were averaged, resulting in a single power value per participant, channel, and frequency band. For simplicity and consistency in the statistical analysis, these values were further aggregated across the previously defined regions of interest.

Regarding HRV variables, the time domain parameters considered in this study were the standard deviation of normal R-R intervals (SDNN),

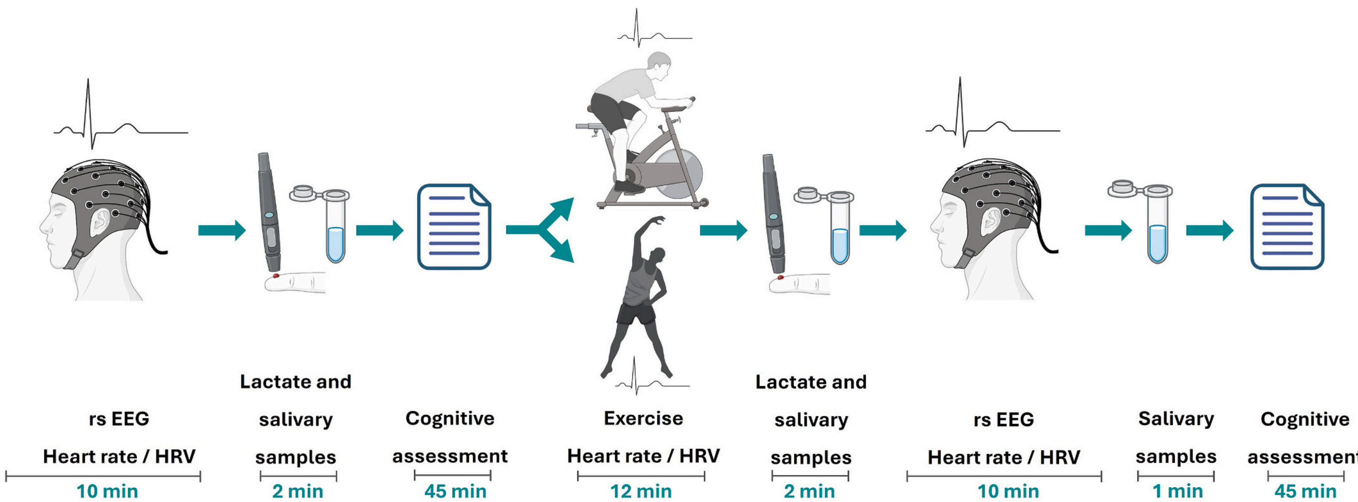

Fig. 1. Graphical representation of the study protocol including key steps and assessments at t1, t2 and t3.

the square root of the mean of the squares of successive R-R intervals differences (RMSSD) which were calculated before (t1, 10 min sitting during the EEG measures with eyes open and closed), during (t2, 12 min of the exercise) and post exercise conditions (t3, 10 min post). The RMSSD represents parasympathetic activity, while the SDNN represents sympathetic and parasympathetic activity (global index), yet does not allow to distinguish when changes in HRV are due to increased sympathetic tone or withdrawal of vagal tone, thus indicating an interaction between sympathetic and parasympathetic (Gullett et al., 2023; Rodrigues et al., 2020). These data were analyzed using Kubios HRV Scientific software and filters were applied to control and correct the effect of breathing, noise, and beat quality were applied.

2.2.4.2. Saliva samples. Saliva samples were coded and stored at −20 °C for approximately three and a half months before ELISAs were performed (sCORT and sAA levels). On that day, the samples were removed from the freezer several hours in advance and kept at 4 °C, the temperature at which the centrifuge was set. The required volume of each sample was then taken to perform both ELISAs, and they were centrifuged at 1500 rpm for 15 min, resulting in a clear supernatant of low viscosity. Both sCORT and sAA have individually been identified as meaningful and reliable markers of stress systems (Granger et al., 2007; Moreno-Fernández et al., 2023). sCORT and sAA concentrations were measured in duplicate using several commercially available enzyme-linked immunosorbent assay (Human Alpha-amylase Kinetic reaction for saliva samples (1-1902-1); Human Cortisol (expanded range) Kit for saliva samples (1-3002-1, Salimetrics®, BioNOVA científica S.L., Madrid, Spain). sCORT and sAA levels were expressed in nmol/L and U/mL, respectively (Ali and Pruessner, 2012). As mentioned, these physiological measurements were recorded before starting exercise (t1), immediately after finishing both exercise sessions (t2), and 10 min after exercise ended (t3). Besides, the area under the curve, with respect to ground or zero (AUCg), was first calculated for the raw, untransformed values of both sAA and cortisol using the trapezoid formula described earlier (Pruessner et al., 2003). This score incorporates information regarding both baseline and reactivity individually for Alpha-amylase and cortisol, within one score. We then divided the Alpha-amylase AUCg by the cortisol AUCg to derive an overall ratio variable of Alpha-amylase over cortisol based on the individual AUCg variables, and named this AOCg (Ali and Pruessner, 2012; Moreno-Fernández et al., 2023).

2.3. Statistical analysis

All statistical analyses were performed using SPSS 25 (IBM SPSS Statistics, Corporate headquarters, New Orchard Road, Armonk, New York 10,504–1722, USA). All p values were two-tailed, and the level of significance was taken as $p \leq 0.05$. Descriptive analyses (mean ± SEM) were carried out for all the measurements analyzed in the study (more details are displayed in Table 1 and Table 2). In a first analysis, GROUP (CO / RAU) and SEX (men / women) were considered between-factors with two levels each and two-way MANOVA was carried out to analyze possible differences between experimental conditions in socio-demographic and online questionnaire variables. A further analysis included GROUP (CO / RAU), SEX (men/women) and EXERCISE (cycle / stretching) as between factors with two levels each. Then, we performed a four-way repeated measurements ANOVA for all variables registered pre and post-exercise session. In the present study, we chose to include SEX as a factor rather than as a covariate, because it is known that this variable interacts with the other experimental factors (alcohol and exercise) and may modulate the effects of the conditions under investigation.

For rsEEG data, we conducted a percentage change analysis for each subject, comparing pre- and post-exercise measurements of both the offset and slope of the aperiodic component, and peak power in the delta, theta, alpha and beta bands across the following regions of interest (ROIs): anterior, central, left and right lateral, and posterior regions, using the formula [(post-pre)/pre] × 100 (Kavcic et al., 2021; Kim et al., 2022). Subsequently, a four way MANOVA was performed with GROUP, SEX, and EXERCISE as between subject factors. Appropriate Bonferroni post hoc comparisons were conducted when significant differences were found, and partial eta-squared (η_p^2) was calculated to determine effect size. This measure represents the proportion of variance in the dependent variables that is uniquely explained by each independent variable or interaction, after controlling for the other effects. It ranges from 0 to 1, with higher values indicating larger effect sizes. Commonly used thresholds for interpretation are 0.01 for a small effect, 0.06 for a medium effect, and 0.14 for a large effect (Lakens, 2013; Norouzian and Plonsky, 2017).

3. Results

3.1. Differences between groups in substance use, impulsivity, emotional regulation, weekly physical activity and anthropometric variables

The RAU group showed significantly higher scores than the CO group in alcohol and cannabis use, as measured by the AUDIT and CAST, respectively, regardless of participants' sex (AUDIT: $F_{(1,100)} = 219.32$, $p = 0.001$, $\eta_p^2 = 0.70$; CAST: $F_{(1,\ 100)} = 13.97$, $p = 0.001$, $\eta_p^2 = 0.13$; Bonferroni post hoc test following the significant group effect). In

Table 2
Mean ± SEM values of the different variables measured in the study for each experimental condition.

	CO				RAU				*p* values	η_p^2
	Cycle		Stretching		Cycle		Stretching			
	Women	Men	Women	Men	Women	Men	Women	Men		
DAQ pre	6.63 ± 1.86	7.2 ± 0.8	7.07 ± 0.53	6.5 ± 0.5	9.26 ± 0.68	8.7 ± 0.56	8.5 ± 1.55	8.75 ± 0.49		
DAQ post	6.26 ± 0.14	7.4 ± 1.17	7 ± 0.55	6.17 ± 0.17	9.79 ± 1.14	7.7 ± 0.47	8.21 ± 1.52	8.75 ± 0.85	$p = 0.24$	
STAIs pre	13.11 ± 1.26	8.8 ± 2.08	15.73 ± 1.94	13.67 ± 1.96	16.05 ± 1.52	15.4 ± 1.4	17.21 ± 1.79	11.25 ± 3.57		
STAIs post	10.41 ± 1.05	8 ± 1.84	11 ± 1.55	7.5 ± 2.17	17.47 ± 1.70	12 ± 1.01	12.29 ± 1.68	6.5 ± 3.66	*$p = 0.012$	0.07
***d*2-TOTpre**	441.19 ± 12.24	455.80 ± 42.79	438.67 ± 13.41	427.74 ± 15.1	446 ± 12.32	400.3 ± 17.08	466.14 ± 20.68	392 ± 10.21		
***d*2-TOTpost**	507.81 ± 12.63	510.8 ± 38.67	497.67 ± 12.56	462.5 ± 21.64	515.53 ± 13.46	451 ± 18.88	513.93 ± 16.15	454.75 ± 17.38	$p = 0.57$	
***d*2-VARpre**	13.19 ± 0.89	11.2 ± 1.39	10.13 ± 0.68	12.29 ± 1.37	10.95 ± 0.76	15.1 ± 1.8	11.14 ± 0.96	11 ± 0.82		
***d*2-VARpost**	10.77 ± 0.83	10.6 ± 1.21	12.53 ± 1.19	12.5 ± 1.48	13.05 ± 0.74	15.4 ± 1.52	11.5 ± 1.02	11 ± 1.78	$p = 0.19$	
***d*2-CONpre**	176.96 ± 5.51	192.60 ± 18.61	182.20 ± 6.88	175.7 ± 0.97	184.11 ± 6.38	160.4 ± 9.04	191.29 ± 10.51	150.5 ± 4.29		
***d*2-CONpost**	218.04 ± 6.82	226.40 ± 19.70	213.40 ± 7.18	197.17 ± 14.81	226.95 ± 7.51	189.8 ± 11.52	218 ± 8.02	183.25 ± 5.57	$p = 0.47$	
***d*2-Omissions pre**	16.31 ± 3.19	11.2 ± 4.91	9.47 ± 1.72	12.24 ± 5.48	8.37 ± 1.4	13.2 ± 3.1	8.93 ± 2.44	23.25 ± 11.03		
***d*2-Omissions post**	11 ± 2.13	2.8 ± 1.2	7.67 ± 1.84	8 ± 4.16	5.74 ± 1.22	9.3 ± 1.72	6.86 ± 1.81	26.5 ± 11.38	*$p = 0.04$	0.05
***d*2-Comissions pre**	0.42 ± 0.17	0.2 ± 0.2	0.4 ± 0.21	0.22 ± 0.16	0.37 ± 0.17	0.5 ± 0.22	0.29 ± 0.16	0.5 ± 0.29		
***d*2-Comissions post**	0.5 ± 0.22	0 ± 0	0.27 ± 0.15	0.83 ± 0.83	0.42 ± 0.23	0.5 ± 0.22	0.64 ± 0.27	0.5 ± 0.29	$p = 0.49$	
TESEN3 pre (s)	107.82 ± 3.81	115 ± 9.59	112.43 ± 7.49	97.89 ± 7.63	101.51 ± 3.33	104.28 ± 5.96	125.45 ± 9.19	98.67 ± 3.02		
TESEN3 post (s)	85.28 ± 2	82.8 ± 5.63	85.02 ± 3.19	83.12 ± 7.69	82.2 ± 3.27	93.57 ± 5.77	84.25 ± 2.74	73.98 ± 4.88	$p = 0.78$	
TESEN4 pre (s)	124.01 ± 4.22	110.76 ± 4.61	116.67 ± 6.15	124.63 ± 12.24	115.33 ± 6.38	130.83 ± 9.01	151.15 ± 14.1	128.61 ± 14.54		
TESEN4 post (s)	109.39 ± 4.37	107.98 ± 8.69	117.56 ± 9.29	120.43 ± 15.05	104.58 ± 4.66	112.43 ± 6.32	118.49 ± 13.2	93.05 ± 10.13	$p = 0.69$	
LyN pre	10.48 ± 0.33	10.6 ± 0.51	10.47 ± 0.45	10.83 ± 0.87	9.74 ± 0.48	10 ± 0.61	9.07 ± 0.53	9.75 ± 0.75		
LyN post	10.96 ± 0.34	12.2 ± 0.49	10.87 ± 0.51	11.83 ± 1.22	11.05 ± 0.51	12.1 ± 0.69	10.43 ± 0.64	11.5 ± 0.29	$p = 0.92$	
FDTflex pre	20.03 ± 1.42	14.75 ± 1.17	19.44 ± 1.61	19.71 ± 4.45	19.13 ± 1.35	19.31 ± 1.33	19.24 ± 1.63	22.75 ± 2.21		
FDTflex post	16.58 ± 0.85	11.94 ± 1.65	14.86 ± 1.51	17.68 ± 3.4	14.48 ± 1.04	17.66 ± 0.96	14.52 ± 1.47	16.41 ± 2	$p = 0.40$	
FDTinh pre	13.71 ± 1.01	9.08 ± 1.31	13.63 ± 1.64	11.02 ± 0.73	11.72 ± 0.89	14.22 ± 1.19	12.59 ± 1.18	16.4 ± 2.47		
FDTinh post	10.95 ± 0.84	7.73 ± 1.73	10.91 ± 1.22	11.31 ± 1.26	8.79 ± 0.71	12.06 ± 1.38	10.13 ± 1.11	11 ± 0.85	$p = 0.06$	
Verbal fluency pre	39.59 ± 1.48	37.4 ± 2.46	42.87 ± 2.43	43.17 ± 3.33	39 ± 2.21	39.9 ± 3.21	39.29 ± 1.53	38.75 ± 4.53		
Verbal fluency post	45.04 ± 1.27	38.2 ± 2.56	47.07 ± 2.84	44.83 ± 3.63	48.72 ± 2.71	49.1 ± 3.37	44 ± 2.52	34 ± 6.47	+$p = 0.016$	0.07
Lactate pre (mmol/L)	2.73 ± 0.19	2.35 ± 0.26	2 ± 0.13	2.53 ± 0.32	3.57 ± 0.63	2.48 ± 0.28	2.16 ± 0.25	2.88 ± 0.44		
Lactate post (mmol/L)	11.43 ± 0.97	9.35 ± 1.23	4.9 ± 0.98	3.4 ± 0.81	10.51 ± 1.1	9.4 ± 1.36	2.85 ± 0.32	2.75 ± 0.57	*$p = 0.001$	0.3
RPE (t1)	7.22 ± 0.21	6.88 ± 0.88	8.93 ± 0.45	9.93 ± 1	7.71 ± 0.32	6.8 ± 0.24	9.11 ± 0.49	9.5 ± 1.32		
RPE (t2)	13.61 ± 0.33	13.38 ± 0.47	10.43 ± 0.53	10.93 ± 0.9	13.53 ± 0.37	15.15 ± 0.51	9.57 ± 0.57	11.88 ± 1.45	# $p = 0.02$	0.07
RPE (t3)	15.56 ± 0.37	15.75 ± 0.63	9.17 ± 0.73	8.86 ± 1.1	16.42 ± 0.3	17.4 ± 0.31	8.5 ± 0.47	9 ± 1.22	# $p = 0.03$ + $p = 0.02$	0.07 0.04
Watts (t1)	32.08 ± 0.08	32.1 ± 0.02			32.16 ± 0.1	32.19 ± 0.07				
Watts (t2)	187.85 ± 5.32	250.88 ± 28.02			191.36 ± 8.58	232.33 ± 12.54			# $p = 0.03$	0.05
Watts (t3)	228.74 ± 11.04	286 ± 28.22			239.1 ± 14.58	252.5 ± 9.63			# $p = 0.02$	0.05
HRRmax (%)	80%	73%	34%	31,7%	76,17%	65.25%	28.4%	35.7%	&$p = 0.03$	0.05
Reached HR	170.27 ± 2.02	156.75 ± 7.95	115.24 ± 4.87	106 ± 3.74	164.83 ± 3.52	149.13 ± 5.82	100.27 ± 2.98	106.67 ± 7.88	@$p = 0.001$% $p = 0.04$	0.66 0.66
HR (t1)	94.93 ± 1.76	83.63 ± 9.51	91.57 ± 2.45	90.06 ± 3.57	89.35 ± 3.06	78.47 ± 3.17	84.67 ± 3.53	84.25 ± 6.73		

