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The Effects of Caffeine on Health and Perceived Bitterness

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Caffeine is commonly consumed throughout the world in items such as coffee, chocolate, tea, energy drinks, and carbonated soft drinks. Consumers and food manufacturers benefit from discussion surrounding caffeine because consumers use information to drive their purchases. Food manufacturers and producers will find it useful to determine consumer trends such as preferred flavor profiles and preferred caffeine content. By large, caffeine-containing foods are not nutritionally dense but provide benefits, like disease prevention, from caffeine and other phytonutrients. Caffeine is one of the factors that may prohibit consumers from purchasing certain products because of effects on health and bitter tastes.

The ability to detect bitterness comes from the need to survive by avoiding potentially harmful foods, which often have a bitter taste (Melis & Tomassini Barbarossa, 2017). Caffeine's purpose in plants is to protect them from being eaten by insects; caffeine content increases as the plant matures (Olechno, Puscion-Jakubik, Zujko, & Socha, 2021). Despite humans' affinity to avoid bitterness, caffeinated drinks are a common beverage. The purpose of this paper is to describe how caffeine affects health and perceived bitterness, and the ways that the food industry modifies bitter tastes in caffeine-containing products.

Health Effects of Caffeine

There is a concern amongst consumers surrounding the effects caffeine has on their bodies (stress, anxiety, cardiovascular health, sleep problems, caffeine withdrawal, etc.). One key measure used to determine if there is a public health problem concerning caffeine intake is the change in emergency room visits related to high caffeine intake. As of 2010, there has been an increase in emergency room visits where patients reported having an energy drink or high-caffeine drink shortly before the onset of their adverse symptoms (Substance Abuse Mental Health Services Administration, 2011). Other factors may affect the relevancy of this data. It would be helpful to know the other ingredients in the drinks, like sugar or alcohol, or the activities people were involved in when the accident/symptom occurred.

Reasons for consuming coffee or other caffeinated beverages include improving concentration and reducing fatigue (Olechno et al., 2021). Effects of caffeine typically last around 10 hours (Cleveland Clinic, 2020). This explains the alertness and jitteriness one may feel throughout the day after drinking caffeine, and why it is recommended to avoid drinking caffeine late in the day.

Excessive caffeine intake in adults (people over 18 years of age) is defined as greater than 400 milligrams per day (Office of the Assistant Secretary for Health (OASH), 2020a). This is equal to about five cups of coffee. Drinking greater than 400 mg/day of caffeine has been shown to raise systolic and diastolic blood pressure but did not affect risk of stroke or cardiovascular disease (CVD) (Steffen, Kuhle, Hensrud, Erwin, & Murad, 2012). Negative effects of excess caffeine are more commonly documented in cases where adults drank energy drinks, many of which have higher caffeine contents (up to 505 mg) than coffee and tea for the same fluid ounce (OASH, 2020a; Reissig, Strain, & Griffiths, 2009). Negative reactions include caffeine toxicity and abnormal heartrate (heart palpitations, cardiac arrest, etc.). In 88% of cases, patients did not have underlying heart conditions, showing that high caffeine intake at one time contributed to the onset of an acute heart condition (OASH, 2020a). Data does not say what patients were doing, such as exercising or other stressful activities, prior to the abnormal heart event. It is expected that high caffeine may also exacerbate existing heart conditions. Note that adverse reactions to caffeine are underreported (OASH, 2020a). Most people do not seek medical attention for reactions that are not perceived as life-threatening.

The findings related to caffeine and immediate health implications are inconsistent. The consensus among health professionals erring on the side of caution is that excessive daily caffeine intake can be detrimental, but a moderate amount each day is not harmful for adults of average health. Moderate caffeine intake (240-400 mg/day) is not correlated to increased risk of premature death caused by disease or cancer; excessive intake is neither protective nor harmful in specific situations in healthy adults (OASH, 2020b). Coffee, in particular, should be avoided by people with gastrointestinal conditions including sensitivity, cancer, ulcers, acid reflux, etc. and pregnant and lactating women (Olechno et al, 2021). Note that the Institute of Medicine (2014) recognizes that caffeine effects are individualized, and that there needs to be more data surrounding genetic predispositions, such as heart conditions and sensitivity to caffeine, and circumstances in which caffeine is consumed, such as during exercise. Adverse reactions can occur in an individual who had a low dose of caffeine, and no reaction can occur in an individual who had a high dose.

Other data suggests that there are no significant correlations between high-caffeine intake and adverse reactions (OASH, 2020a). Studies involving the United States, United Kingdom, Germany, Canada, Brazil, Sweden, and Australia found no significant increase in heart rate or increase in blood pressure within an hour after consuming a high-caffeine, low-sugar energy drink (Burrows, Pursey, Neve, & Stanwell, 2013). This shows that sugar, along with genetics, may affect how caffeine is metabolized. Slow metabolism of caffeine is characterized by heart palpitations and/or anxiety after consumption of caffeine, while rapid metabolism does not appear to exhibit these symptoms (Olechno et al, 2021). The level of caffeine needed to promote negative effects in an individual with slow caffeine metabolism varies. This suggests the existence of caffeine sensitivity and that reactions to caffeine are highly individualized.

