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Effects of caffeine on human behavior

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Abstract

The literature suggests that the following effects on behavior of adult humans may occur when individuals consume moderate amounts of caffeine. (1) Caffeine increases alertness and reduces fatigue. This may be especially important in low arousal situations (e.g. working at night). (2) Caffeine improves performance on vigilance tasks and simple tasks that require sustained response. Again, these effects are often clearest when alertness is reduced, although there is evidence that benefits may still occur when the person is unimpaired. (3) Effects on more complex tasks are difficult to assess and probably involve interactions between the caffeine and other variables which increase alertness (e.g. personality and time of day). (4) In contrast to the effects of caffeine consumption, withdrawal of caffeine has few effects on performance. There is often an increase in negative mood following withdrawal of caffeine, but such effects may largely reflect the expectancies of the volunteers and the failure to conduct "blind" studies. (5) Regular caffeine usage appears to be beneficial, with higher users having better mental functioning. (6) Most people are very good at controlling their caffeine consumption to maximise the above positive effects. For example, the pattern of consumption over the day shows that caffeine is often consumed to increase alertness. Indeed, many people do not consume much caffeine later in the day since it is important not to be alert when one goes to sleep. In contrast to effects found from normal caffeine intake, there are reports that have demonstrated negative effects when very large amounts are given or sensitive groups (e.g. patients with anxiety disorders) were studied. In this context caffeine has been shown to increase anxiety and impair sleep. There is also some evidence that fine motor control may be impaired as a function of the increase in anxiety. Overall, the global picture that emerges depends on whether one focuses on effects that are likely to be present when caffeine is consumed in moderation by the majority of the population or on the effects found in extreme conditions. The evidence clearly shows that levels of caffeine consumed by most people have largely positive effects on behavior. Excessive consumption can lead to problems, especially in sensitive individuals.

Keywords: Caffeine; Mental performance; Mood; Attention; Memory; Caffeine withdrawal

1. Introduction

The aim of the present article is to review the effects of caffeine on human behavior. The main areas of behavior reviewed are mood, mental performance and sleep. Certain areas, although related to behavior, such as the underlying CNS mechanisms, are not reviewed in detail. This is because most of the research in this area has involved animal studies. These have provided plausible mechanisms for many of the effects observed in humans, but whether specific details (e.g. effects of dose) generalize across species is unknown. Other areas, such as the claims that caffeine is addictive, are not covered here but are discussed in a paper by Dews et al. in this issue.

In all areas it is important to make a distinction between the effects of amounts of caffeine that are normally consumed from food and drinks, and the very different effects observed with excessive amounts or in very sensitive individuals. Unlike other areas of research (e.g. studies of health effects), most studies of the behavioral effects of caffeine have examined acute changes following a single dose. Less is known about effects of regular consumption, although there are now enough data on this topic to draw tentative conclusions. In addition to studying the effects of caffeine consumption, the research has also considered possible changes in behavior as a function of caffeine withdrawal. A critical appraisal of claims that caffeine withdrawal influences performance and mood is provided.

It is important to note that in research reviewed in all subsequent sections, there is considerable variation in the methodology and measuring devices. This has the disadvantage that it is often difficult to compare different studies. However, persistence of effects across a range of methodologies enhances the validity of the reported observations.

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2. Effects of caffeine on mood

2.1. Acute effects of caffeine on mood

2.1.1. Increases in alertness

A large number of studies have shown that consumption of caffeine leads to increased alertness (or reduced fatigue). These effects have often been demonstrated using paradigms involving low alertness situations (e.g. following administration of benzodiazepines—Johnson et al., 1990; early morning—Smith et al., 1992; working at night—Smith et al., 1993a; when the person has a cold—Smith et al., 1997a; and sleep loss—Bonnet et al., 1995). However, beneficial effects of caffeine have been demonstrated in individuals in an alert state (e.g. Leathwood and Pollet, 1982; Rusted, 1994, 1999; Smith et al., 1994a,b; Warburton, 1995). Many of these studies have used quite high doses of caffeine (e.g. 250 mg—Johnson et al., 1990; 3 mg/kg—Smith et al., 1994a,b), which would not be consumed typically in a single drink in real-life situations. However, other studies have demonstrated similar effects with realistic doses (e.g. Leathwood and Pollet, 1982; Warburton, 1995). These results have implications for many practical situations in that safety is often at risk when alertness is low. However, a better impression of this will be seen when the data from performance tasks are considered. Many of the studies have administered caffeine in coffee and it is unclear whether it is the caffeine alone, or caffeine in combination with other compounds in the coffee, which underlies the behavioral effects. Recent research (Smith et al., 1999b) has shown that it is the caffeine rather than the combination of the caffeine and the type of drink in which it is presented that is important. Similar results have also been demonstrated with caffeine given as a capsule and in a drink. Other research also shows few differences between decaffeinated coffee and drinks such as fruit juice. All of these pieces of evidence point to caffeine as the main determinant of the behavioral effects of caffeinated beverages.