(*continued on next page*)

Table 2 (*continued*)

	CO				RAU				*p* values	η_p^2
	Cycle		Stretching		Cycle		Stretching			
	Women	Men	Women	Men	Women	Men	Women	Men		
HR (t2)	154.96 ± 2.67	134.44 ± 9.79	101.10 ± 4.39	92.44 ± 3.11	144.60 ± 4.54	122.97 ± 3.38	88.2 ± 3.23	90.75 ± 8.65	*p = 0.001	0.68
HR (t3)	169.64 ± 2.03	151.5 ± 5.42	91.79 ± 5.98	85.28 ± 5.43	163.17 ± 3.60	148.19 ± 5.97	77.57 ± 3.14	83 ± 8.01	*p = 0.001	0.68
RMSSD pre (t1)	50.18 ± 9.50	84.81 ± 26.96	41.74 ± 4.68	51.36 ± 12.93	51.93 ± 16	81.69 ± 24.36	51.63 ± 6.71	50.47 ± 16.13		
RMSSD exercise (t2)	21.86 ± 6.99	39.7 ± 13.68	44 ± 11.71	47.07 ± 11.42	29.63 ± 11.74	45.43 ± 20.2	63.95 ± 23.83	55.8 ± 4.7		
RMSSD post (t3)	17.21 ± 3.44	34.19 ± 14.19	38 ± 7.36	97.03 ± 27.12	31 ± 7.52	45.09 ± 13.57	63.91 ± 9.53	73.79 ± 0.71	*p = 0.001	0.17
SDNN pre (t1)	45.46 ± 5.78	90.44 ± 31.36	48.94 ± 4.99	66.42 ± 9.86	53.66 ± 14.74	84 ± 20.11	58.28 ± 7.92	57.71 ± 12.87		
SDNN exercise (t2)	19.53 ± 3.50	33.82 ± 9.13	46.63 ± 9.32	59.71 ± 10.03	26.94 ± 7.88	43.27 ± 13.22	64.44 ± 16.38	68.74 ± 11.92	*p = 0.002	0.20
SDNN post (t3)	21.20 ± 3.98	38.786 ± 8.86	46.88 ± 8.54	95.35 ± 18.94	32.4 ± 6.64	46.66 ± 11.15	63.07 ± 8.36	76.01 ± 5.25	*p = 0.001	0.20
sAA (U/mL) t1	41.66 ± 4.5	38.26 ± 14.29	33.5 ± 3.7	37.56 ± 7.75	31.14 ± 5.35	31.57 ± 8.53	29.59 ± 3.38	17.65 ± 5.15		
sAA (U/mL) t2	54.92 ± 6.05	43.79 ± 21.29	34.61 ± 8.81	42 ± 8.2	32.87 ± 4.68	47.61 ± 9.17	30.57 ± 5.45	22.43 ± 4.89	*p = 0.03	0.04
sAA (U/mL) t3	38.74 ± 3.53	41.66 ± 17.08	29.22 ± 3.42	44.85 ± 11.3	30.68 ± 4.46	36 ± 7.1	34.55 ± 4.84	29.39 ± 8.13		
sCORT (nmol/L) t1	0.19 ± 0.02	0.18 ± 0.06	0.19 ± 0.03	0.23 ± 0.06	0.19 ± 0.02	0.28 ± 0.06	0.19 ± 0.03	0.14 ± 0.05		
sCORT (nmol/L) t2	0.14 ± 0.01	0.11 ± 0.04	0.11 ± 0.01	0.13 ± 0.03	0.11 ± 0.01	0.18 ± 0.03	0.14 ± 0.02	0.08 ± 0.03	++p = 0.01	0.06
sCORT (nmol/L) t3	0.2 ± 0.03	0.24 ± 0.07	0.12 ± 0.01	0.15 ± 0.03	0.15 ± 0.03	0.17 ± 0.02	0.12 ± 0.02	0.11 ± 0.02	++p = 0.01	0.06
sAA/sCORT (AOCg)	337.82 ± 32.71	237.76 ± 31.28	276.08 ± 58.51	213.42 ± 52.35	217.77 ± 32.78	202.23 ± 50.01	223.68 ± 42.58	311.894 ± 119.07	p = 0.2	

Values are means ± SEM.
@ represents significant differences between both *Exercise* conditions ($p \leq 0.05$).
% represents significant differences between men and women (*Sex*, $p \leq 0.05$).
& represents significant differences between exercise conditions depending on the participant's sex (*Exercise x Sex*, $p \leq 0.05$).
* represents significant differences in exercise conditions depending on the moment (t1, t2, t3) (*Time x Exercise*, $p \leq 0.05$).
+ represents significant differences between CO and RAU depending on the exercise performed and moment (t1, t2, t3) (*Time x Group x Exercise*, $p \leq 0.05$).
# represents significant differences between CO and RAU depending on the participant's sex and moment (t1, t2, t3) (*Time x Group x Sex*, $p \leq 0.05$).
++ represents significant differences in the interaction *Time x Group x Exercise x Sex* ($p \leq 0.05$).

addition, the RAU group reported smoking a higher number of tobacco cigarettes per day ($F_{(1,\ 100)} = 10.46$, $p = 0.002$, $\eta_p^2 = 0.10$). Higher impulsivity was also observed in the RAU group, reflected in higher UPPS total scores ($F_{(1,\ 100)} = 7.99$, $p = 0.006$, $\eta_p^2 = 0.08$) and in the subscales of lack of perseverance ($F_{(1,\ 100)} = 4.54$, $p = 0.04$, $\eta_p^2 = 0.05$), lack of premeditation ($F_{(1,\ 100)} = 6.65$, $p = 0.01$, $\eta_p^2 = 0.07$), and positive urgency ($F_{(1,\ 100)} = 5.10$, $p = 0.03$, $\eta_p^2 = 0.05$). No main effects of sex were found for any variable. However, a significant GROUP × SEX interaction was observed for the AUDIT-C (item 3) ($F_{(1,\ 100)} = 1.97$, $p = 0.001$, $\eta_p^2 = 0.06$) and for the emotional interference subscale of the DERS ($F_{(1,\ 100)} = 4.48$, $p = 0.04$, $\eta_p^2 = 0.05$). Specifically, women in the RAU group showed higher emotional interference scores than men in the same group ($p = 0.008$), whereas no such sex differences were observed in the CO group. No significant differences were observed in the levels (min/week) of vigorous (VPA), moderate (VPM), or total physical activity (totPA) between the CO and RAU groups (VPA: $F_{(1,100)} = 3.45$, $p = 0.06$; VPM: $F_{(1,100)} = 0.16$, $p = 0.69$; totPA: $F_{(1,100)} = 3.59$, $p = 0.06$), between sexes (VPA: $F_{(1,100)} = 0.72$, $p = 0.4$; VPM: $F_{(1,100)} = 0.21$, $p = 0.65$; totPA: $F_{(1,100)} = 0.02$, $p = 0.89$), not in the interaction between *Group x Sex* (VPA: $F_{(1,100)} = 0.15$, $p = 0.7$; VPM: $F_{(1,100)} = 0.003$, $p = 0.96$; totPA: $F_{(1,100)} = 2.63$, $p = 0.11$).

Regarding anthropometric measures, women exhibited a lower waist-to-hip ratio than men, irrespective of group ($F_{(1,\ 100)} = 5.60$, $p = 0.02$, $\eta_p^2 = 0.06$). No other anthropometric variables showed significant differences between groups (see Table 1 and Fig. 2 for further details).

3.2. *Differential effects of exercise on cognitive and psychological-related variables*

Repeated measures ANOVA revealed a significant *Time x Group x Exercise* interaction for the number of words produced in the phonological fluency test ($F_{(1,\ 89)} = 6.10$, $p = 0.016$, $\eta_p^2 = 0.07$). Post hoc analyses showed that phonological fluency improved in the RAU group after intense exercise ($p = 0.004$). To control potential practice effects, change scores have been included ($\%\Delta = ((\bar{X}\text{ post-}\ \bar{X}\text{ pre})/\ \bar{X}\text{ pre}) * 100$). The rate of change for this difference was higher for the RAU group than for the CO group after a cycling session (19.59 versus 7.93, $p = 0.009$). The cycling session also reduced the number of omissions in the *d2* test, independently of GROUP and SEX (*Time x Exercise*: $F_{(1,\ 89)} = 4.24$, $p = 0.04$, $\eta_p^2 = 0.05$; post hoc: $p = 0.024$). The rate of change for this difference was higher for the cycling session than the stretching (−10.87 versus −2.68, $p = 0.02$). In addition, state anxiety decreased after the stretching condition in both groups (*Time x Exercise*: $F_{(1,\ 89)} = 6.60$, $p = 0.012$, $\eta_p^2 = 0.07$; post hoc: $p = 0.05$). No significant effects were found for the remaining variables (see Table 2 and Fig. 2 for details).

