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The effect of caffeine on cognitive processes, sleep and sports performance

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Abstract

Introduction: Caffeine is one of the most frequently used psychostimulants in the world. It is present in many drinks consumed around the world. Its stimulating effect on the central nervous system has been known for years. Moreover, many athletes take it before competitions to achieve better results. The aim of this study is to present the effect of caffeine on cognitive abilities, sleep and performance in sports.

Material and methods: We searched for materials for this work in the Pubmed and Google Scholar databases using the keywords: "caffeine", "caffeine sport", "caffeine sleep", "caffeine brain", "caffeine side effects". Then we analyzed the selected materials.

Aim of the study: The effect of caffeine on cognitive abilities, sleep and sports performance.

Conclusion: Caffeine helps improve concentration and attention, increases physical performance, supports short-term memory, and may also improve mood by stimulating the production of dopamine. However, you should pay attention to the side effects of its use and withdrawal syndrome.

Keywords: caffeine; caffeine sport; caffeine sleep; caffeine brain

Introduction

Caffeine, one of the most frequently consumed psychoactive compounds in the world, has played an important role in human daily life for centuries. Found in coffee, tea, chocolate and energy drinks, it has become an integral part of the diet of many people. Its popularity is due to its unique stimulating properties that have a direct impact on the functioning of the body - both physically and mentally. This study analyzes the impact of caffeine on various aspects of human life, including cognitive abilities, sleep and sports activity. Particular attention has been paid to research on the benefits and potential risks of its consumption to better understand how it may support or interfere with everyday functioning. The role of caffeine in the context of addiction, regulation of circadian rhythm and impact on long-term health is also presented. The aim of the work is not only to present a comprehensive picture of the effects of caffeine, but also to assess its place in the lifestyle of modern people. The analysis will cover both the positive and negative effects of its consumption, allowing for a better understanding of how caffeine affects the body and mind and what place it occupies in our daily routine.

Mechanism of action of caffeine

Caffeine (1,3,7-trimethylxanthine) is a chemical compound from the group of purine alkaloids, occurring naturally in the seeds, leaves and fruits of many plants, such as coffee (Coffea arabica), tea (Camellia sinensis), guarana (Paullinia cupana) and cocoa (Theobroma cacao). It is a psychoactive substance that acts as a stimulant of the central nervous system (CNS) and has broad physiological effects. [1,2] From a biochemical point of view, caffeine is a lipophilic compound, which means that it easily penetrates cell membranes, including the blood-brain barrier. After ingestion, it is quickly absorbed in the gastrointestinal tract, reaching its maximum concentration in blood plasma within 15-45 minutes. It is metabolized mainly in the liver by cytochrome P450 enzymes, mainly by the CYP1A2 isoenzyme, into active metabolites: theophylline, paraxanthine and theobromine. [3] The mechanism of action of caffeine is mainly based on its ability to block adenosine receptors (mainly A1 and A2A). Adenosine is a neurotransmitter that plays a key role in regulating energy levels, sleepiness and vascular function, promoting fatigue. Caffeine, by inhibiting its action, increases neuronal activity and the release of neurotransmitters such as dopamine, noradrenaline and acetylcholine, which leads to improved alertness, concentration and mood.[2,4,5] As a biochemical substance, caffeine has a pleiotropic effect, affecting not only the nervous system, but also the cardiovascular system (e.g. by increasing heart rate), skeletal muscles (increasing physical performance), the respiratory system (bronchodilation) and the digestive system (stimulation).

secretion of digestive juices).[1] Understanding the biochemical properties of caffeine allows for precise determination of its effects in a health and functional context, making it the subject of numerous studies in the field of pharmacology and medicine.