One must now consider why some studies have failed to find effects of caffeine on alertness. For example, Svensson et al. (1980) found no effect of 100 mg of caffeine on the mood state of 23 volunteers. Similarly, Swift and Tiplady (1988) found no effect of 200 mg of caffeine on the mood of elderly volunteers. This lack of effect could possibly reflect sample size or other details of the methodology. Lieberman (1992) suggests that beneficial effects of caffeine on alertness are most easily demonstrated when circadian alertness is low and mood is measured in the context of doing demanding performance tasks. Rusted (1999) also suggests that mood effects occur after changes in performance, and this may account for the absence of effects in certain studies.

Another possible explanation of the failure to find positive mood changes in certain studies is that they are masked by increases in negative mood. Indeed, a number of results suggest that caffeine may increase anxiety and these are reviewed below.

2.1.2. Increases in anxiety

Anecdotal evidence suggests that when individuals have an excessive amount of caffeine they may become anxious. Similarly, some psychiatric patients attribute their problems to consumption of caffeine, which has led to a diagnosis of "caffeinism". Other patients, especially those with anxiety disorders, report that caffeine may exacerbate their problems. The validity of these questions will now be assessed by consideration of the literature on these topics.

Lieberman (1992) stated that "... it appears that caffeine can increase anxiety when administered in single bolus doses of 300 mg or higher, which is many times greater than the amount present in a single serving of a typical caffeine-containing beverage. However, in lower doses it appears to have little effect on this mood-state or, under certain circumstances, it may even reduce anxiety levels. It has also been observed that caffeine reduces self-rated depression when administered in moderate doses (Lieberman, 1988)."

The literature supports Lieberman's view since only a small proportion of the studies reviewed show increases in anxiety following administration of caffeine. Stern et al. (1989) found that individuals who choose a high dose of caffeine reported positive mood changes whereas non-choosers reported anxiety and dysphoria. Loke (1988) found that caffeine reduced fatigue but also led to increased tension and nervousness. Increased anxiety was also reported following caffeine by Loke et al. (1985) where the doses were high (either 3 or 6 mg/kg). Similarly, Sicard et al. (1996) found increased anxiety following 600 mg of caffeine. Green and Suls (1996) also found that caffeine increased anxiety, and again the volunteers were consuming very high amounts (125 mg caffeine per cup of coffee over the day). Overall, these results suggest that increases in anxiety following caffeine are often only found following consumption of amounts that would rarely be ingested by the majority of people.

It is now important to assess whether caffeine leads to mood problems when the person ingesting it already has a high level of anxiety. It has been claimed that some people abstain from caffeinated drinks because of the accompanying jitteriness and nervousness (Goldstein et al., 1969). Other authors have even gone as far as to suggest that caffeine acts as a "fairly convincing model of generalised anxiety" (Lader and Bruce, 1986). Caffeinism refers to a constellation of symptoms associated with very high caffeine intake that are virtually indistinguishable from severe chronic anxiety (Greden, 1974). Caffeinism is usually associated with daily intakes of between 1000 and 1500 mg. However, it appears to be a rather specific condition and there is little evidence for correlations between caffeine intake and anxiety in either non-clinical volunteers (Lynn, 1973; Hire, 1978) or psychiatric outpatients (Eaton and Mcleod, 1984).

Correlational studies of associations between caffeine and anxiety have a number of methodological problems. Although it is better to examine the anxiety-producing effects of a direct caffeine challenge, much of this research has used very high doses (e.g. 6.6 mg/kg—Veleber and Templer, 1984; 10 mg/kg—Charney et al., 1985), which makes it difficult to determine whether the issue is relevant to doses more representative of normal consumption. Other studies have used a caffeine challenge with psychiatric patients with anxiety disorders (e.g. Bruce et al., 1992), although even with this group there is little evidence that smaller doses exacerbate the existing anxiety (Mathew and Wilson, 1990).

Other research examined whether caffeine is capable of increasing the anxiety induced by other stressors. Shanahan and Hughes (1986) found that 400 mg of caffeine increased anxiety when paired with a stressful task. However, other research (e.g. Hasenfratz and Battig, 1992; Smith et al., 1997b) has not been able to provide any evidence of interactive effects of caffeine and stress.

Overall, the literature suggests that extremely high doses of caffeine may increase anxiety, but that this is rarely seen within the normal range of ingestive behavior.

The next section considers another area where caffeine is claimed to be associated with adverse effects, namely when it is withdrawn.

2.1.3. Caffeine withdrawal and mood

Caffeine withdrawal has been widely studied because it is meant to provide crucial evidence on whether caffeine is addictive or leads to some kind of dependence. The most frequent outcome measure has been reporting of headache, but mood has been examined in other studies. Ratcliff-Crain et al. (1989) reported that caffeine deprivation led to increased reporting of stress by heavy coffee drinkers. This has recently been confirmed by Schuh and Griffiths (1997), who found that caffeine withdrawal was associated with feelings of fatigue and decreased feelings of alertness. Indeed, Silverman et al. (1992) found that about 10% of volunteers with a moderate daily intake (235 mg per day) reported increased depression and anxiety when caffeine was withdrawn.