3.3. *Exercise-related variables and psychophysiological results*

3.3.1. *Cycling exercise increased physiological activation and effort, with group and sex differences*

Lactate levels increased significantly only after sub-maximal exercise compared to stretching condition regardless of the GROUP and SEX

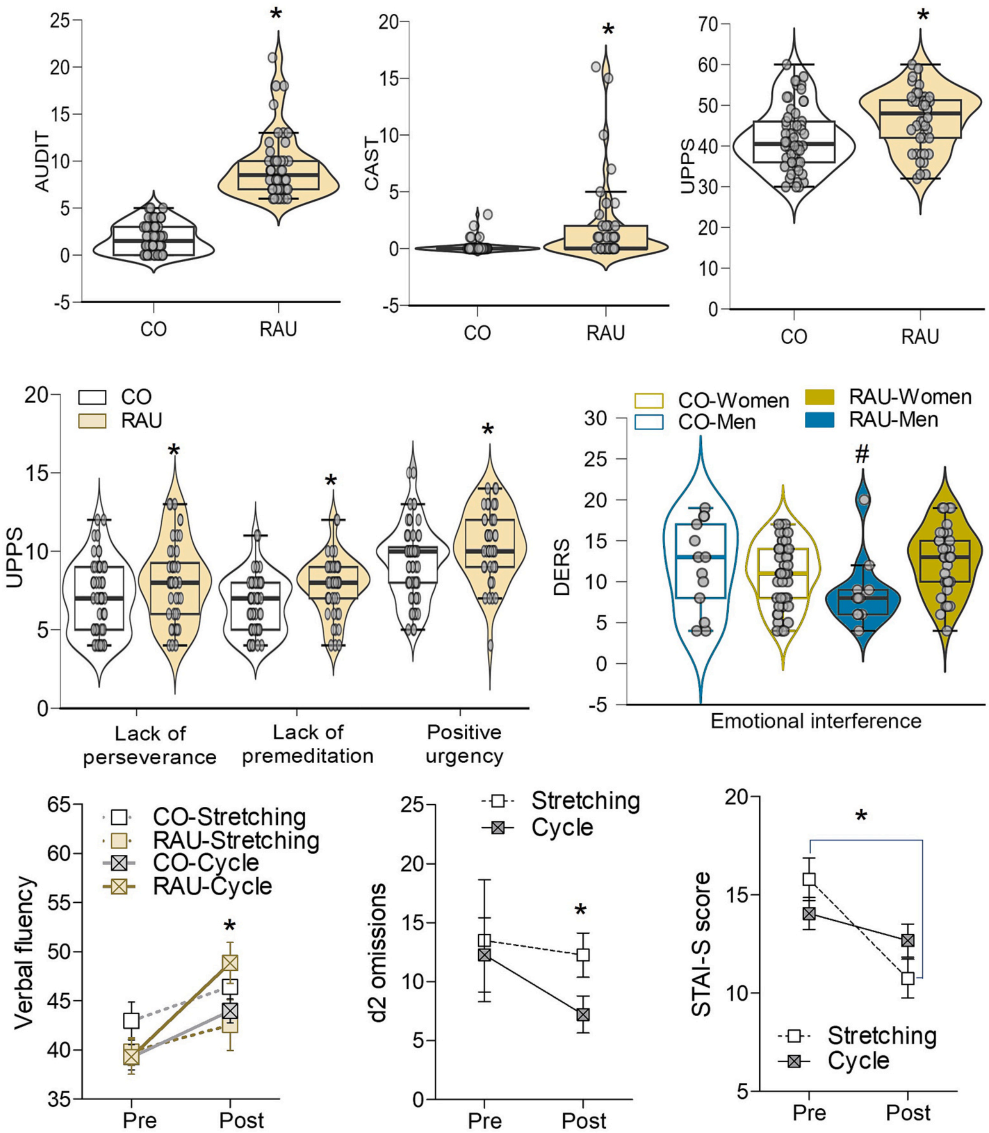

Fig. 2. Group differences in substance use, impulsivity, emotional regulation, and cognitive performance. The RAU group showed higher AUDIT ($p = 0.001$), CAST ($p = 0.001$) and UPPS scores ($p = 0.006$) than the CO group, including lack of perseverance ($p = 0.04$), premeditation ($p = 0.01$), and positive urgency ($p = 0.03$), with no main sex effects. A GROUP × SEX interaction was found for emotional interference ($p = 0.04$), with higher scores in RAU women ($p = 0.008$). Phonological fluency improved in the RAU group after intense exercise ($p = 0.004$). Stretching reduced state anxiety in both groups ($p = 0.05$) and cycling reduced omissions regardless of sex or group ($p = 0.024$). All data are mean ± S.E.M. and statistically significant differences were considered when $p \leq 0.05$ (*).

factors (*Time x Exercise*: $F_{(1, 92)} = 45.22$, $p = 0.001$, $\eta_p^2 = 0.3$). Regarding RPE variable, interactions *Time x Group x Sex*, as well as *Time x Group x Exercise* were significant ($F_{(2, 192)} = 6.63$, $p = 0.002$ $\eta_p2 = 0.07$; $F_{(2, 192)} = 3.91$, $p = 0.02$ $\eta_p2 = 0.04$, respectively) revealing that at t2 and t3 of the cycling session, RAU men showed higher perceived effort than CO men ($p = 0.03$; $p = 0.02$) and regardless of SEX at t3 in the cycling session, RAU group showed higher RPE score than the CO group ($p = 0.004$). In contrast to the higher effort perception, at 8 and 12 min of cycling session, RAU men showed lower watts compared to the CO men (*Time x Group x Sex*: $F_{(2,112)} = 4.05$, $p = 0.01$, $\eta_p2 = 0.05$; $p = 0.03$ and $p = 0.02$, respectively).

Concerning HRRmax (%), we found a significant interaction *Exercise x Sex* ($F_{(1, 100)} = 4.66$, $p = 0.03$, $\eta_p^2 = 0.05$) indicating that women which performed cycling exercise reached higher HRRmax (%) compared to men ($p = 0.03$). The cycling exercise produced the highest HR, regardless of participants' sex or group ($F_{(1, 100)} = 184.52$, $p = 0.001$, $\eta_p^2 = 0.66$; post hoc: $p = 0.001$). In addition, the main effect of SEX was significant ($F_{(1, 100)} = 4.19$, $p = 0.04$, $\eta_p^2 = 0.66$; post hoc: $p = 0.04$), indicating that women reached higher HR values than men. No other interactions among the variables (GROUP, SEX, and EXERCISE) were statistically significant. With respect to the HR achieved at the three time points evaluated during the exercise (t1, t2 and t3), we observed that only the interaction *Time x Exercise* was significant ($F_{(2, 190)} = 203.39$, $p = 0.001$, $\eta_p^2 = 0.68$) showing that cycling exercise induced higher HR than stretching at t2 ($p = 0.001$) and t3 ($p = 0.001$).

3.3.2. Cycling exercise induced changes in HRV and hormonal related responses

Time x Exercise interactions were significant for both RMSSD and SDNN ($F_{(2, 166)} = 16.52$, $p = 0.001$, $\eta_p^2 = 0.17$; $F_{(2, 166)} = 19.66$, $p = 0.001$, $\eta_p^2 = 0.20$), showing that cycling exercise reduced RMSSD and SDNN at t3 ($p = 0.004$; $p = 0.005$). SDNN was also reduced at t2 after intense cycling compared to stretching, regardless of GROUP or SEX ($p = 0.002$). For sAA hormonal levels, a significant *Time x Exercise* interaction was observed ($F_{(2, 168)} = 3.78$, $p = 0.03$, $\eta_p^2 = 0.04$), with higher sAA levels at t2 during cycling, independently of group and sex ($p =$

0.02). A significant *Time x Group x Exercise x Sex* interaction was found for sCORT ($F_{(2,\ 158)} = 4.77$, $p = 0.01$, $\eta_p^2 = 0.06$). Post hoc analyses indicated that in the CO group, women had lower sCORT levels at t3 during the stretching session ($p = 0.01$), whereas RAU men showed higher sCORT at t2 during cycling ($p = 0.01$), while no sex or group differences were found at t1. No additional statistically significant post hoc differences were observed for sCORT beyond those already reported. The ratio of sAA to sCORT (AOCg) did not show significant differences across any experimental conditions (more details in Table 2 and Fig. 3).

3.3.3. EEG oscillatory and aperiodic activity varied by group and sex depending on exercise conditions

Regarding EEG power results, we observed that RAU men showed higher delta oscillatory activity across the central area from pre- to post-stretching exercise compared to CO men (*Group x Sex x Exercise*: $F_{(1,\ 90)} = 3.73$, $p = 0.05$, $\eta_p^2 = 0.04$; $p = 0.014$; $q = 0.028$). The interaction *Group x Exercise* was also significant revealing that the CO group that performed stretching exercises had a higher theta oscillatory activity across the anterior ($F_{(1,\ 90)} = 6.84$, $p = 0.01$, $\eta_p^2 = 0.07$; $p = 0.007$; $q = 0.028$), the left lateral ($F_{(1,\ 90)} = 5.27$, $p = 0.02$, $\eta_p^2 = 0.06$; $p = 0.04$; $q = 0.04$) and the posterior ROIs ($F_{(1,\ 90)} = 6.67$, $p = 0.001$, $\eta_p^2 = 0.07$; $p = 0.049$; $q = 0.04$) from pre- to post-session (Fig. 4). Concerning EEG aperiodic component results, slope and offset values were obtained for each region of interest and group. Our results suggest that CO women who underwent the stretching condition had a higher change rate in their central ROI slope (*Group x Sex x Exercise*: $F_{(1,89)} = 7.913$ $p = 0.006$, $\eta_p^2 = 0.08$). A *Group x Sex x Exercise* interaction was also found in the posterior ROI offset ($F_{(1,92)} = 7.956$, $p = 0.006$, $\eta_p^2 = 0.08$), where RAU women who stretched had a higher offset change rate.

4. Discussion

To our knowledge, this is the first study focused on investigating the psychological, cognitive and psychophysiological responses of young adults with RAU, but not meeting criteria for binge drinking as indicated by the AUDIT-C (item 3, see Table 1) and a matched healthy CO group after a single short bout of aerobic exercise compared to a stretching exercise condition.

4.1. The RAU group showed higher scores in several impulsivity-related variables

Our results showed that, as in previous studies by our group (Sampedro-Piquero et al., 2024), both RAU men and women scored higher in the UPPS-P subscales of lack of perseverance and premeditation, as well as in positive urgency. Several studies have described a positive association between high impulsivity and drug use in young people (Rømer Thomsen et al., 2018). These results suggest that RAU men and women with low scores for premeditation may neglect to consider the negative consequences of alcohol use before engaging in drinking (Shin et al., 2012). Moreover, positive urgency was associated with alcohol-related problems suggesting the need to develop interventions to help young people avoid alcohol consumption when experiencing positive emotional states (Smith and Cyders, 2016). It would therefore be of interest to these young people to learn to replace RAU with brief exercise practice in response to these emotional states. We did not observe a reduction in the desire for alcohol consumption in the RAU group. Some authors have suggested that craving, or the desire to consume, is uncommon among young individuals, as they typically do not have a long history of dependence or severe substance use in most