Data surrounding long-term, total mortality related to caffeine are more consistent and compelling. Four cups of coffee a day is believed to reduce the risk of total mortality by three to four percent (OASH, 2020b). Three cups of coffee a day is suspected to benefit the cardiovascular system, more so in women than in men, and reduce the risk of type 2 diabetes, liver cancer, endometrium cancer, and stroke in healthy adults because coffee has a positive effect on blood lipid levels and metabolism of sugar (OASH, 2020b). Though more studies are warranted, it appears that caffeine alone also delays exhaustion during exercise and increases oxygen uptake (Burrows et al, 2013). These claims are the main reason companies choose to market energy drinks as energy boosters, supplements to the diet, and pre-workout products. Note that these studies involved people who were already moderately active and healthy.

The American Academy of Pediatrics' position on caffeine in children and adolescents (ages 0-18) is that high-caffeine intake has not been adequately proven safe for these age groups and should not be consumed by them (Loomans, Hodland, van der Stelt, van der Wal, Koot, van den Bergh, & Vrijkotte, 2012; OASH, 2020a). For ethical reasons, studies of high-caffeine intake on these populations are limited. Since there is not enough evidence to accurately determine safe caffeine levels for this age group, caffeine should be avoided by this population.

There is also some evidence to suggest that caffeine slightly masks the effects of alcohol, leading to more adverse alcohol-related events (Roemer & Stockwell, 2017). The addition of caffeine reduces the perception of impairment but does not make the individual any less intoxicated or any more able to perform physical tasks, like driving (Roemer & Stockwell, 2017; OASH, 2020a). In other words, cognitive and speaking ability appear normal, but motor skills and muscle reflexes are slow. Furthermore, because of the masking effect, people may believe they are less intoxicated than they are, leading to increased alcohol consumption, increased metabolism of alcohol by the liver, and increased alcohol-related incidents and health problems (Roemer & Stockwell, 2017; OASH, 2020a). For this reason, high-caffeine energy drinks should not be consumed with alcoholic beverages (such as the popular Vodka Red Bull mix), nor should coffee be used to "sober up." High-caffeine intake should also be used with caution when using certain supplements, medications, and other drugs.

Caffeinated drinks, such as energy drinks, are not regulated by the Food and Drug Administration (FDA) (Seifert, Schaechter, Hershorin, & Lipshultzz, 2011). They are considered a dietary supplement instead of a food/beverage or drug because they are not nutritionally dense and do not claim to cure or treat any disease. Because of the dangers of mixing alcohol with caffeine, caffeinated products should have a warning on the package stating that caffeine and alcohol should not be consumed together, which follows in the footsteps of Health Canada mandates (OASH, 2020a).

There are discrepancies between caffeinated and decaffeinated coffee that may lead researchers to investigate decaffeinated coffee's protective benefits. Some studies done on decaffeinated coffee suggest that protective benefits are coming from coffee, not just caffeine (Ding, Bhupathiraju, Chen, van Dam, & Hu, 2014; Jiang, Zhang, & Jiang, 2014; Huxley, Lee, Barzi, Timmermeister, Czernichow, Perkovic, et al, 2009). More evidence is needed to determine if the reduced risk of total mortality is due to the caffeine or a combination of factors in coffee, such as phytonutrients and antioxidants.

For individuals that are not sensitive to caffeine, moderate daily caffeine intake can be beneficial in decreasing their risk of developing type 2 diabetes, certain cancers, and CVD. Caffeine has not been adequately proven safe for children under 18 years of age and should not be consumed in high amounts by this population. For adults of average health, with no sensitivity to caffeine, less than 400 mg of caffeine per day is considered a moderate amount. Any more than that is considered excessive and may be accompanied by adverse reactions, such as anxiety. When drinking alcohol, caffeine may make a person feel less inebriated despite the opposite being true. Therefore, alcohol and caffeine should not be consumed together.

Factors that Affect Caffeine in Coffee and Tea

The levels of caffeine in coffee depend on how coffee is brewed and roasted. Methods of brewing coffee have changed over time. Arabica coffee beans have about 0.9-1.2% caffeine by dry weight, 0-1% caffeine when roasted, and an average of 1.876 g caffeine/L coffee when brewed (Olechno et al, 2021). Roasting typically occurs between 390 and 500 degrees Fahrenheit (Olechno et al, 2021). Variations are light, medium, medium-dark, and dark. Roasting causes a loss of caffeine, but roasting also enhances flavor, which is desirable among consumers (Olechnon et al, 2021). Roasted, ground Arabica coffee beans will be the reference product for this discussion.