Other researchers (e.g. James, 1994) have argued that caffeine has no beneficial behavioral effects but merely removes negative effects associated with caffeine withdrawal. Smith (1995) has argued against this general view of caffeine effects on a number of grounds. First, it cannot account for the behavioral effects seen in animals or non-consumers, where withdrawal cannot occur. Secondly, caffeine withdrawal cannot account for behavioral changes following caffeine consumption after a short period of abstinence or the greater effects of caffeine when arousal is low. Finally, claims about the negative effects of caffeine withdrawal require closer examination since they can often be interpreted in ways other than caffeine dependence (e.g. expectancy—Smith, 1996a; Rubin and Smith, 1999). Indeed, in most of the studies that have demonstrated increases in negative effect following caffeine withdrawal, the subjects have not been blind but have been told or even instructed to abstain from caffeine. This is clearly very different from the double-blind methodology typically used to study effects of caffeine challenge.

2.2. Caffeine and mood: a summary

The preceding sections confirm the suggestions about effects of caffeine on mood that were made at the start. To reiterate, the literature shows that:

- caffeine, even in low doses, may increase alertness and this is readily apparent in low arousal situations
- high doses of caffeine can lead to increased anxiety in some individuals
- caffeine withdrawal increases negative affect but this may reflect expectancy effects. It is also unlikely that this can account for the positive mood effects produced by caffeine when given to non-consumers or to volunteers who have not had caffeine withdrawn.

The next section considers effects of caffeine on the efficiency of mental performance.

3. Caffeine and performance efficiency

3.1. Studies before 1990

There are already a number of extensive reviews (e.g. Lieberman, 1992) which have summarized early studies of the effects of caffeine on human performance. This section outlines the main points to emerge from such reviews, and is then followed by a critical evaluation of more recent research in this area.

3.1.1. Mechanisms of action

There is a great deal of evidence to shows that caffeine blocks the effects of the naturally occurring neuromodulator adenosine (Snyder, 1984). This produces a net increase in CNS activity because the inhibitory action of adenosine is blocked. The effects of caffeine on adenosine activity, and the subsequent effects for neurotransmitters such as norepinephrine, occur at concentrations found as a function of dietary intake. Other mechanisms have been demonstrated (e.g. calcium mobilisation, prostaglandin antagonism, phosphodiesterase inhibition), but these only become relevant when caffeine is administered in doses that are at least 20–30 times higher than those found in the diet (Snyder, 1984). In humans peak plasma levels occur 15–45 min after ingestion and its plasma half-life is 5–6 h. Different mammals use different pathways to metabolise caffeine, and many studies of animal behavior are, therefore, not relevant to its effects on humans.

3.1.1.1. Early views of behavioral effect of caffeine. Most consumers of caffeine regard it as a mild stimulant when consumed in moderate doses, as recognised over 400 years ago by Pietro della Vale (cited by Tannahill, 1989). Reviews written in the 1980s (e.g. Sawyer et al., 1982; Dews, 1984) suggested that the effects were highly variable and the subject of considerable controversy. Indeed, Dews (1984) has suggested that when caffeine is administered in the doses found in foods, its effects are "so slight and subtle that the investigator is usually glad to be able to detect them".

The above view probably reflects the numerous problems associated with early studies of caffeine. First, many studies have used insensitive tests and designs. It is quite plausible that the effects of small doses of caffeine will be marginal and many of the negative results may well reflect the absence of appropriate statistical power. This problem is often compounded by the use of weak experimental designs (e.g. no baseline data) and failure to consider individual differences.

3.1.1.2. Effects on different functions

3.1.1.2.1. Sensory functions. Lieberman (1992) stated that "there is no evidence to suggest that moderate doses of caffeine have direct effects on sensory function, although well controlled studies using state-of-the-art methods have not been conducted".

3.1.1.2.2. Simple and choice reaction time. There are a number of studies which have shown beneficial effects of caffeine on simple reaction time (e.g. Clubley et al., 1979) and choice reaction time (Smith et al., 1977; Lieberman et al., 1987; Roache and Griffiths, 1987). Other studies have demonstrated such effects in some groups but not others (e.g. the elderly but not the young—Swift and Tiplady, 1988) and with some doses but not others (beneficial effects with 200 and 400 mg but not 600 mg—Roache and Griffiths, 1987).

3.1.1.3. Vigilance

Several papers suggest that caffeine, in moderate doses, will improve vigilance (Regina et al., 1974; Clubley et al., 1979). Indeed, Lieberman (1992) suggests that beneficial effects can be observed with doses as low as 32 mg "when a sensitive test is employed in an appropriate testing paradigm".