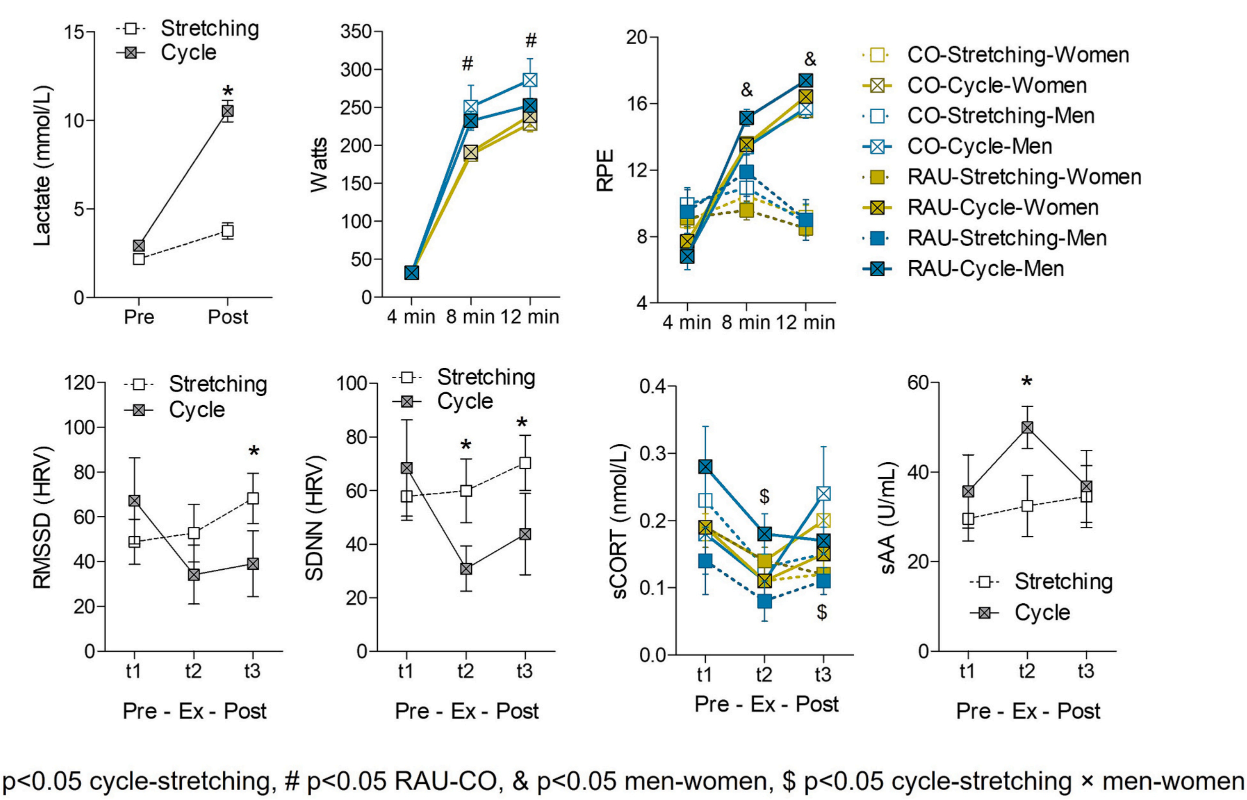

Fig. 3. Physiological and hormonal responses to a single short bout of aerobic exercise and stretching conditions across time, group, and sex. Lactate levels increased only after cycling, regardless of group and sex ($p = 0.001$). RAU men showed lower watts than CO men at 8 and 12 min ($p = 0.03$, $p = 0.02$) and reported higher RPE than RAU women ($p = 0.03$, $p = 0.04$). Cycling reduced RMSSD and SDNN at t3 ($p < 0.01$), and SDNN was also lower at t2 ($p = 0.002$), independently of group and sex. For sCORT, a Time × Group × Exercise × Sex interaction was found ($p = 0.01$), with lower levels in CO women at t3 (stretching) and higher levels in RAU men at t2 (cycling). sAA increased at t2 during cycling ($p = 0.02$). All data are mean ± S.E.M. and statistically significant differences were considered when $p \leq 0.05$ (* $p \leq 0.05$ cycle-stretching, # $p \leq 0.05$ RAU-CO, & $p \leq 0.05$ men-women, \$ $p \leq 0.05$ cycle-stretching × men-women).

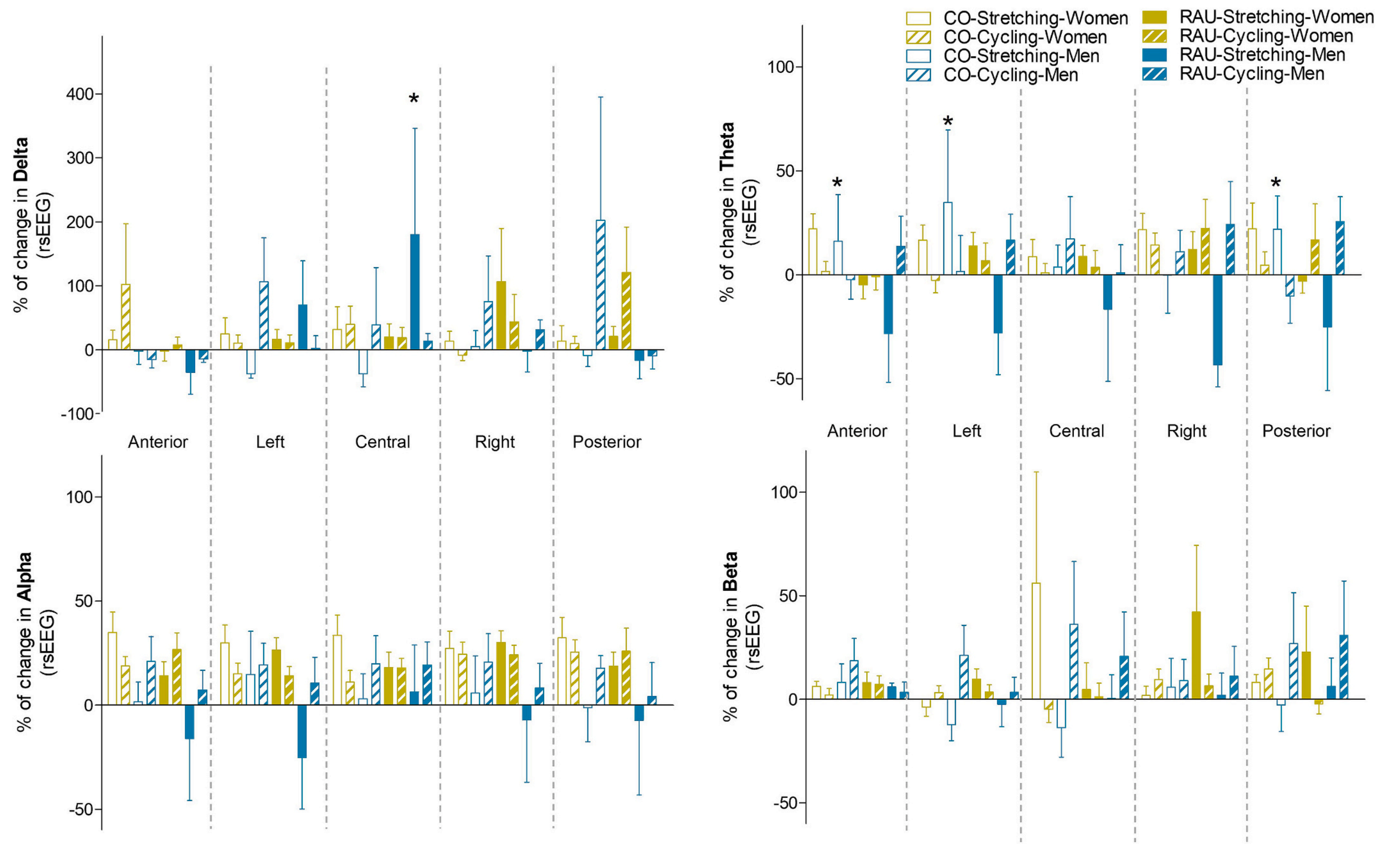

Fig. 4. Overall effects of exercise session on post as compared to pre rsEEG (percentage of change = [(post-pre)/pre] × 100)). Men in the RAU group exhibited significantly higher central delta activity from pre- to post-stretching exercise compared to men in the CO group ($p = 0.014$). Additionally, the CO group which performed stretching exercises showed significantly increased theta activity in the anterior, left lateral, and posterior regions from pre- to post-session all $p < 0.05$. The ROIs correspond to anterior, central, left and right lateral and posterior. All data are mean ± S.E.M. and statistically significant differences were considered when $p \leq 0.05$ (*).

cases (Fernandez-Artamendi and Weidberg, 2016). Therefore, the application or assessment of this symptom appears to be of questionable usefulness in relation to risky consumption, as is the case with our sample.

4.2. The RAU men showed higher perceived effort and sCORT levels were higher in the RAU group after a cycling session

It is also noteworthy that, although all subjects were selected based on the criterion of engaging in less than 150 min of weekly exercise and no differences were found between groups in the min/week of physical activity (vigorous or moderate), the data recorded for watts achieved and perceived exertion suggest that the men in the RAU group were in poorer physical condition. They reported a high level of effort during the middle and final stages of intense exercise (8 and 12 min), despite achieving lower power outputs than the CO group (see Table 2). Regarding hormonal results, previous studies have found that short environmentally demanding events, i.e. acute stress or exercise (Strahler et al., 2017), result in an immediate peak of sAA (Weiss et al., 2019) and subsequent sCORT increase (Biedermann et al., 2017). Our results are aligned with both time and exercise effects on sAA and sCORT, but additionally, showed a relevant interaction of alcohol use and sex on sCORT levels, although owing to the imbalance in the number of men and women in the study, these data should be interpreted with caution. Thus, in our study, RAU men showed higher sCORT levels after the cycling condition compared to CO, which is consistent with the significantly higher perceived effort (RPE) found in this group. This suggests that RAU among young men could be associated with an enhanced reactivity of the HPA axis under exercise conditions. This finding contrasts with the alcohol-related blunted cortisol response reported in previous studies (Chen et al., 2020; Hagan et al., 2019). This result could provide further support that HPA axis changes may play a role in increasing AUD risk among young adults with RAU who do not yet meet diagnostic criteria for AUD and may influence their continued use and alcohol relapse risk (Sinha et al., 2011). However, other research has found no change in cortisol response (Bibbey et al., 2015). Moreover, sCORT release may differ depending on the nature of the stressor, whether it is perceived as a threat or a challenge (Caplin et al., 2021; Wunsch et al., 2019). In this context, for sedentary individuals such as those in our sample, acute exercise can initially function as a physiological challenge, as the body must adapt and respond to this demanding situation (Hackney and Walz, 2013). In fact, this specific exercise-induced sCORT release could eventually be beneficial for brain and cognition (Chen et al., 2017), suggesting an interesting outcome for potential interventions. Finally, since fitness is known to modulate hormonal responses to exercise, incorporating objective fitness measurements (e.g., VO_2peak, standardized submaximal tests) would allow us to control for this confounding variable.

4.3. The single short bout of cycling transiently improved verbal fluency in the RAU group, while the stretching session induced greater changes in rsEEG activity

Due to the modest effect sizes observed and the fact that our exercise protocol was based on a single-session design, we considered that the cognitive improvements and the associated brain changes found were transient rather than representing permanent alterations in brain function. Regarding our cognitive performance results, we observed that a cycling session transiently enhanced phonological verbal fluency in the RAU group, which is known to be related to frontal lobe functioning (Cipolotti et al., 2020). It is a noteworthy and relatively unexplored finding which cannot be explained by the practice effect due the nature of the task which has shown to be robust against this effect (Bartels et al., 2010; Basso et al., 1999). Metzger et al. (2017) conducted one of the few studies that examined the relationship between exercise performance and verbal performance. They found cerebral blood flow to be increased to both the frontal and temporal areas, especially in Broca's area during movement. These findings demonstrate that exercise not only elevates cerebral blood flow in the PFC, but that this hemodynamic response extends to several other cortical regions, including those associated with verbal processing. Other studies have also found that both single-bout and long-term exercise facilitate creativity and divergent thinking which are also related to better execution in fluency tasks (Gondola and Tuckman, 1985, Gondola, 1986, Gondola, 1987). Interestingly, a recent study carried out by Khanna et al. (2025) has also observed that young adults who had engaged in vigorous exercise produced more words during the fluency task, and they were lower-frequency and shorter after exercise as compared to before exercise. These results suggest that verbal processing could be highly influenced by cardiovascular exertion enhancing verbal processing in the form of greater and deeper lexical access as compared to before exercise or stretching conditions. Moreover, the high rate of change observed in the RAU group after the cycling session in the verbal fluency task suggests a limited learning effect in this test (see Results section). Concerning the rest of cognitive results (Table 2), we observed a general enhanced performance regardless of the GROUP and EXERCISE, and for that reason, we cannot exclude a possible practice effect, despite having selected tests which seem to be less sensitive to *testing* effect (Roediger and Karpicke, 2006). For instance, complex working memory tasks known as transformation span tasks, such as the Letters and Numbers Sequencing test applied in our study, have shown smaller retest effects than N-back, updating or coordination tasks being more recommended in this sort of study (Scharfen et al., 2018). However, as another possible explanation for the general improvement in cognitive performance observed in the stretching CO group, it is plausible that there were certain expectations of improvement (expectation-driven placebo effects) within this group that might not have been observed with a passive CO group (reading or watching a movie) (Szabo, 2013; Oberste et al., 2016). Nevertheless, our active CO group, which performed the stretching exercise, did not display changes in variables related to effort, such as lactate (Borg et al., 1987; Haase et al., 2024) and HRV-related measures (Banach et al., 2004; Lamberts et al., 2024) suggesting that it was an appropriate experimental CO group (Oberste et al., 2017). Finally, and in contrast to the expected results, a previous study also found that intense physical activity did not affect cognitive performance, and the participant could sustain mental effort until failure at the same level as the CO group (Holgado et al., 2024). This result agrees with our findings as we did not observe a negative impact of cycling exercise on cognition despite the volunteers' effort.