Methods of brewing coffee have changed over time. Currently, filtered brewing is the most common method to brew coffee, which yields about 80 mg per cup of coffee, depending on various factors (OASH, 2020b). Other brewing methods are: pouring water over ground coffee beans, percolating, cold brewing, and the French press (Olechno et al, 2021). Important factors that affect caffeine include brewing time, water temperature, coffee/water ratio, the particle size of ground beans, vapor pressure (in the case of espresso coffee), and age of the coffee bean before roasting (Olechno et al, 2021). Green coffee beans have the least amount of caffeine because they are less mature.

During processing, time, temperature, and pressure affect the caffeine yield. The amount of time is dependent on the temperature of water used and the pressure the coffee is under.

Coffee is slightly soluble in water, and solubility increases as temperature increases (Olechno et al, 2021). This results in higher caffeine content in the coffee. Coffee made with a French press had to be brewed for 420 minutes with room temperature water in order to yield similar amounts of caffeine as French press coffee brewed with boiling water for six minutes (Olechno et al, 2021). Cold brew from a coffee machine also required more time to brew because of the lower water temperature used. As expected, when brewed with an espresso machine, espresso coffee had the highest caffeine content because of the pressure applied to high heat; the French press had the second most; and pouring water over ground coffee yielded the least (Olechno et al, 2021). However, continuing the espresso method for longer than threshold time will not increase the caffeine content but will dilute the concentration of caffeine because of the additional water added (Olechno et al, 2021). Overall, espresso coffees consistently have the highest caffeine content while using the least amount of roasted coffee beans because they use higher water temperatures and more pressure (Olechno et al, 2021).

Similar to coffee, tea leaves that are less mature have less caffeine. Green tea has the least, followed by oolong, white, and black tea having the most. Black tea refers to the method of taking fresh tea leaves from a tea tree and processing it via withering, rolling, fermentation, and drying (Mao, Li, Wang, Fan, Song, et al, 2022). Full fermentation is the key processing method that gives black tea its unique taste and high-caffeine content (Mao et al, 2022). Oolong and white tea are semi-fermented, and green tea is not fermented (Bobkova, Demianova, Belej, Harangozo, Bobko, et al, 2021). Black tea typically has more caffeine and antioxidants than green tea because black tea leaves are 100% processed while green tea leaves are 40% processed (Bobkova et al, 2021). Green tea leaves are not oxidized as much as black, white, and oolong tea leaves.

Oxidation of coffee beans, tea leaves, and cocoa beans is the most important part of the production process for these products. Oxidation during roasting or drying (374 – 420 degrees Fahrenheit for coffee beans) changes the composition of the fatty acids within the beans or leaves and leads to the development of flavor and aroma in the products (Budryn, Nebesny, Zyzelwicz, Oracz, Miskiewicz, Rosicka-Kaczmarek, 2012). Too much oxidation leads to a rancid product, which is why these products are packaged in air-tight containers.

The key factors of processing or roasting of coffee, tea, and cocoa are time, temperature, and pressure. Oxidation is the mechanism in roasting that disrupts the oils in these plant products, causing the familiar flavors and aromas that consumers associate with coffee, tea, and chocolate. Once processed, these products should be packaged in airtight containers and stored in cool, dry places to prevent further oxidation.

Relationship Between Caffeine and Perceived Bitterness

Within the food industry, there is an emphasis on inhibiting and masking bitterness, especially from caffeine, in beverages and foods. The best ways to test consumer acceptance of a product is to perform sensory evaluations or sample markets. Bitter inhibitors/blockers include sugar, certain artificial sweeteners, and other products, like Sweegen's natural bitter blockers (Adaikalavan, Blanc, McCormick, Zeevaart, Joassard, & Juneja, 2022). The human tongue has specific taste protein-coupled receptors for detecting bitterness (bitter agonists); this involves a complex combination of approximately 25 members of the taste family 2 receptors (TAS2R), whereas other tastes (agonists) are sensed by only one receptor (Suess, Brockhoff, Meyerhof, & Hofmann, 2018). The TAS2Rs that are sensitive to caffeine (3.0 mmol/L) are TAS2R7, TAS2R10, TAS2R14, TAS2R43, and TAS2R46 (Suess et al, 2018). To block bitterness in foods, the food industry needs products that act on multiple bitter receptors at the same time.