Other researchers (e.g. Loke and Meliska, 1984) have failed to demonstrate significant effects of caffeine on vigilance, but there is an absence of data suggesting that it may actually lead to impairments.

3.1.1.4. Memory and cognition

Although there have been a large number of early studies of effects of caffeine on more complex cognitive processes, it is hard to draw definitive conclusions. If, for example, one considers verbal learning tasks then one finds a large number of studies which have shown no effect of caffeine (e.g. Clubley et al., 1979; File et al., 1982; Battig et al., 1984; Loke et al., 1985). Many of these failures to detect effects on memory were carried out using a methodology that was sensitive enough to detect caffeine effects on psychomotor or sustained attention tasks (e.g. Lieberman et al., 1987; Roache and Griffiths, 1987).

It would appear from these early studies that the effects of caffeine on cognitive performance are often too small to detect as general group effects. Some positive results have been obtained (e.g. Erikson et al., 1985) but only in very specific conditions (when testing was conducted at a slow, not a fast rate). Again, however, there appears to be little evidence suggesting impairments following consumption of caffeine.

3.1.1.5. Simulation of real-life tasks

Regina et al. (1974) examined the effects of caffeine on a simulated driving task. The results showed beneficial effects of caffeine and confirmed findings using laboratory vigilance tasks. Studies conducted by the military (cited by Lieberman, 1992) have also shown that caffeine can improve a critical military task, namely sentry duty.

3.1.1.6. Caffeine and daytime sleepiness

Beneficial effects of caffeine in low arousal situations will be considered more closely in a following section. However, studies conducted in the 1980s clearly demonstrated that caffeine can remove the sedative effects of certain drugs (e.g. diazepam—File et al., 1982; Roache and Griffiths, 1987).

3.1.1.7. Caffeine, personality and time of day

Research by Revelle and colleagues (see Revelle et al., 1987, for a review) showed that caffeine facilitated the performance of impulsive individuals and impaired the performance of non-impulsive individuals taking complex cognitive tests in the morning. In the evening, the opposite pattern of results was observed. This has been interpreted in terms of relationships between optimum levels of arousal and complex tasks performance. Such effects do not appear with simple tasks, where even high levels of alertness facilitate performance.

3.1.1.8. Adverse effects of caffeine on performance

3.1.1.8.1. Fine motor performance. Anecdotally, it has been suggested that the increased arousal induced by consumption of caffeine impairs hand steadiness. However, early studies failed to demonstrate such effects (e.g. Lieberman et al., 1987) or found them only in non-consumers (e.g. Kuznicki and Turner, 1986).

3.1.1.8.2. Caffeine withdrawal. Lieberman (1992) discusses the effects of caffeine on headache and mood but cites no evidence to suggest that it influences performance. This issue will be discussed again in a later section.

3.1.1.9. A cost–benefit analysis of early studies of the behavioral effects of caffeine

Lieberman (1992) reaches the following conclusions about the beneficial and adverse behavioral effects of caffeine. "When caffeine is consumed in the range of doses found in many foods, it improves the ability of individuals to perform tasks requiring sustained attention, including simulated automobile driving. In addition, when administered in the same dose range, caffeine increases self-reported alertness and decreases sleepiness". "Adverse behavioral effects occur when caffeine is consumed in excessive doses or by individuals who are overly sensitive to the substance".

Overall, the early studies suggested that consumption of caffeine may have beneficial effects which can improve safety in automobile driving, other transport operations and industry. The next section reviews more recent research to see whether adjustments to this view are required.

3.1.2. A summary of results from studies of caffeine and performance conducted prior to 1990

- A number of different CNS mechanisms by which caffeine could change performance were identified
- Early reviews of the performance effects suggested that effects were variable and slight
- There appeared to be no direct effects of caffeine on sensory functions
- A number of studies showed that caffeine improved simple and choice reaction time
- Sustained attention has also been shown to be improved by caffeine
- Effects of caffeine on memory have not been demonstrated
- Simulations of real-life tasks (e.g. driving) have shown beneficial effects of caffeine
- Caffeine has been shown to remove impairments produced by decreases in arousal
- Complex interactions between caffeine, personality and time of day have been reported
- Some studies have shown that caffeine impairs fine motor control
- A cost–benefit analysis suggested that doses of caffeine similar to those consumed by the majority of the population increase alertness and the ability to sustain attention. Adverse effects occur when excessive doses are consumed or when caffeine is given to certain sensitive individuals

3.2. Research since 1990

Recent studies of effects of caffeine on performance have confirmed many of the earlier results. For example, the beneficial effects of caffeine on psychomotor speed and vigilance have been replicated (Frewer and Lader, 1991; Mitchell and Redman, 1992; Fine et al., 1994). Similarly, the absence of group effects in more complex cognitive tasks has also been observed (Loke, 1990, 1992). Isolated reports of caffeine-induced impairments are also to be found (e.g. decreased hand steadiness—Bovim et al., 1995). Research has continued to study the effects of caffeine on attention tasks with one aim being to identify mechanisms underlying the effects. For example, Smith et al. (1999a) and Smith (2001) have shown that caffeine increases the speed of processing new stimuli, confirming results reported by Streufert et al. (1997). Lorist and Snel (1997) have also shown that target detection and response preparation are enhanced by caffeine, and Ruijter et al. (1999) have demonstrated that the quantity of information processed is greater after caffeine. In contrast, no effects of caffeine on output processes (e.g. movement time) have been demonstrated (Lorist, 1998), nor has caffeine been shown to reduce resistance to distraction (Kenemans and Verbaten, 1998).