Although physical exercise has been shown to positively affect brain function and cognition, the underlying neurophysiological mechanisms remain relatively under-explored. Different types and intensities of physical exercise are generally expected to elicit distinct effects on brain electrical activity (Gramkow et al., 2020), as each exercise modality involves specific patterns of movement, cognitive demands, and neural network activation. These differences, in turn, are likely to engage distinct brain regions and modulate various EEG frequency bands. The present research observed that stretching sessions induced an enhancement of delta and theta activity in different ROIs, although we would like to note that the effect sizes observed for these differences were in the small-to-moderate range. Specifically, we observed higher delta activity over the central cortex in the RAU group compared to the CO group. Delta oscillations are typically associated with deep sleep and relaxation states (Torres-Herraez et al., 2022). Therefore, changes in delta activity following the stretching session may reflect a state of increased self-reflection, positive emotions, and calmness during the rest period (Bodda and Diwakar, 2025; Imagawa et al., 2023; Malhotra et al., 2024). This finding may be particularly relevant, as enhanced delta activity in fronto-central regions has been linked to improved self-regulation and longer periods of abstinence, suggesting that this type of exercise could serve as a useful strategy to support these outcomes (Januszko et al., 2021).

However, we also observed a theta activity increase after stretching in the CO group compared to the RAU group, regardless of the participant's sex, in different ROIs (anterior, left lateral and posterior). Previous studies have shown that theta activity in the mid-frontal cortex plays a key role in detecting when cognitive control or focused attention is needed. This activity appears to be sensitive to physical movement, as different types of movement – and even slight variations within the same movement - can modulate frontal theta power (Müller et al., 2025). These findings support the hypothesis proposed by Sauseng et al. (2007), which suggests that anterior theta activity reflects the amount of mental effort required during physical tasks. In this sense, our stretching session was composed of different and coordinated movements to induce stretching in different parts of the body, so it could explain the observed results. Along with this, theta waves are typically linked to states of deep relaxation (Kochupillai, 2015) and play a crucial role in sensorimotor integration, which is also needed during stretching exercises (Bland and Oddie, 2001; Hosang et al., 2022).

Contrary to expectations, the stretching session induced greater changes in brain activity than our high-intensity exercise session. The greater changes in brain activity observed after the stretching session, compared to high intensity cycling, may be explained by several factors. Stretching promotes parasympathetic activation and relaxation, which can enhance slow-wave activity (delta and theta), while intense exercise induces sympathetic dominance and physiological stress that temporarily suppresses such effects (Imagawa et al., 2023). Additionally, stretching encourages interoceptive awareness and mindfulness-like states, such as calmness and self-reflection, that are linked to increased activity in slow-frequency bands (Malhotra et al., 2024). For sedentary individuals, these mentally engaging aspects of stretching may have a more pronounced neural impact than the physically demanding nature of intense cycling, which could induce fatigue or cognitive overload, limiting post-exercise neural modulation (Labelle et al., 2013). Therefore, future research should take into consideration the variability in brain activity that different exercise modes and intensities can elicit, as well as participants' fitness levels, with the aim of optimizing exercise adherence (Hallgren et al., 2018).

Although participants were questioned and evaluated regarding their physical condition and the possible presence of drowsiness or dizziness following both exercise protocols, alternative explanations for the observed findings cannot be entirely excluded. In this regard, previous research has associated increases in slow oscillatory activity (theta and delta) with states of mental fatigue (Jap et al., 2009; Wascher et al., 2014), as well as with reduced vigilance or arousal during wakefulness (He et al., 2025; Luna et al., 2023). However, and in contrast to the findings reported by Luna et al. (2023), the increase in frontal delta/theta activity observed in our present study was not accompanied by impairments in attentional or executive performance in the subsequent cognitive tasks administered to the participants. With respect to this issue, the literature presents two opposing interpretations of theta oscillations. On the one hand, theta activity (4–8 Hz) has been described in conditions of alert cognitive control, commonly referred to as frontal midline theta; on the other hand, it has also been observed under conditions of drowsiness during sleep deprivation, where it is considered a marker of increasing sleep pressure during wakefulness. A recent study demonstrated that both cognitive load and sleep deprivation were associated with increased theta power in medial prefrontal cortical regions; however, sleep deprivation additionally produced more widespread theta increases across several other, predominantly frontal, areas

(Snipes et al., 2022).

5. Conclusions

In conclusion, this study provides new evidence on the psychological, cognitive, and neurophysiological effects of a single bout of physical exercise in young adults with RAU compared to healthy controls. Notably, the cycling session was associated with transient improvements in verbal fluency in the RAU group, suggesting that even a brief period of aerobic exercise can facilitate cognitive functions related to frontal lobe activity. At the same time, and contrary to initial expectations, the stretching session induced more pronounced changes in rsEEG activity, particularly in the delta and theta frequency bands. Hence, acute cycling may be useful for transiently enhancing certain cognitive functions, whereas stretching-based protocols could be more acceptable and helpful for inducing relaxation or self-regulatory brain states in sedentary RAU youth. These findings highlight the importance of tailoring exercise-based interventions to the specific psychological and physiological profiles of young adults with RAU. A limitation of the present study is the absence of an objective measure of cardiorespiratory fitness (e.g., VO_2peak or a standardized submaximal test). Although physical activity level did not differ between CO and RAU groups at baseline, self-reported activity does not fully capture individual differences in fitness. Therefore, unmeasured variability in cardiorespiratory fitness may still have influenced autonomic and hormonal responses to the exercise conditions and cannot be completely ruled out as a potential confounding factor.

CRediT authorship contribution statement

A.S. Elliott: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **B. Regodón-Virgos:** Writing – original draft, Methodology, Investigation, Formal analysis. **A. Cordellat-Marzal:** Writing – original draft, Validation, Methodology, Investigation. **E. Stern:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **A. Capilla:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **R.D. Moreno-Fernández:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **P. Sampedro-Piquero:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that there are no conflicts of interest.

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Data availability

The data that support the findings of this study are available on request from the corresponding author.

References

Ali, N., Pruessner, J.C., 2012. The salivary alpha amylase over cortisol ratio as a marker to assess dysregulations of the stress systems. Physiol. Behav. 106, 65–72. https://doi.org/10.1016/j.physbeh.2011.10.003.

Allen, J.P., Litten, R.Z., Fertig, J.B., Babor, T., 1997. A review of research on the Alcohol Use Disorders Identification Test (AUDIT). Alcohol. Clin. Exp. Res. 21 (4), 613–619.

Antón-Toro, L.F., Bruña, R., Suárez-Méndez, I., Correas, Á., García-Moreno, L.M., Maestú, F., 2021. Abnormal organization of inhibitory control functional networks in future binge drinkers. Drug Alcohol Depend. 218, 108401. https://doi.org/10.1016/j.drugalcdep.2020.108401.

Atienza, F.L., Moreno, Y., Balaguer, I., 2000. Análisis de la dimensionalidad de la Escala de Autoestima de Rosenberg en una muestra de adolescentes valencianos. *Revista de Psicología*. Universitas Tarraconensis XXII (1-2), 29–42.

Avdija, A., 2022. Substance use and stress-induced cognitive impairment: the causes of anxiety and depression among college students. J. Drug Educ. 51 (3–4), 70–81. https://doi.org/10.1177/00472379221148384.

Banach, T., Grandys, M., Juszczak, K., Kolasińska-Kloch, W., Zoładź, J., Laskiewicz, J., Thor, P.J., 2004. Heart rate variability during incremental cycling exercise in healthy untrained young men. Folia Med. Cracov. 45 (1–2), 3–12.

Bardo, M.T., Compton, W.M., 2015. Does physical activity protect against drug abuse vulnerability? Drug Alcohol Depend. 153, 3–13. https://doi.org/10.1016/j.drugalcdep.2015.05.037.

Bartels, C., Wegrzyn, M., Wiedl, A., Ackermann, V., Ehrenreich, H., 2010. Practice effects in healthy adults: a longitudinal study on frequent repetitive cognitive testing. BMC Neurosci. 11, 118. https://doi.org/10.1186/1471-2202-11-118.

Basso, M.R., Bornstein, R.A., Lang, J.M., 1999. Practice effect of commonly used measures of executive across twelve months. Clin. Neuropsychol. 13, 283–292. https://doi.org/10.1076/clin.13.3.283.1743.

Bekkos, C.H., Sujan, M.A.J., Stunes, A.K., Tari, A.R., Aagård, N., Brobakken, C.L., Brevig, M.S., Syversen, U., Wang, E., Mosti, M.P., 2025. Acute effects of a single bout of high-intensity strength and endurance exercise on cognitive biomarkers in young adults and elderly men: a within-subjects crossover study. J. Transl. Med. 23 (1), 685. https://doi.org/10.1186/s12967-025-06685-y.

Berner, M.M., Kriston, L., Bentele, M., Härter, M., 2007. The alcohol use disorders identification test for detecting at-risk drinking: a systematic review and meta-analysis. J. Stud. Alcohol Drugs 68 (3), 461–473. https://doi.org/10.15288/jsad.2007.68.461.

Bhambhani, Y., Malik, R., Mookerjee, S., 2007. Cerebral oxygenation declines at exercise intensities above the respiratory compensation threshold. Respir. Physiol. Neurobiol. 156 (2), 196–202. https://doi.org/10.1016/j.resp.2006.08.009.

Bibbey, A., Phillips, A.C., Ginty, A.T., Carroll, D., 2015. Problematic Internet use, excessive alcohol consumption, their comorbidity and cardiovascular and cortisol reactions to acute psychological stress in a student population. J. Behav. Addict. 4 (2), 44–52. https://doi.org/10.1556/2006.4.2015.006.

Biedermann, S.V., Biedermann, D.G., Wenzlaff, F., Kurjak, T., Nouri, S., Auer, M.K., Wiedemann, K., Briken, P., Haaker, J., Lonsdorf, T.B., Fuss, J., 2017. An elevated plus-maze in mixed reality for studying human anxiety-related behavior. BMC Biol. 15 (1), 125. https://doi.org/10.1186/s12915-017-0463-6.

Bland, B.H., Oddie, S.D., 2001. Theta band oscillation and synchrony in the hippocampal formation and associated structures: the case for its role in sensorimotor integration. Behav. Brain Res. 127 (1–2), 119–136. https://doi.org/10.1016/S0166-4328(01)00358-8.

Blume, A.W., Marlatt, G.A., Schmaling, K.B., 2000. Executive cognitive function and heavy drinking behavior among college students. Psychol. Addict. Behav. 14 (3), 299–302.

Bodda, S., Diwakar, S., 2025. Interconnections and global transitions among functional states encode activity-related dynamics as brain topology changes after yoga training. Sci. Rep. 15, 16845 (2025). https://doi.org/10.1038/s41598-025-00134-y.

Borg, G., Hassmén, P., Lagerström, M., 1987. Perceived exertion related to heart rate and blood lactate during arm and leg exercise. Eur. J. Appl. Physiol. Occup. Physiol. 56 (6), 679–685. https://doi.org/10.1007/BF00424810.

Brickenkamp, R., Cubero, N.S., 2002. D2: Test de atención. Spain, TEA Ediciones, Madrid.

Broman-Fulks, J.J., Berman, M.E., Rabian, B.A., Webster, M.J., 2004. Effects of aerobic exercise on anxiety sensitivity. Behav. Res. Ther. 42 (2), 125–136. https://doi.org/10.1016/S0005-7967(03)00103-7.

Brown, R.A., Prince, M.A., Minami, H., Abrantes, A.M., 2016. An exploratory analysis of changes in mood, anxiety and craving from pre- to post-single sessions of exercise, over 12 weeks, among patients with alcohol dependence. Ment. Health Phys. Act. 11, 1–6. https://doi.org/10.1016/j.mhpa.2016.04.002.

Buela-Casal, G., Guillén-Riquelme, A., Seisdedos Cubero, N., 1986. Cuestionario de Ansiedad Estado-Rasgo. TEA Ediciones.

Buriel, Y., Gramunt Fombuena, N., Böhm, P., Rodés, E., Peña-Casanova, J., 2004. Fluencia verbal. Estudio normativo piloto en una muestra española de adultos jóvenes (20 a 49 años). Neurología 19 (4), 153–159.

Cándido, A., Orduna, E., Perales, J.C., Verdejo-García, A., Billeux, J., 2012. Validation of a short Spanish version of the UPPS-P impulsive behaviour scale. Trastornos Adictivos 14, 73–78. https://doi.org/10.1016/S1575-0973(12)70048-X.