Perhaps the most common and readily available ingredients that reduce perceived bitterness and that consumers and manufacturers have access to are table sugar and milk. Table sugar by itself or in high amounts can have a bitter aftertaste, but when used in combination with bitter foods, reduces the overall perception of bitterness without reducing the overall sweetness provided by the sugar (Suess et al, 2018; Adaikalavan, 2022). Milk is commonly used in tea, coffee, and chocolate to reduce bitterness by reducing the amount of free bitter compounds available to bind to protein receptors on the tongue (Suess et al, 2018). Despite these readily available and easy-to-use products, consumer trends are leaning toward sugar alternatives and low-fat options for health reasons (Adaikalavan, 2022).

The natural bitterness found in cocoa beans can be offset by the addition of natural bitter blockers, such as benzoic acid. The perception of caffeine bitterness by receptors can also reduce bitterness by targeting the 2,4-dihydroxybenzoic acid molecule when using hydroxylated benzoic acid amides in bitter blocking compounds (Suess et al, 2018). Benzoic acid occurs naturally in certain foods, like cranberries and strawberries (Soltoft-Jensen & Hansen, 2005). Benzoic acid can be extracted from these foods or made synthetically and used as an additive. The popular combination of chocolate-covered cranberries and chocolate-covered strawberries can decrease the bitterness and provide a tartness that hides left over bitterness in chocolate and make it acceptable to consumers. The natural bitterness of cocoa beans is offset by the added sugar and milk in processing, plus the addition of natural bitter blockers (cranberries or strawberries).

Derivatives of synthetic vanillyl alcohol (derived from vanillin) may also serve to reduce the perception of caffeine bitterness by 23-35% (Suess et al, 2018). Vanillin and vanillin derivatives are used in the food industry as flavoring agents in food and beverages. Vanillyl alcohol is a flavoprotein that acts on the protein-coupled receptors that detect bitterness to inhibit the perception of bitterness (van der Heuvel, Fraaije, Laane, & Berkel, 2001). Synthetic vanillyl is derived from the protein vanillylamine, which can be synthesized from capsaicin, commonly found in many varieties of red chili peppers (van der Heuvel et al, 2001). Therefore, red peppers provide a widely accessible compound to produce artificial vanilla flavors that inhibit bitterness. Because capsaicin can be converted enzymatically to a precursor of vanillin, the burning associated with capsaicin in red peppers should be alleviated. The result is vanillin, which can help control bitterness.

Another ingredient used to reduce bitterness is lemon/lemon grass/lemon balm (Suess et al, 2018). Lemon grass and lemon balm were shown to significantly reduce bitterness in black tea (Suess et al, 2018). The active ingredient in lemon grass and lemon balm that provide the bitter blocker is an oxygenated monoterpene, citronellal (Suess et al, 2018). Citronellal compounds target TAS2R43 and TAS2R46 (Suess et al, 2018). This common flavoring and fragrance ingredient is associated with citronella candles and lemony scents/tastes. The first carbon in the molecule is oxygenated to receive these inhibitory effects (Suess et al, 2018). The benefit to consumers and manufacturers using citronellal compounds in reducing bitterness of tea is that low amounts (25ppm citronellal/100mL black tea infusion) can be used and still produce a significant reduction (32%) in perceived bitterness (Suess et al, 2018). This results in a more acceptable taste profile. A product employing this is Bigelow's Lemon Lift tea bags (black tea with lemon flavor) (RC Bigelow Inc, 2022).

Bitterness is an unwanted flavor in coffee, chocolate, and tea, and the food industry has successfully found ways to reduce and mask it. Sugar is perhaps the most common way to balance bitter flavors in beverages and desserts. Milk/creamer, vanilla, benzoic acid from certain fruits, and lemon are other effective ways to reduce bitterness from caffeine in beverages and foods.

Conclusion

The relationship between caffeine content and perceived bitterness and the health effects of caffeine on the human body are integral to understanding consumer demands and purchasing habits of consumers. More conclusive data is needed to determine the health effects of caffeine on the body. Generally, caffeine in moderate amounts is safe. Excessive amounts should be avoided because it is not protective, but it is not harmful for those who have high caffeine metabolism and are overall healthy adults. Those who metabolize caffeine slowly may experience anxiety, heart palpitations, and other adverse reactions. When drinking alcohol, caffeine should be avoided in excessive amounts, and consumers should be aware that they are not less drunk when mixing the two. When used safely, caffeine can be a useful stimulant or enjoyed in food or beverage.

Markets that want less caffeine may choose tea over coffee and energy drinks, while those who want more caffeine will choose espresso coffees and high-caffeine energy drinks. Though consumers may want caffeinated drinks, they may not want the bitter taste that comes with caffeine. The food industry mainly employs the use of sugar, sugar alternatives, and milk/creamer to reduce the overall perception of bitterness. Tea drinkers may also use sugar or lemon to block the bitter taste. Derivatives of benzoic acid and foods containing benzoic acid are also commonly used by the food industry, especially in the use of chocolate-covered cranberries and strawberries. This market will continue to grow, and food manufacturers will find it useful to stay on top of consumer trends and knowledge.

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