Research has also sought to link performance effects seen with laboratory tasks with possible effects in real-life activities. Brice and Smith (2001a) found that caffeine improved both performance on a driving simulator and laboratory tests of attention. Similarly, when performance of reaction time tasks was measured before and after a normal working day, caffeine consumption during the day was seen to reduce the slowing of reaction times seen at the end of the day (suggesting that caffeine may maintain performance levels at work).

A major research issue has been whether caffeine can remove impairments produced by fatigue or drugs. These studies are now briefly reviewed.

3.2.1. Effects of caffeine in low arousal states

A number of studies from the late 1980s and early 1990s show that caffeine removes the performance impairments produced by sleep loss, fatigue, working at night or by sedative drugs (Rogers et al., 1989; Johnson et al., 1990, 1991; Nicholson et al., 1990; Zwyghuizen-Doorenbos et al., 1990). These findings have important implications for safety-critical jobs and for maintaining operational efficiency in low alertness situations. Indeed, other research has shown that the decreased alertness produced by consumption of lunch can be eliminated by consumption of caffeinated coffee (Smith et al., 1991a; Smith and Phillips, 1993). Furthermore, alertness is often reduced by minor illnesses such as the common cold, and recent research has shown that caffeine can remove the impaired performance and negative mood associated with these illnesses (Smith et al., 1997a). The ability of caffeine to counteract the effects of fatigue has been confirmed using simulations of driving (Horne and Reyner, 1996; Reyner and Horne, 1997) and also simulated assembly-line work (Muehlbach and Walsh, 1995). The latter study demonstrated significant improvements after caffeine on five consecutive nights and showed no decrements when caffeine was withdrawn. Effects of caffeine on more complex cognitive tasks are again less clear (Linde, 1995), which may reflect the importance of individual differences.

Some of the above studies allow one to assess the magnitude of the beneficial effects of caffeine. For example, Smith et al. (1993a) found that consumption of caffeine at night maintained individuals at the levels seen in the day. Another approach has been to compare the effects of caffeine with other approaches aimed at counteracting sleepiness. Bonnet and Arand (1994a,b) report that the combination of a prophylactic nap and caffeine was more effective in maintaining nocturnal alertness than was the nap alone.

Other research has demonstrated that administration of caffeine can remove impairments produced by sedative drugs (e.g. alcohol—Kerr et al., 1991; Hasenfratz et al., 1993; Rush et al., 1993; Hasenfratz and Battig, 1994; Scopolamine—Riedel et al., 1995; Lorazepam—Rush et al., 1994a; Triazolam—Rush et al., 1994b).

One issue is whether positive effects of caffeine are largely restricted to low alertness situations. Battig and Buzzi (1986) argued that caffeine can improve performance beyond a mere restoration of fatigue. Other studies have shown that fatigued subjects show larger performance after caffeine than do well-rested volunteers (Linde, 1994; Lorist et al., 1994a,b). This pattern of results fits with the conclusion of Smith (1994, 1996b, 1998), namely that effects of small doses of caffeine are most easily demonstrated in low alertness paradigms whereas more global effects can be observed with doses of 200–300 mg. Indeed, very high doses may increase the risk of producing some of the adverse effects described earlier, as has been confirmed in a study of the dose–response relationships of caffeine (Hasenfratz and Battig, 1994). The results of this last study suggested that beneficial behavioral effects were found with doses comparable to those found in caffeine-containing beverages. Furthermore, these levels of caffeine do not exacerbate negative effects produced by stressful conditions (e.g. electrical shocks—Hasenfratz and Battig, 1992; noise—Smith et al., 1997b).

It is highly likely that many different CNS mechanisms underlie the effects of caffeine on behavior. Caffeine's major effect is as an antagonist of the adenosine receptors, which in turn affects the release of a variety of neurotransmitters (e.g. noradrenaline, acetylcholine, dopamine and the GABA/benzodiazepine system). One approach to understanding the CNS mechanisms underlying the effects of caffeine has been to combine pharmacological challenges with administration of caffeine. Alertness can be reduced by changing a number of the neurotransmitter systems. For example, by using clonidine, a drug which reduces the turnover of central noradrenaline, it is possible to mimic sleep deprivation in a period of a few hours. Smith and Brice (2001) report results from a study combining caffeine/placebo and clonidine/placebo conditions. Caffeine was found to reverse the effects of clonidine but produce few effects when the volunteers were alert. However, some effects of caffeine (e.g. the beneficial effect on encoding of new information; the cardiovascular effects) were not related to changes in the noradrenergic system. Indeed, Rusted and Smith (unpublished) have shown that the encoding of new information reflects the cholinergic system and there is evidence from other studies (Riedel et al., 1995) that caffeine also influences this neurotransmitter.