Caplin, A., Chen, F.S., Beauchamp, M.R., Puterman, E., 2021. The effects of exercise intensity on the cortisol response to a subsequent acute psychosocial stressor. Psychoneuroendocrinology 131, 105336. https://doi.org/10.1016/j.psyneuen.2021.105336.

Chang, Y.K., Labban, J.D., Gapin, J.I., Etnier, J.L., 2012. The effects of acute exercise on cognitive performance: a meta-analysis. Brain Res. 1453, 87–101. https://doi.org/10.1016/j.brainres.2012.02.068. May 9.

Chen, C., Nakagawa, S., An, Y., Ito, K., Kitaichi, Y., Kusumi, I., 2017. The exercise-glucocorticoid paradox: how exercise is beneficial to cognition, mood, and the brain while increasing glucocorticoid levels. Front. Neuroendocrinol. 44, 83–102. https://doi.org/10.1016/j.yfrne.2016.12.001.

Chen, K., Hollunder, B., Garbusow, M., Sebold, M., Heinz, A., 2020. The physiological responses to acute stress in alcohol-dependent patients: a systematic review. Eur. Neuropsychopharmacol. 41, 1–15. https://doi.org/10.1016/j.euroneuro.2020.09.003.

Chen, P., Gu, Y., Shakila Mazalan, N., Koh, D., Du, W., Luo, Y., 2025. Effects of mind-body exercise intervention on anxiety among women: a meta-analysis. Front. Psychol. 16, 1652882. https://doi.org/10.3389/fpsyg.2025.1652882.

Cipolotti, L., Molenberghs, P., Dominguez, J., Smith, N., Smirni, D., Xu, T., Shallice, T., Chan, E., 2020. Fluency and rule breaking behaviour in the frontal cortex. Neuropsychologia 137, 107308. https://doi.org/10.1016/j.neuropsychologia.2019.107308.

Ciria, L.F., Perakakis, P., Luque-Casado, A., Sanabria, D., 2018. Physical exercise increases overall brain oscillatory activity but does not influence inhibitory control in young adults. Neuroimage 181, 203–210. https://doi.org/10.1016/j.neuroimage.2018.07.009.

Conigrave, K.M., Hall, W.D., Saunders, J.B., 1995. The AUDIT questionnaire: choosing a cut-off score. Alcohol use disorder identification test. Addiction 90 (10), 1349–1356. https://doi.org/10.1046/j.1360-0443.1995.901013496.x.

Conroy, D.E., Ram, N., Pincus, A.L., Coffman, D.L., Lorek, A.E., Rebar, A.L., Roche, M.J., 2015. Daily physical activity and alcohol use across the adult lifespan. Health Psychol. 34 (6), 653–660. https://doi.org/10.1037/hea0000157.

Contel-Guillamón, M., Gual Solé, A., Colom Farran, J., 1999. Test para la identificación de trastornos por uso de alcohol (AUDIT): Traducción y validación del AUDIT al catalán y castellano. Adicciones 11 (4), 337–347. https://doi.org/10.20882/adicciones.613.

Cox, S.S., Lieberthal, J., 2005. Intercountry adoption: young adult issues and transition to adulthood. Pediatr. Clin. N. Am. 52 (5), 1495–1506. https://doi.org/10.1016/j.pcl.2005.06.005.

Craig, C.L., Marshall, A.L., Sjöström, M., Bauman, A.E., Booth, M.L., Ainsworth, B.E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J.F., Oja, P., 2003. International physical activity questionnaire: 12-country reliability and validity. Med. Sci. Sports Exerc. 35 (8), 1381–1395. https://doi.org/10.1249/01.MSS.0000078924.61453.

Cuenca-Royo, A.M., Sanchez-Niubo, A., Forero, C.G., Torrens, M., Suelves, J.M., Domingo-Salvany, A., 2012. Psychometric properties of the CAST and SDS scales in young adult cannabis users. Addict. Behav. 37, 709–715. https://doi.org/10.1016/j.addbeh.2012.02.012.

de Goede, J., van der Mark-Reeuwijk, K.G., Braun, K.P., le Cessie, S., Durston, S., Engels, R.C.M.E., Goudriaan, A.E., Moons, K.G.M., Vollebergh, W.A.M., de Vries, T. J., Wiers, R.W., Oosterlaan, J., 2021. Alcohol and brain development in adolescents and young adults: a systematic review of the literature and advisory report of the Health Council of the Netherlands. Adv. Nutr. 12 (4), 379–1410. https://doi.org/10.1093/advances/nmaa170.

Dietrich, A., 2006. Transient hypofrontality as a mechanism for the psychological effects of exercise. Psychiatry Res. 145 (1), 79–83. https://doi.org/10.1016/j.psychres.2005.07.033. Nov 29.

Dodge, T., Clarke, P., Dwan, R., 2017. The relationship between physical activity and alcohol use among adults in the United States. Am. J. Health Promot. 31 (2), 97–108. https://doi.org/10.1177/0890117116664710.

Dong, B.E., Chen, H., Sakata, K., 2020. BDNF deficiency and enriched environment treatment affect neurotransmitter gene expression differently across ages. J. Neurochem. 154 (1), 41–55. https://doi.org/10.1111/jnc.15017. Epub 2020 Jun 12. Erratum in: J Neurochem. 2021 Jul;158(1):74. doi: 10.1111/jnc.15437. Jul.

Donoghue, T., Haller, M., Peterson, E.J., Varma, P., Sebastian, P., Gao, R., Noto, T., Lara, A.H., Wallis, J.D., Knight, R.T., Shestyuk, A., Voytek, B., 2020. Parameterizing neural power spectra into periodic and aperiodic components. Nat. Neurosci. 23, 1655–1665. https://doi.org/10.1038/s41593-020-00744-x.

Ekkekakis, P., 2009. Illuminating the black box: investigating prefrontal cortical hemodynamics during exercise with near-infrared spectroscopy. J. Sport Exerc. Psychol. 31 (4), 505–553. https://doi.org/10.1123/jsep.31.4.505.

Encuesta sobre alcohol y otras drogas en España, EDADES, 2024. Ministerio de Sanidad, Plan Nacional sobre Drogas.

Fernandes, G.S., Lewis, G., Hammerton, G., Abeysekera, K., Mahedy, L., Edwards, A., Lewis, G., Hickman, M., Heron, J., 2020. Alcohol consumption and internalising disorders in young adults of ALSPAC: a population-based study. J. Epidemiol. Community Health 74 (12), 1023–1027. https://doi.org/10.1136/jech-2020-213922.

Fernandez-Artamendi, S., Weidberg, S., 2016. Avances en la evaluación de las adicciones. Papeles del Psicólogo 37 (1), 52–61.

Flores-Bonilla, A., Richardson, H.N., 2020. Sex differences in the neurobiology of alcohol use disorder. Alcohol Research 40 (2), 04. https://doi.org/10.35946/arcr.v40.2.04.

Garber, C.E., Blissmer, B., Deschenes, M.R., Franklin, B.A., Lamonte, M.J., Lee, I.M., Nieman, D.C., Swain, D.P., American College of Sports Medicine, 2011. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Med. Sci. Sports Exerc. 43 (7), 1334–1359. https://doi.org/10.1249/MSS.0b013e318213fefb.

Gawor, A., Hogervorst, E., Wilcockson, T., 2021. Does an acute bout of moderate exercise reduce alcohol craving in university students? Addict. Behav. 123, 107071. https://doi.org/10.1016/j.addbeh.2021.107071.

Gondola, J.C., 1986. The enhancement of creativity through long- and short-term exercise programs. J. Soc. Behav. Pers. 1 (1), 77–82.

Gondola, J.C., 1987. The effects of a single bout of aerobic dancing on selected tests of creativity. J. Soc. Behav. Pers. 2 (2), 275–278.

Gondola, J.C., Tuckman, B.W., 1985. Effects of a systematic program of exercise on selected measures of creativity. Percept. Mot. Skills 60, 53–54. https://doi.org/10.2466/pms.1985.60.1.53.

Gramkow, M.H., Hasselbalch, S.G., Waldemar, G., Frederiksen, K.S., 2020. Resting state EEG in exercise intervention studies: a systematic review of effects and methods. Front. Hum. Neurosci. 14, 155. https://doi.org/10.3389/fnhum.2020.00155.

Granger, D.A., Kivlighan, K.T., el-Sheikh, M., Gordis, E.B., Stroud, L.R., 2007. Salivary alpha-amylase in biobehavioral research: recent developments and applications. Ann. N. Y. Acad. Sci. 1098, 122–144. https://doi.org/10.1196/annals.1384.008.

Gullett, N., Zajkowska, Z., Walsh, A., Harper, R., Mondelli, V., 2023. Heart rate variability (HRV) as a way to understand associations between the autonomic nervous system (ANS) and affective states: a critical review of the literature. Int. J. Psychophysiol. 192, 35–42. https://doi.org/10.1016/j.ijpsycho.2023.08.001.

Gür, F., Can Gür, G., 2020. Is exercise a useful intervention in the treatment of alcohol use disorder? Systematic review and meta-analysis. Am. J. Health Promot. 34 (5), 520–537. https://doi.org/10.1177/0890117120913169.

Haase, R., Dunst, A.K., Nitzsche, N., 2024. The influence of pedaling frequency on blood lactate accumulation in cycling sprints. Int. J. Sports Med. 45 (8), 608–615. https://doi.org/10.1055/a-2255-5254.

Hackney, A.C., Walz, E.A., 2013. Hormonal adaptation and the stress of exercise training: the role of glucocorticoids. Trends Sport Sci. 20 (4), 165–171.

Hagan, M.J., Modecki, K., Moctezuma Tan, L., Luecken, L., Wolchik, S., Sandler, I., 2019. Binge drinking in adolescence predicts an atypical cortisol stress response in young adulthood. Psychoneuroendocrinology 100, 137–144. https://doi.org/10.1016/j.psyneuen.2018.10.002.

Hallgren, M., Vancampfort, D., Giesen, E.S., Lundin, A., Stubbs, B., 2017. Exercise as treatment for alcohol use disorders: systematic review and meta-analysis. Br. J. Sports Med. 51 (14), 1058–1064. https://doi.org/10.1136/bjsports-2016-096814.

Hallgren, M., Andersson, V., Ekblom, Ö., Andréasson, S., 2018. Physical activity as treatment for alcohol use disorders (FitForChange): study protocol for a randomized controlled trial. Trials 19 (1), 106. https://doi.org/10.1186/s13063-017-2435-0.

Hallgren, M., Herring, M.P., Vancampfort, D., Hoang, M.T., Andersson, V., Andreasson, S., Abrantes, A.M., 2021a. Changes in craving following acute aerobic exercise in adults with alcohol use disorder. J. Psychiatr. Res. 142, 243–249. https://doi.org/10.1016/j.jpsychires.2021.08.007.

Hallgren, M., Vancampfort, D., Hoang, M.T., Andersson, V., Ekblom, Ö., Andreasson, S., Herring, M.P., 2021b. Effects of acute exercise on craving, mood and anxiety in non-treatment seeking adults with alcohol use disorder: an exploratory study. Drug Alcohol Depend. 220, 108506. https://doi.org/10.1016/j.drugalcdep.2021.108506.

He, Z., Zhang, C., Xie, T., Ma, N., 2025. Dynamic neural activity and vigilance impairment during prolonged wakefulness: a resting-state EEG study. Biol. Psychol. 201, 109138. https://doi.org/10.1016/j.biopsycho.2025.109138.

Herbert, C., 2025. Exercising4Cognition: can short bouts of aerobic exercise improve cognitive performance in healthy adults for primary health prevention? Previous findings and suggestions for the future. Healthcare (Basel) 13 (4), 368. https://doi.org/10.3390/healthcare13040368. Feb 10.

Herbert, C., Meixner, F., Wiebking, C., Gilg, V., 2020. Regular physical activity, short-term exercise, mental health, and well-being among university students: the results of an online and laboratory study. Front. Psychol. 11, 509. https://doi.org/10.3389/fpsyg.2020.00509.

Herrera-Díaz, A., Mendoza-Quiñones, R., Melie-Garcia, L., Martínez-Montes, E., Sanabria-Diaz, G., Romero-Quintana, Y., Salazar-Guerra, I., Carballoso-Acosta, M., Caballero-Moreno, A., 2016. Functional connectivity and quantitative EEG in women with alcohol use disorders: a resting-state study. Brain Topogr. 29 (3), 368–381. https://doi.org/10.1007/s10548-015-0467-x.