The effect of caffeine on cognitive processes

Cognitive processes, crucial for the functioning of the mind, include a number of complex information processing mechanisms, such as perception, attention, memory, learning, as well as thinking and decision-making. Focus, the ability to selectively focus on a specific stimulus or task while ignoring others, is one of the most important aspects of attention and plays a fundamental role in cognitive processes. There are many substances that are central nervous system stimulants, including methylphenidate, caffeine and modafinil. Caffeine affects cognitive processes mainly by affecting the nervous system and blocking adenosine receptors. An increase in neuronal activity and an increase in the level of neurotransmitters such as dopamine and noradrenaline additionally stimulates cognitive processes, including attention, memory and executive functions. A 2021 study compared the effects of the above-mentioned stimulants on the central nervous system. Caffeine only improved attention and alertness [6,7], which is consistent with its known effects on increasing energy and alertness, but did not improve performance on memory tasks. [6] The choice of the appropriate stimulant should therefore be adapted to the effect we expect improvement of memory, attention or reduction of fatigue. However, you should pay attention to the side effects of caffeine. It turns out that regular consumption of moderate doses of caffeine, although it may temporarily improve reaction speed, in the long run may reduce the accuracy and efficiency of working memory, which may result from overload of the nervous system. [8] This effect does not disappear immediately after discontinuation of caffeine, suggesting that short-term withdrawal does not fully reverse the negative effects on memory. After caffeine withdrawal, there is a decrease in the ability to concentrate and pay attention, which may be the result of a sudden lack of stimulation to which the body has become accustomed. [9] There is evidence that exercise can improve memory, but consuming caffeine before exercise may reduce these benefits. Caffeine consumption before exercise resulted in impaired short-term memory and the ability to absorb and recall auditory information. Regular caffeine consumption may therefore blunt the long-term effects of exercise on improving memory and learning. [10] Regular coffee improves mood, reduces mental fatigue, fatigue and headaches more than placebo or decaffeinated coffee. At the same time, it increases the feeling of nervousness (jitteriness), especially in young women and older men.[7] In contrast, daily caffeine consumption may lead to a reduction in gray matter

volume in the medial temporal lobe. [8] Caffeine also has a differential effect on brain activation in people with mild cognitive impairment and in healthy people. In healthy people, it enhances activation in frontal-striate regions, key for working memory and cognitive control, while in people with mild cognitive impairment it causes more diffuse activation in posteromedial brain regions such as the temporal and parietal lobes, which may indicate mechanisms compensatory. While caffeine has no direct benefits on cognitive function in older adults, it acts as a "normalizer" of brain activity, increasing functional connectivity between key brain regions in people with mild cognitive impairment. Caffeine's effects also include vasoconstriction, which leads to an overall decrease in cerebral blood flow [11], while the phenolic components of coffee have the opposite effect, improving blood flow and oxygen delivery [7]. This suggests a potential synergy, with phenols supporting blood flow and caffeine increasing brain activity and oxygen metabolism. Further research should include chronic caffeine consumption and studies of other psychostimulants to better understand its impact on the aging brain and the development of Alzheimer's disease. Caffeine's increased neuronal firing may lead to a higher demand for synaptic regeneration, which the body may not be able to fully provide with regular caffeine consumption. This may result in insufficient regeneration of nerve cells in the long term.[8] Deep delta waves in EEG are a marker of the intensity of deep sleep, which is important for restoring alertness and cognitive functions. Disruption of NREM and REM sleep (e.g., by caffeine) may negatively impact memory, attention, and decision-making following sleep deprivation.[12] Caffeine has important but complex effects on cognition and brain health. While it improves attention and alertness, long-term use may be associated with negative effects on memory, neural recovery and cognitive health, especially if it interferes with sleep. Caffeine should be used carefully, taking into account individual needs, goals, and potential side effects.

The effect of caffeine on sleep

Sleep is a natural physiological state of the body in which there is a decrease in consciousness, motor activity and reaction to external stimuli. It is crucial for the regeneration of the body and mind, as well as for mental and physical health. Sleep is divided into different phases that perform different functions in the process of regeneration and maintaining the body's balance.[13] An adult needs an average of 7-9 hours of sleep a day, although individual needs may vary. It is worth taking care of the quality and regularity of sleep to support health and well-being. Sleep is divided into two main stages [14,15]:

1. **NREM (Non-Rapid Eye Movement)**:
    - It covers approximately 75-80% of all sleep.
    - It consists of four subphases:
        - Phase 1: the transition between wakefulness and sleep, lasts several minutes.
        - Stage 2: light sleep, in which muscles relax and brain waves slow down.
        - Phase 3 and 4: deep sleep (slow wave sleep), crucial for the regeneration of the body and immune system.
2. **REM (Rapid Eye Movement)**:
    - It constitutes approximately 20-25% of sleep.
    - It is characterized by rapid eye movement, increased brain activity and dreams.
    - It is crucial for memory consolidation and emotion processing