There are five other areas that need to be considered here. The first is concerned with the role of individual differences in personality.

3.2.2. *Caffeine and impulsivity*

A number of studies have confirmed the interactive effects of caffeine and the personality dimension of impulsivity (Smith et al., 1991b, 1994b; Gupta, 1988a,b; Gupta and Gupta, 1999). Some of these results fit predictions from the Yerkes-Dodson law which states that performance is an inverted-U function of arousal with a negative relationship between optimal arousal and task difficulty. Anderson (1994) found that performance was an interactive function of task difficulty, caffeine and impulsivity. Performance on an easy letter cancellation task was improved as caffeine dose increased, but on a difficult task impulsive subjects (less aroused) improved while non-impulsive subjects (more aroused) improved then deteriorated. Other results do not fit this pattern and could reflect other individual differences such as expectancies or caffeine usage.

3.2.3. *Expectancy effects*

Fillmore and colleagues (Fillmore and Vogel-Sprott, 1992, 1994, 1995; Fillmore, 1994, 1999) have clearly demonstrated that effects of caffeine depend on a person's expectations. Indeed, these expectations can generalize to placebo conditions if the individual is led to expect that they are consuming a caffeinated beverage. In many experiments the role of expectations has not been assessed and these could account for at least some of the conflicting results in the caffeine literature.

Another possible confounding factor is the role of regular levels of consumption.

3.2.4. Regular level of caffeine consumption

There has been far less research on the effects of regular caffeine consumption than on acute effects. However, a number of papers suggest that high consumers demonstrate better performance (Loke, 1988, 1989; Smith et al., 1993b). This view is confirmed by other studies which suggest that non-consumers of caffeine have the worst performance (Jacobsen and Thurman-Lacey, 1992) especially when challenged with caffeine. There are exceptions which have shown high users to be impaired (Mitchell and Redman, 1992), although these effects are often restricted to the performance of specific tasks.

The strongest evidence for beneficial effects of regular caffeine consumption comes from a study by Jarvis (1993). He examined the relationship between habitual coffee and tea consumption and cognitive performance using data from a cross-sectional survey of a representative sample of over 9000 British adults. Subjects completed tests of simple reaction time, choice reaction time, incidental verbal memory and visuo-spatial reasoning, in addition to providing self-reports of usual coffee and tea intake. After controlling extensively for potential confounding variables, a dose–response trend to improved performance with higher levels of coffee consumption (best performance associated with about 400 mg caffeine per day) was found for all tests. Estimated overall caffeine consumption showed a dose–response relationship to improved cognitive performance that was strongest in those who had consumed high levels for the longest time period (the 55 years + age group). Studies by Hogervorst et al. (1998) and Rogers and Dernoncourt (1998) have failed to replicate these effects using acute caffeine challenges which suggests that the above effects do reflect regular consumption patterns rather than recent intake of caffeine.

Overall, the previous sections confirm that the effects of caffeine on performance are largely beneficial. However, this view has recently been questioned by James (1994), who argues that the beneficial effects of caffeine are really only removal of negative effects produced by caffeine withdrawal. The final section considers whether caffeine withdrawal does actually impair performance efficiency.

3.2.5. Effects of caffeine withdrawal on performance

The view that beneficial effects of caffeine reflect degraded performance in the caffeine-free conditions (James, 1994) crucially depends on the strength of the evidence for withdrawal effects. James states that "there is an extensive literature showing that caffeine withdrawal has significant adverse effects on human performance". If one examines the details of the studies cited to support this view (Griffiths et al., 1990; Hughes et al., 1990, 1991; van Dusseldorp and Katan, 1990; Silverman et al., 1992) one finds that some of them do not even examine performance, and that where they do, any effects are selective, not very pronounced, and largely unrelated to the beneficial effects of caffeine reported in the literature.

Rogers et al. (1995) have reviewed a number of studies of caffeine withdrawal and performance. They conclude that "...in a review of recent studies we find no unequivocal evidence of impaired psychomotor performance associated with caffeine withdrawal". Indeed, they found that caffeine improved performance in both deprived volunteers and non-consumers (Richardson et al., 1994). Furthermore, other studies which suggest that withdrawal may impair performance (e.g. Rizzo et al., 1988; Bruce et al., 1991) can be interpreted in other ways than deprivation (e.g. changes in state—Overton, 1984). Other research (e.g. Griffiths et al., 1986) has failed to demonstrate negative effects of caffeine withdrawal on performance. Another problem for the caffeine withdrawal explanation of improved performance following caffeine is that it cannot account for the beneficial effects of caffeine observed even when volunteers abstain for a short period of time (Smith et al., 1994b; Warburton, 1995).