Hervas, G., Jodar, R., 2008. Adaptación al castellano de la escala de dificultades en regulación emocional. Clínica y Salud 19, 139–156.

Hofmann, S.G., Asnaani, A., Vonk, I.J., Sawyer, A.T., Fang, A., 2012. The efficacy of cognitive behavioral therapy: a review of meta-analyses. Cogn. Ther. Res. 36 (5), 427–440. https://doi.org/10.1007/s10608-012-9476-1.

Holgado, D., Leubaz, L., Ruggeri, P., Borragán, G., Luque-Casado, A., Bekinschtein, T., Sanabria, D., Place, N., 2024. Is Intense Physical Exercise Detrimental for Cognition? A Novel Approach Based on Subjective, Behavioral and Physiological Responses to a Cognitive Effort to Failure to Failure. Preprint. https://doi.org/10.31234/osf.io/tb7qm_v4.

Horenstein, A., Kaplan, S.C., Butler, R.M., Heimberg, R.G., 2021. Social anxiety moderates the relationship between body mass index and motivation to avoid exercise. Body Image 36, 185–192. https://doi.org/10.1016/j.bodyim.2020.11.010.

Hosang, L., Mouchlianitis, E., Guérin, S.M.R., Karageorghis, C.I., 2022. Effects of exercise on electroencephalography-recorded neural oscillations: a systematic review. Int. Rev. Sport Exerc. Psychol. 17 (2), 926–979. https://doi.org/10.1080/1750984X.2022.2103841.

Imagawa, N., Mizuno, Y., Nakata, I., Komoto, N., Sakebayashi, H., Shigetoh, H., Kodama, T., Miyazaki, J., 2023. The impact of stretching intensities on neural and

autonomic responses: implications for relaxation. Sensors (Basel) 23 (15), 6890. https://doi.org/10.3390/s23156890.
Januszko, P., Gmaj, B., Piotrowski, T., Kopera, M., Klimkiewicz, A., Wnorowska, A., Wołyńczyk-Gmaj, D., Brower, K.J., Wojnar, M., Jakubczyk, A., 2021. Delta resting-state functional connectivity in the cognitive control network as a prognostic factor for maintaining abstinence: an eLORETA preliminary study. Drug Alcohol Depend. 218, 108393. https://doi.org/10.1016/j.drugalcdep.2020.108393.
Jap, B.T., Lal, S., Fischer, P., Bekiaris, E., 2009. Using EEG spectral components to assess algorithms for detecting fatigue. Expert Syst. Appl. 36, 2352–2359. https://doi.org/10.1016/j.eswa.2007.12.043.
Kang, J.G., Kim, M.S., 2022. Neuropsychological profile of college students who engage in binge drinking. Front. Psychol. 13, 873654. https://doi.org/10.3389/fpsyg.2022.873654.
Kavcic, V., Daugherty, A.M., Giordani, B., 2021. Post-task modulation of resting state EEG differentiates MCI patients from controls. Alzheimers Dement (Amst) 13 (1), e12153. https://doi.org/10.1002/dad2.12153.
Kearney, C.A., 2008. School absenteeism and school refusal behavior in youth: a contemporary review. Clin. Psychol. Rev. 28 (3), 451–471. https://doi.org/10.1016/j.cpr.2007.07.012.
Khanna, M.M., Guenther, C.L., Eckerson, J.M., Talamante, D., Yeh, M.E., Forby, M., Hopkins, K., Munger, E., Rauh, G., Chelluri, S., Schmidt, C., Walocha, I., Sacco, M., 2025. Vigorous exercise enhances verbal fluency performance in healthy young adults. Brain Sci. 15 (1), 96. https://doi.org/10.3390/brainsci15010096.
Kim, Y.G., Kim, S.E., Lee, J., Hwang, S., Yoo, S.S., Lee, H.W., 2022. Neuromodulation using transcranial focused ultrasound on the bilateral medial prefrontal cortex. J. Clin. Med. 11 (13), 3809. https://doi.org/10.3390/jcm11133809.
Klamert, L., Craike, M., Bedi, G., Kidd, S., Pascoe, M.C., Parker, A.G., 2023. Behaviour change techniques in physical activity-focused interventions for young people at risk of problematic substance use: a systematic review and meta-analysis. Early Interv. Psychiatry 17 (12), 1139–1153. https://doi.org/10.1111/eip.13467.
Kliszczewicz, B., Williamson, C., Bechke, E., McKenzie, M., Hoffstetter, W., 2018. Autonomic response to a short and long bout of high-intensity functional training. J. Sports Sci. 36 (16), 1872–1879. https://doi.org/10.1080/02640414.2018.1423857. Aug.
Kochupillai, V., 2015. Quantitative analysis of EEG signal before and after sudharshana kriya yoga. Int. J. Publ. Mental Health Neurosci. 2 (2), 19–22.
Labelle, V., Bosquet, L., Mekary, S., Bherer, L., 2013. Decline in executive control during acute bouts of exercise as a function of exercise intensity and fitness level. Brain Cogn. 81 (1), 10–17. https://doi.org/10.1016/j.bandc.2012.10.001.
Lakens, D., 2013. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front. Psychol. 4, 863. https://doi.org/10.3389/fpsyg.2013.00863.
Lamberts, R.P., van Erp, T., Javaloyes, A., Eken, M.M., Langerak, N.G., Tam, N., 2024. Reliability of recovery heart rate variability measurements as part of the Lamberts Submaximal Cycle Test and the relationship with training status in trained to elite cyclists. Eur. J. Appl. Physiol. 124 (6), 1659–1668. https://doi.org/10.1007/s00421-023-05385-z.
Lambourne, K., Tomporowski, P., 2010. The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. Brain Res. 1341, 12–24. https://doi.org/10.1016/j.brainres.2010.03.091. Jun 23.
Lardier, D.T., Coakley, K.E., Holladay, K.R., Amorim, F.T., Zuhl, M.N., 2021. Exercise as a useful intervention to reduce alcohol consumption and improve physical fitness in individuals with alcohol use disorder: a systematic review and meta-analysis. Front. Psychol. 12, 675285. https://doi.org/10.3389/fpsyg.2021.675285.
Leasure, J.L., Neighbors, C., Henderson, C.E., Young, C.M., 2015. Exercise and alcohol consumption: what we know, what we need to know, and why it is important. Front. Psychol. 6, 156. https://doi.org/10.3389/fpsyt.2015.00156.
Legleye, S., Karila, L., Beck, F., Reynaud, M., 2007. Validation of the CAST, a general population cannabis abuse screening test. J. Subst. Abus. 12, 233–242. https://doi.org/10.1080/14659890701476532.
Lisha, N.E., Martens, M., Leventhal, A.M., 2011. Age and gender as moderators of the relationship between physical activity and alcohol use. Addict. Behav. 36 (9), 933–936. https://doi.org/10.1016/j.addbeh.2011.04.003.
López-Caneda, E., Cadaveira, F., Correas, A., Crego, A., Maestú, F., Rodríguez Holguín, S., 2017. The brain of binge drinkers at rest: alterations in theta and beta oscillations in first-year college students with a binge drinking pattern. Front. Behav. Neurosci. 11, 168. https://doi.org/10.3389/fnbeh.2017.00168.
Love, A., James, D., Willner, P.A., 1998. Comparison of two alcohol craving questionnaires. Addiction 93, 1091–1102. https://doi.org/10.1046/j.1360-0443.1998.937109113.x.
Luna, F.G., Aguirre, M.J., Martín-Arévalo, E., Ibáñez, A., Lupiáñez, J., Barttfeld, P., 2023. Different oscillatory rhythms anticipate failures in executive and arousal vigilance. Front. Cognit. 2, 1128442. https://doi.org/10.3389/fcogn.2023.1128442.
Malhotra, V., Jiwane, R., Cidral-Filho, F.J., 2024. Comparative analysis of the effects of exercise and kapalbhati pranayama on heart rate variability and electroencephalogram activity: unveiling physiological and cognitive insights. Mymensingh Med. J. 33 (3), 897–907.
Martínez-Calderon, J., Casuso-Holgado, M.J., Muñoz-Fernandez, M.J., Garcia-Muñoz, C., Heredia-Rizo, A.M., 2023. Yoga-based interventions may reduce anxiety symptoms in anxiety disorders and depression symptoms in depressive disorders: a systematic review with meta-analysis and meta-regression. Br. J. Sports Med. 57 (22), 1442–1449. https://doi.org/10.1136/bjsports-2022-106497.
McMorris, T., Tomporowski, P., Audiffren, M. (Eds.), 2009. Exercise and Cognitive Function. Wiley Blackwell. https://doi.org/10.1002/9780470740668.
Metzger, F.G., Ehlis, A.C., Haeussinger, F.B., Schneeweiss, P., Hudak, J., Fallgatter, A.J., Schneider, S., 2017. Functional brain imaging of walking while talking–an fNIRS study. Neuroscience 343, 85–93. https://doi.org/10.1016/j.neuroscience.2016.11.032.
Moore, M.J., Werch, C., 2008. Relationship between vigorous exercise frequency and substance use among first-year drinking college students. J. Am. Coll. Heal. 56 (6), 686–690. https://doi.org/10.3200/JACH.56.6.686-690.
Moreno-Fernández, R.D., García-León, D., Peñas, G., Martín-Romero, R., Buades-Sitjar, F., Sampedro-Piquero, P., 2023. Immersive virtual plus-maze to examine behavior and psychophysiological-related variables in young people with problematic alcohol and cannabis consumption. Neurobiol. Stress 26, 100564. https://doi.org/10.1016/j.ynstr.2023.100564.
Moreno-Fernández, R.D., Bernabéu-Brotons, E., Carbonell-Colomer, M., Buades-Sitjar, F., Sampedro-Piquero, P., 2024. Sex-related differences in young binge drinkers on the neurophysiological response to stress in virtual reality. Front. Public Health 12, 1348960. https://doi.org/10.3389/fpubh.2024.1348960.
Müller, G., Salem, A., Schöllhorn, W.I., 2025. Effects of complex whole-body movements on EEG activity: a scoping review. Front. Psychol. 16, 1547022. https://doi.org/10.3389/fpsyg.2025.1547022.
Mumtaz, W., Vuong, P.L., Xia, L., Malik, A.S., Rashid, R.B.A., 2017. An EEG-based machine learning method to screen alcohol use disorder. Cogn. Neurodyn. 11 (2), 161–171. https://doi.org/10.1007/s11571-016-9416-y.
Murray, N.P., Russoniello, C., 2012. Acute physical activity on cognitive function: a heart rate variability examination. Appl. Psychophysiol. Biofeedback 37 (4), 219–227. https://doi.org/10.1007/s10484-012-9196-z. PMID: 22543813. Dec.
Musselman, J.R.B., Rutledge, P.C., 2010. The incongruous alcohol-activity association: physical activity and alcohol consumption in college students. Psychol. Sport Exerc. 11 (6), 609–618. https://doi.org/10.1016/j.psychsport.2010.07.005.
Nadkarni, A., Garber, A., Costa, S., Wood, S., Kumar, S., MacKinnon, N., Ibrahim, M., Velleman, R., Bhatia, U., Fernandes, G., Weobong, B., Rane, A., 2019. Auditing the AUDIT: a systematic review of cut-off scores for the Alcohol Use Disorders Identification Test (AUDIT) in low- and middle-income countries. Drug Alcohol Depend. 202, 123–133. https://doi.org/10.1016/j.drugalcdep.2019.04.031.
Norouzian, R., Plonsky, L., 2017. Eta- and partial eta-squared in L2 research: a cautionary review and guide to more appropriate usage. Second. Lang. Res. 34 (2), 257–271. https://doi.org/10.1177/0267658316684904.
Oberste, M., Bloch, W., Hubner, S.T., Zimmer, P., 2016. Do reported effects of acute aerobic exercise on subsequent higher cognitive performances remain if tested against an instructed self-myofascial release training control group? A randomized controlled trial. PLoS One 11, e0167818. https://doi.org/10.1371/journal.pone.0167818.
Oberste, M., Hartig, P., Bloch, W., Elsner, B., Predel, H.G., Ernst, B., Zimmer, P., 2017. Control group paradigms in studies investigating acute effects of exercise on cognitive performance-an experiment on expectation-driven placebo effects. Front. Hum. Neurosci. 11, 600. https://doi.org/10.3389/fnhum.2017.00600.
Oostenveld, R., Fries, P., Maris, E., Schoffelen, J.M., 2011. FieldTrip: open-source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. Comput. Intell. Neurosci. 2011, 156869. https://doi.org/10.1155/2011/156869.
Peltier, M.R., Verplaetse, T.L., Mineur, Y.S., Petrakis, I.L., Cosgrove, K.P., Picciotto, M.R., McKee, S.A., 2019. Sex differences in stress-related alcohol use. Neurobiol. Stress 10, 100149. https://doi.org/10.1016/j.ynstr.2019.100149.
Piazza-Gardner, A.K., Barry, A.E., 2012. Examining physical activity levels and alcohol consumption: are people who drink more active? Am. J. Health Promot. 26 (3), e95–104. https://doi.org/10.4278/ajhp.100929-LIT-328.
Pinna, T., Edwards, D.J., 2020. A systematic review of associations between interoception, vagal tone, and emotional regulation: potential applications for mental health, wellbeing, psychological flexibility, and chronic conditions. Front. Psychol. 11, 1792. https://doi.org/10.3389/fpsyg.2020.01792.
Portellano, J.A., Martínez Arias, R.T., 2014. Test de los Senderos. TEA Ediciones, Madrid, Spain.
Pruessner, J.C., Kirschbaum, C., Meinlschmid, G., Hellhammer, D.H., 2003. Two formulas for computation of the area under the curve represent measures of total hormone concentration versus time-dependent change. Psychoneuroendocrinology 28 (7), 916–931. https://doi.org/10.1016/s0306-4530(02)00108-7.
Rodrigues, J., Studer, E., Streuber, S., Meyer, N., Sandi, C., 2020. Locomotion in virtual environments predicts cardiovascular responsiveness to subsequent stressful challenges. Nat. Commun. 11 (1), 5904. https://doi.org/10.1038/s41467-020-19736.
Roediger, H.L., Karpicke, J.D., 2006. Test-enhanced learning: taking memory tests improves long-term retention. Psychol. Sci. 17 (3), 249–255. https://doi.org/10.1111/j.1467-9280.2006.01693.x.
Rømer Thomsen, K., Callesen, M.B., Hesse, M., Kvamme, T.L., Pedersen, M.M., Pedersen, M.U., Voon, V., 2018. Impulsivity traits and addiction-related behaviors in youth. J. Behav. Addict. 7 (2), 317–330. https://doi.org/10.1556/2006.7.2018.22.
Ryan, S.A., Kokotailo, P., COMMITTEE ON SUBSTANCE USE AND PREVENTION, 2019. Alcohol use by youth. Pediatrics 144 (1), e20191357. https://doi.org/10.1542/peds.2019-1357.
Sampedro-Piquero, P., Buades-Sitjar, F., Capilla, A., Zancada-Menéndez, C., González-Baeza, A., Moreno-Fernández, R.D., 2024. Risky alcohol use during youth: impact on emotion, cognitive networks, and resting-state EEG activity. Prog. Neuro-Psychopharmacol. Biol. Psychiatry 132, 110994. https://doi.org/10.1016/j.pnpbp.2024.110994.
Sanchis-Navarro, E., Luna, F.G., Lupiáñez, J., Huertas, F., 2024. Benefits of a light-intensity bout of exercise on attentional networks functioning. Sci. Rep. 14 (1), 25745. https://doi.org/10.1038/s41598-024-77175-2.
Saunders, J.B., Aasland, O.G., Babor, T.F., de la Fuente, J.R., Grant, M., 1993. Development of the Alcohol Use Disorders Identification Test (AUDIT): WHO Collaborative Project on Early Detection of Persons with Harmful Alcohol