Sleep has many functions:

- Physical regeneration: During sleep, the body repairs tissues, strengthens the immune system and regulates hormonal processes.[16]
- Mental recovery: Sleep supports emotional processing, learning and memory. [17]
- Emotional regulation: Getting enough sleep helps stabilize your mood and manage stress, which is crucial for mental health.[18]
- Regulation of the nervous system: Sleep helps maintain the balance of neurotransmitters and cleanse the brain of toxins [19]

Sleep deficiency can lead to many health problems, such as a weakened immune system, problems with concentration and memory, increased risk of chronic diseases such as obesity, diabetes or heart disease, and emotional disorders, including depression and anxiety.[20]
The stimulating effect of caffeine may disturb sleep. Consuming 400 mg of caffeine (an amount equivalent to several cups of coffee) even 6 hours before bedtime can reduce sleep time by over an hour. Sleep disturbances include both objective shortening of sleep duration and fragmentation (frequent, short-term awakenings) [21]. Regular caffeine consumption during the day lengthens the time needed to enter the REM phase and delays its accumulation during the

night. Even when caffeine is consumed 13.5 hours before bedtime, its effect on REM sleep is noticeable, suggesting that not only blood caffeine concentrations but also other mechanisms (e.g., circadian regulation) influence sleep. [22] When caffeine is consumed in the morning, at noon and in the afternoon (>8 hours before bedtime), healthy, habitual caffeine consumers do not observe significant changes in the structure of nighttime sleep or the subjective quality of sleep, but when consumed shortly before bedtime (e.g. 1 hour before) can significantly disrupt sleep, especially its initiation and intensity in the first half of the night. [23] Regular caffeine consumption may be less disruptive to nighttime sleep than one-time consumption in the evening. Sleep recovery after deprivation is disrupted by caffeine consumption even at moderate doses (~350 mg). It shortens the total sleep time, reduces the duration of the N3 phase and the REM phase, increases sleep fragmentation (more long awakenings) and worsens the stability and organization of sleep (more frequent transitions between sleep phases, shorter sleep cycles). [12] Regular caffeine consumption affects the adenosine receptor system, which may reduce the effectiveness of sleep regeneration. Habitual caffeine consumption may lead to the body's adaptation, but at the same time intensify the negative effects of its acute consumption, especially on sleep after deprivation [12].

The effect of caffeine on athletes

Many athletes take caffeine. Is this confirmed in scientific works? One study examined whether caffeine increases maximum oxygen consumption (V'O2max). The increase in V'O2max after taking caffeine was small (1.2% compared to the placebo group), but it translated into a noticeable improvement in performance - a 20% increase in running time until exhaustion. It is explained by increased peak heart rate (HRpeak) and increased maximum ventilation (VEmax). The increase in these parameters is probably related to the blockade of adenosine receptors and greater secretion of adrenaline and norepinephrine. [24] Both coffee and pure caffeine have been shown to improve endurance performance, indicating that coffee may be an effective and more natural option instead of caffeine alone. [25–27] Moreover, the increase in performance after caffeine consumption is not due to greater fat oxidation. Improved performance may be related to the effect of caffeine on adenosine receptors in muscles, which improves the mechanics of muscle contractions. [25] This is especially important for athletes who may choose coffee because of its taste, easy availability and additional valuable ingredients. A high dose of caffeine (approximately 9.2 mg/kg) increases the number of repetitions in strength exercises using a barbell (horizontal and incline bench press) and did not affect the subjectively perceived physical effort, even though the participants performed more repetitions.[28] This