The effects of caffeine withdrawal are still controversial. This can be seen when one looks at reviews of the topic (Daly and Fredholm, 1999; Nehlig, 1999) and at empirical studies. For example, James (1998) showed that caffeine withdrawal impaired short-term memory performance but caffeine ingestion had no effect. In contrast, Smith (1999) reported that caffeine improved attention in both those who had been deprived of caffeine for a short period and those who had no caffeine for 7 days. In this study caffeine withdrawal had no effect on performance. Studies of children (Goldstein and Wallace, 1997; Bernstein et al., 1998) have suggested that caffeine withdrawal may have negative effects on mood and performance. Other studies (e.g. Comer et al., 1997) suggest that effects of withdrawal are restricted to mood and that performance is unaltered. Like many areas of caffeine research, some of the effects that have been attributed to withdrawal are open to other interpretations. For example, Lane (1997), Phillips-Bute and Lane (1997) and Lane and Phillips-Bute (1998) compared days when mid-morning coffee was either caffeinated or decaffeinated. Caffeine consumption was associated with better performance and mood. The authors interpret this as a negative effect of caffeine withdrawal whereas one could interpret it as a positive effect of caffeine. Other studies of caffeine withdrawal effects have methodological problems such as the lack of pre-drink baselines (e.g. James, 1998; Robelin and Rogers, 1998) or the consideration of asymmetric transfer when using within subject designs (e.g. James, 1998). Indeed, while there have been a great number of studies of the behavioral effects of caffeine, there are still a large number of methodological issues that need further consideration and these are outlined below.

One method that can resolve whether caffeine effects are due to removal of caffeine withdrawal is to study the effects on caffeine on the behavior of non-consumers. Smith et al. (2001) describe results from three studies that, used this technique. All studies were able to show beneficial effects of caffeine in both regular consumers and non-consumers, which raises serious doubts about the caffeine withdrawal explanation.

3.2.6. Methodological issues

3.2.6.1. Consumption regimen. Most studies of the effects of caffeine have administered a single large dose, often equivalent to the person's total daily consumption level. Caffeine is usually ingested in a number of smaller doses (Brice and Smith, 2002) and it is unclear whether effects observed after a single large dose are the same as those produced by an identical level produced by consuming several caffeine containing drinks over a longer time period. Smith and Brice (2001a,b) describe a study that examined this issue and found that the improved mood and enhanced performance found after a single dose of 200 mg were also observed following four doses of 65 mg given at hourly intervals (which resulted in an identical final level to the single 200 mg dose).

3.2.6.2. Metabolism of caffeine. Most of the beneficial effects of caffeine show a linear dose–response relationship up to about 300 mg and this is then followed by either a flattening of the curve or, sometimes, impaired performance at higher doses. Brice and Smith (2001b) examined the relationship between metabolism of a fixed dose of caffeine (as indicated by saliva levels) and mood and performance changes and found that there was no strong association between the two. This is not too surprising in that it is not caffeine levels in the periphery per se which produce the behavioral changes but secondary CNS mechanisms. The individual differences in the metabolism of the caffeine may be very different from the individual differences in the CNS mechanisms which, plausibly, accounts for the lack of a strong association between plasma (or saliva levels) and behavioral changes.

3.2.6.3. Effects of low doses. A number of studies (e.g. Lieberman et al., 1987; Durlach, 1998; Smith et al., 1999b) have shown that beneficial effects of doses of caffeine typically found in commercial products can now be demonstrated in both measures of mood and performance.

3.3. Caffeine and mental performance: a summary

A detailed review of recent studies confirmed views described in a review by Lieberman (1992). To reiterate, the literature shows:

- Caffeine, in doses that would be obtained in normal consumption of caffeinated products, improves performance of vigilance tasks and simple tasks which benefit from a high level of alertness.
- The beneficial effects of caffeine can be most easily demonstrated in low arousal situations. However, improved performance has been shown when reduced alertness is not involved.
- Caffeine improves performance of artificial tasks and simulations of driving and industrial work. These findings suggest that it will be of benefit in safety-critical situations and will improve operational efficiency.
- Effects on more complex cognitive tasks are less clear cut, probably because of the moderating influence of factors such as personality and time of day. However, even this area shows few costs of caffeine consumption.
- It has been claimed that the positive effects of caffeine really reflect removal of negative effects of caffeine withdrawal. This view cannot account for effects observed in non-consumers or non-deprived individuals. In addition, there is little evidence of caffeine withdrawal impairing tasks which show improvements following ingestion of caffeine.
- More research is required on the effects of regular levels of caffeine consumption on performance efficiency. However, there is some evidence that high consumption is associated with better performance, especially in the elderly.
- A cost–benefit analysis of the effects of caffeine on performance reveals that this is an area where most of the evidence suggest benefits.