Consumption–II. Addiction 88 (6), 791–804. https://doi.org/10.1111/j.1360-0443.1993.tb02093.x.

Sauseng, P., Hoppe, J., Klimesch, W., Gerloff, C., Hummel, F.C., 2007. Dissociation of sustained attention from central executive functions: local activity and interregional connectivity in the theta range. Eur. J. Neurosci. 25, 587–593. https://doi.org/10.1111/j.1460-9568.2006.05286.

Scharfen, J., Jansen, K., Holling, H., 2018. Retest effects in working memory capacity tests: a meta-analysis. Psychon. Bull. Rev. 25 (6), 2175–2199. https://doi.org/10.3758/s13423-018-1461-6.

Sedó, M., 2007. FDT. Test de los Cinco Dígitos. Ediciones TEA.

Shin, S.H., Hong, H.G., Jeon, S.M., 2012. Personality and alcohol use: the role of impulsivity. Addict. Behav. 37 (1), 102–107. https://doi.org/10.1016/j.addbeh.2011.09.006.

Sibley, B.A., Beilock, S.L., 2007. Exercise and working memory: an individual differences investigation. J. Sport Exerc. Psychol. 29 (6), 783–791. https://doi.org/10.1123/jsep.29.6.783. Dec.

Simonton, A.J., Young, C.C., Brown, R.A., 2018. Physical activity preferences and attitudes of individuals with substance use disorders: a review of the literature. Issues Ment. Health Nurs. 39 (8), 657–666. https://doi.org/10.1080/01612840.2018.1429510.

Sinha, R., Fox, H.C., Hong, K.I., Hansen, J., Tuit, K., Kreek, M.J., 2011. Effects of adrenal sensitivity, stress- and cue-induced craving, and anxiety on subsequent alcohol relapse and treatment outcomes. Arch. Gen. Psychiatry 68 (9), 942–952. https://doi.org/10.1001/archgenpsychiatry.2011.49.

Smith, G.T., Cyders, M.A., 2016. Integrating affect and impulsivity: the role of positive and negative urgency in substance use risk. Drug Alcohol Depend. 163 (1), S3–S12. https://doi.org/10.1016/j.drugalcdep.2015.08.038.

Snipes, S., Krugliakova, E., Meier, E., Huber, R., 2022. The theta paradox: 4-8 Hz EEG oscillations reflect both sleep pressure and cognitive control. J. Neurosci. 42 (45), 8569–8586. https://doi.org/10.1523/JNEUROSCI.1063-22.2022.

Spielberger, C.D., Gorsuchm, R.L., Lushene, R.E., 1970. Manual for the State-Trait Anxiety Inventory. Consulting Psychologist Press, Palo Alto.

Stillman, C.M., Cohen, J., Lehman, M.E., Erickson, K.I., 2016. Mediators of physical activity on neurocognitive function: a review at multiple levels of analysis. Front. Hum. Neurosci. 10, 626. https://doi.org/10.3389/fnhum.2016.00626.

Stockings, E., Hall, W.D., Lynskey, M., Morley, K.I., Reavley, N., Strang, J., Patton, G., Degenhardt, L., 2016. Prevention, early intervention, harm reduction, and treatment of substance use in young people. Lancet Psychiatry 3 (3), 280–296. https://doi.org/10.1016/S2215-0366(16)00002-X.

Stoica, T., Knight, L.K., Naaz, F., Patton, S.C., Depue, B.E., 2021. Gender differences in functional connectivity during emotion regulation. Neuropsychologia 156, 107829. https://doi.org/10.1016/j.neuropsychologia.2021.107829.

Strahler, J., Skoluda, N., Kappert, M.B., Nater, U.M., 2017. Simultaneous measurement of salivary cortisol and alpha-amylase: application and recommendations. Neurosci. Biobehav. Rev. 83, 657–677. https://doi.org/10.1016/j.neubiorev.2017.08.015.

Substance Abuse and Mental Health Services Administration, 2025. Key Substance Use and Mental Health Indicators in the United States: Results from the 2024 National Survey on Drug Use and Health (HHS Publication No. PEP25-07-007, NSDUH Series H-60). Center for Behavioral Health Statistics and Quality, Substance Abuse and Mental Health Services Administration.

Szabo, A., 2013. Acute psychological benefits of exercise: reconsideration of the placebo effect. J. Ment. Health 22, 449–455. https://doi.org/10.3109/09638237.2012.734657.

Tanaka, H., Monahan, K.D., Seals, D.R., 2001. Age-predicted maximal heart rate revisited. J. Am. Coll. Cardiol. 37 (1), 153–156. https://doi.org/10.1016/s0735-1097(00)01054-8.

The MathWorks Inc, 2023. MATLAB Version: 23.2.0.2515942 (R2023b). The MathWorks Inc., Natick, Massachusetts. https://www.mathworks.com.

Tomporowski, P.D., Ganio, M.S., 2006. Short-term effects of aerobic exercise on executive processing, memory, and emotional reactivity. Int. J. Sport Exerc. Psychol. 4 (1), 57–72. https://doi.org/10.1080/1612197X.2006.9671784.

Torres, O.V., Estep, J.C., Gwin, M., Aramovich, N.P., Thomas, G., Villalta, L., 2023. Distress symptoms and alcohol consumption: anxiety differentially mediates drinking across gender. Front. Psychol. 14, 1191286. https://doi.org/10.3389/fpsyg.2023.1191286.

Torres-Herraez, A., Watson, T.C., Rondi-Reig, L., 2022. Delta oscillations coordinate intracerebellar and cerebello-hippocampal network dynamics during sleep. J. Neurosci. 42 (11), 2268–2281. https://doi.org/10.1523/JNEUROSCI.1479-21.2021.

Ussher, M., Sampuran, A.K., Doshi, R., West, R., Drummond, D.C., 2004. Acute effect of a brief bout of exercise on alcohol urges. Addiction 99 (12), 1542–1547. https://doi.org/10.1111/j.1360-0443.2004.00919.x.

Venezia, A.C., Quinlan, E., Roth, S.M., 2017. A single bout of exercise increases hippocampal Bdnf: influence of chronic exercise and noradrenaline. Genes Brain Behav. 16 (8), 800–811. https://doi.org/10.1111/gbb.12394. Nov.

Verburgh, L., Königs, M., Scherder, E.J., Oosterlaan, J., 2014. Physical exercise and executive functions in preadolescent children, adolescents and young adults: a meta-analysis. Br. J. Sports Med. 48 (12), 973–979. https://doi.org/10.1136/bjsports-2012-091441.

von der Pahlen, B., Santtila, P., Witting, K., Varjonen, M., Jern, P., Johansson, A., Sandnabba, N.K., 2008. Factor structure of the Alcohol Use Disorders Identification Test (AUDIT) for men and women in different age groups. J. Stud. Alcohol Drugs 69 (4), 616–621. https://doi.org/10.15288/jsad.2008.69.616.

Wascher, E., Rasch, B., Sänger, J., Hoffmann, S., Schneider, D., Rinkenauer, G., Heuer, H., Gutberlet, I., 2014. Frontal theta activity reflects distinct aspects of mental fatigue. Biol. Psychol. 96, 57–65. https://doi.org/10.1016/j.biopsycho.2013.11.010.

Weber, C.S., Thayer, J.F., Rudat, M., Wirtz, P.H., Zimmermann-Viehoff, F., Thomas, A., Perschel, F.H., Arck, P.C., Deter, H.C., 2010. Low vagal tone is associated with impaired post stress recovery of cardiovascular, endocrine, and immune markers. Eur. J. Appl. Physiol. 109 (2), 201–211. https://doi.org/10.1007/s00421-009-1341-x.

Wechsler, D., 2008. Escala de Inteligencia de Wechsler Para Adultos 4th Edición: Manual Técnico y de Interpretación. Spain, Pearson, Madrid.

Weiss, L.R., Venezia, A.C., Smith, J.C., 2019. A single bout of hard RPE-based cycling exercise increases salivary alpha-amylase. Physiol. Behav. 208, 112555. https://doi.org/10.1016/j.physbeh.2019.05.016.

Welford, P., Gunillasdotter, V., Andreasson, S., Herring, M.P., Vancampfort, D., Hallgren, M., 2023. Sticking with it? Factors associated with exercise adherence in people with alcohol use disorder. Addict. Behav. 144, 107730. https://doi.org/10.1016/j.addbeh.2023.107730.

World Health Organization, 2024. Global Patient Safety Report 2024. World Health Organization. https://iris.who.int/handle/10665/376928.

Wu, M., Fan, C., Zhao, X., Zhou, J., Liu, H., Li, H., Zhan, X., Jiang, Z., 2024. The effects of mindfulness-based stress reduction in mental and physical health: is mindful breathing key? Mindfulness 15, 2582–2594. https://doi.org/10.1007/s12671-024-02456-w.

Wunsch, K., Wurst, R., von Dawans, B., Strahler, J., Kasten, N., Fuchs, R., 2019. Habitual and acute exercise effects on salivary biomarkers in response to psychosocial stress. Psychoneuroendocrinology 106, 216–225. https://doi.org/10.1016/j.psyneuen.2019.03.015.

Zhang, L., Chu, C.H., Liu, J.H., Chen, F.T., Nien, J.T., Zhou, C., Chang, Y.K., 2020. Acute coordinative exercise ameliorates general and food-cue related cognitive function in obese adolescents. J. Sports Sci. 38 (8), 953–960. https://doi.org/10.1080/02640414.2020.1737386.