indicates that caffeine may support strength endurance and help you perform higher reps in upper body exercises, and may help delay fatigue by reducing the sensation of pain and exertion, allowing your muscles to work longer with a similar sense of exertion. However, attention should be paid to the effects of using caffeine in the context of body regeneration. Caffeine consumption before strength training [29] and before moderate aerobic exercise [30,31] causes a delay in the return of heart rate (HR) and systolic blood pressure to baseline values after the end of exercise. It also causes an increase in sympathetic (excitatory) activity and a withdrawal of vagal (calming) activity during exercise and regeneration, which may increase the load on the nervous system. This effect indicates that caffeine may slow down the regeneration of the cardiovascular system, which is especially important for people who undertake intense training that requires rapid regeneration. [29] Increased sympathetic activity may make it difficult to quickly return blood pressure to normal levels, which may be important for people with hypertension or others who may require blood pressure stabilization after exercise. [30] Caffeine increases aortic stiffness both at rest and during recovery from exercise due to its pressure-increasing effect. Higher aortic stiffness is associated with a greater risk of cardiovascular events and may result in inadequate blood supply to the heart during exercise. [31] Interestingly, consuming caffeine before exercise leads to the automatic selection of higher exercise intensity, even with a similar feeling of fatigue. [32] One study showed that a dose of 6 mg/kg of caffeine had a significant effect on jumping performance, increasing it in most female athletes. This suggests that caffeine may be a beneficial supplement for female athletes practicing sports that require jumping and high power (e.g. volleyball, basketball), while its consumption had no significant effect on maximum isometric strength (isometric thigh pull test), suggesting that caffeine does not increase maximum strength in isometric conditions. The effects of caffeine may be more beneficial for dynamic abilities, such as jumping, than for raw maximal strength.[33] Caffeine consumption (6 mg/kg) one hour before an 800 m race did not improve running performance either on the day of consumption or 24 hours later. This is due to the limited effect of caffeine in tests performed in the evening, as opposed to morning protocols, where the effects are more visible. [34] The analysis shows that caffeine may bring tangible benefits to athletes, especially in endurance and dynamic disciplines, increasing performance and time spent working to exhaustion, but many years of work and research on the effects of this substance are still needed to fully understand its effects.

Discussion

Research shows that caffeine can bring significant benefits to athletes, especially in disciplines requiring endurance and dynamics, improving performance and extending the time of exercise before exhaustion. Nevertheless, further research is necessary to better understand its mechanisms of action. At the same time, caffeine has a complex effect on cognitive functions and brain health - on the one hand, it improves concentration and alertness, on the other hand, with long-term use, it may have a negative impact on memory, regenerative processes of the nervous system and cognitive abilities, especially if it interferes with sleep. Therefore, it is important to use it carefully, taking into account individual goals, needs and possible side effects, including: headache (excessive stimulation of the nervous system), gastrointestinal discomfort (heartburn or reflux may occur due to increased secretion of stomach acid; diarrhea due to increased intestinal motility; stomach pain due to irritation of the mucous membrane), tachycardia or even arrhythmia, dehydration (caffeine has a diuretic effect), decreased calcium absorption, skin problems (e.g. rash), insomnia (difficulty falling asleep, shortened sleep), nervousness and tremor (especially at high doses) [35,36]. The amount of caffeine that causes side effects depends on each person's body weight, gender, age and individual sensitivity. [37] One study highlights the problem of caffeine withdrawal symptoms. About one third of respondents reported withdrawal symptoms such as headaches, sleep disturbances, delirium, fatigue and problems with concentration. These symptoms were particularly common among younger patients, mainly men, and could negatively impact the course of treatment, prolonging recovery. An interesting conclusion is that some patients were not aware of their caffeine intake from hidden sources, such as food, cosmetics or supplements. This can lead to people incorrectly attributing withdrawal symptoms to other causes. In such cases, caffeine withdrawal may have gone unnoticed, and the associated symptoms may have complicated the treatment process. The study authors suggested that therapeutic use of caffeine could help alleviate these symptoms. For example, caffeine could be used to reduce delirium, improve respiratory function, and relieve pain, which would improve the overall quality of care [38].

Summary

Caffeine can be beneficial to the body when consumed in moderate amounts. It helps improve concentration and attention, increases physical performance, supports short-term memory, and may also improve mood by stimulating dopamine production. Additionally, thanks to the antioxidants it contains, it can support cell protection and reduce the risk of some diseases, such as Parkinson's, Alzheimer's or type 2 diabetes. For some people, it also supports

digestion. However, too much caffeine carries some risks. It can cause sleep problems, addiction, increased anxiety levels, irritation of the digestive system and a temporary increase in blood pressure. In summary, moderate caffeine consumption is safe and can provide many benefits, but you should adjust the amount according to your needs and body tolerance to avoid negative effects.

Authors contributions

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