4. Effects of caffeine on sleep

Much of the research on caffeine and sleep has been concerned with removing unwanted sleepiness either when the person is working at night or when they are sleep deprived. The fact that caffeine can remove sleepiness means that it can, of course, interfere with normal sleep. However, patterns of consumption suggest that individuals usually control their caffeine intake to prevent interference with sleep. If large amounts of caffeine are consumed shortly before trying to sleep, then it will undoubtedly disturb sleep. The experimental evidence for such effects is well established and is briefly summarized below.

A number of studies have shown that caffeine increases sleep latency (e.g. Zwyghuizen-Doorenbos et al., 1990), and reduces sleep duration (Hicks et al., 1983). Caffeine often produces its effects by increasing latencies in the first half of the night (Bonnet and Webb, 1979) which is different from the insomnia seen in hypnotic withdrawal (Brezinova et al., 1975). It would not appear, therefore, that caffeine-induced insomnia acts as a good general model of insomnia, as suggested by some researchers (Alford et al., 1996).

There are large individual differences in the effects of caffeine on sleep. For example, one study has shown that even caffeine given in the early morning can influence the subsequent night's sleep (Landolt et al., 1995), whereas other individuals report that they can consume caffeine-containing beverages before bedtime with no adverse impact on their sleep (Colton et al., 1967; Levy and Zylber-Katz, 1983). There are probably many reasons for these differences, but it appears to be established that high consumers appear less likely to report sleep disturbance than those who only consume caffeine infrequently (Snyder and Sklar, 1984). Indeed, other results suggest that tolerance develops to effects of caffeine on sleep (Zwyghuizen-Doorenbos et al., 1990) but that there are no withdrawal effects on sleep when caffeine is no longer given (Searle, 1994). It is also unclear whether the sleep disturbance produced by caffeine has an impact on behavior the next day, with one study showing no changes in mood and performance following caffeine disturbed sleep (Smith et al., 1993b).

While it is quite easy to demonstrate effects of late-night caffeine on sleep, it is much harder to find evidence that high levels of consumption per se will affect sleep. Hicks et al. (1983) conducted a survey to examine the associations between daily caffeine consumption, habitual sleep duration and sleep satisfaction. The results showed an inverse relationship between level of daily consumption of caffeinated drinks and habitual sleep duration, but no significant association between caffeine consumption and sleep satisfaction. Dekker et al. (1993) examined the impact of caffeine consumption on the sleep of locomotive engineers and their spouses. For the engineers only, caffeine consumption was correlated with longer sleep latency. The effect was not apparent in their spouses.

Other surveys have found little evidence of associations between caffeine consumption and sleep. For example, Lee (1992) examined data from 760 nurses. The results showed that age and family factors contributed to differences in sleep much more than caffeine. Similarly, Greenwood et al. (1995) found no effect of caffeine consumption on the sleep of 72 rotating-shift workers. Finally, a study of sleep in elderly women found no differences in level of caffeine consumption in good and poor sleepers (Bliwise, 1992).

Overall, the research on the effects of caffeine on sleep leads to three main conclusions. First, large amounts of caffeine (e.g. over 3 mg/kg in a single beverage) consumed in the late evening will prevent individuals from going to sleep and reduce sleep duration. Effects of smaller doses show large individual variation, with high consumers being more resistant to effects of caffeine on sleep. Secondly, the impact of caffeine-induced changes in sleep on behavior the next day and long-term health is not known. Finally, high levels of caffeine consumption do not appear to be strongly related to sleep parameters. This again suggests that consumption is usually controlled to avoid any potential adverse effects on sleep.

4.1. Caffeine and sleep: a summary

- It is quite clear that high doses of caffeine in the late evening will increase the time taken for some individuals to go to sleep.
- The effects of smaller doses vary from individual to individual, and even when sleep is affected there is no clear evidence that the effects are of a sufficient magnitude to influence health and well-being.
- Indeed, people are usually very good at controlling their caffeine intake, which means that there is not any strong evidence relating level of caffeine consumption to sleep problems.

5. Conclusions

The present article has reviewed the effects of caffeine on mood, mental performance and sleep. In all areas it is apparent that there is a big difference between the effects of amounts of caffeine that are normally consumed and those observed when excessive amounts are ingested, or when very sensitive individuals are studied. Most of the research has examined acute effects of single doses, and further studies are needed to produce a more detailed profile of effects of regular levels of consumption. However, the general picture to emerge is that when caffeine is consumed in moderation by the majority of the population there are unlikely to be many negative effects. Indeed, the positive effects may be important in maintaining efficiency and safety in both the workplace and other environments. Excessive consumption of caffeine will produce problems, and appropriate information should be given to minimise effects in psychiatric patients and other sensitive groups. It is important to balance this with information on the benefits of caffeine, for most consumers can usually control their intake to maximise the beneficial effects and reduce or prevent adverse effects due to over-consumption or consumption at inappropriate times.

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