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ORIGINAL INVESTIGATION

I. Hindmarch · P.T. Quinlan · K.L. Moore · C. Parkin

The effects of black tea and other beverages on aspects of cognition and psychomotor performance

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Abstract Nineteen healthy volunteers ingested 400 ml black tea, coffee, caffeinated water, decaffeinated tea or plain water on three occasions through the day (0900, 1400 and 1900 hours). A 2 × 2 factorial design with caffeine (0, 100 mg) and beverage type (water, tea) was employed, with coffee (100 mg caffeine) as a positive internal control, based on a five-way crossover. A psychometric test battery comprising critical flicker fusion (CFF), choice reaction time (CRT), short-term memory (STM) and subjective sedation (LARS) was performed at regular intervals throughout the day, and intensively so immediately following each beverage. Consumption of tea compared to water was associated with transient improvements in performance (CFF) within 10 min of ingestion and was not affected by the time of day. Caffeine ingestion was associated with a rapid (10 min) and persistent reduction in subjective sedation values (LARS), again independent of time of day, but did not acutely alter CFF threshold. Over the whole day, consumption of tea rather than water, and of caffeinated compared to decaffeinated beverages, largely prevented the steady decline in alertness (LARS) and cognitive capacity observed with water ingestion. The effects of tea and coffee were similar on all measures, except that tea consumption was associated with less variation in CFF over the whole day. No significant treatment effects were apparent in the data for the STM. Tea ingestion is associated with rapid increases in alertness and information processing capacity and tea drinking throughout the day largely prevents the diurnal pattern of performance decrements found with the placebo (no caffeine) condition. It appears that the effects of tea and coffee were not entirely due to caffeine per se; other factors either intrinsic to the beverage (e.g. sensory attributes or the presence of other biologically active substances) or of a psychological nature (e.g. expectancy) are likely to play a significant role in mediating the responses observed in this study.

Key words Caffeine · Tea · Coffee · Psychomotor performance · Cognitive function

I. Hindmarch (✉) · C. Parkin
HPRU, University of Surrey, Milford Hospital, Godalming, Surrey GU7 1UF, UK

P.T. Quinlan · K.L. Moore
Unilever Research, Colworth Laboratory, Bedford MK44 ILQ, UK

Introduction

Caffeine, a methylxanthine derivative, is generally regarded as a mild central nervous system stimulant. Black tea and coffee are the main sources of caffeine in the Western diet, with a typical serving of instant coffee delivering ~ 80 mg caffeine in 200 ml, and brewed black tea ~ 40 mg/200 ml (Barone and Roberts 1984). Caffeine content can vary considerably depending on beverage type and make-up procedures.

Although there are numerous studies on the effects of caffeine and coffee (Loke et al. 1985; Loke 1990; Frewer and Lader 1991; Lorist et al. 1994; Smith et al. 1994), there are few studies describing the acute effects of tea. This is surprising as tea, an infusion of unfermented ("green") or fermented ("black") leaves from the plant *Camelia sinensis*, is the most frequently consumed beverage in the world apart from water (Graham 1992).

To date, there are few studies reporting a psychopharmacological effect of tea consumption independent of caffeine, and these are confined to in vitro or animal models. Chronic administration of decaffeinated green tea in the drinking water of mice exposed to psychosocial stress significantly reduced physiological stress markers and behavioural responses (Henry and Stephens-Larson 1984).

More recently, it has been reported that at least some flavonoids possess a selective and relatively mild affinity for benzodiazepine receptors and a pharmacological profile compatible with that of a partial agonist action (Medina et al. 1997). However, the effect of flavonoids found in tea on these receptors has not been investigated, and these findings have not been followed up with well-controlled human trials. Nevertheless, they raise the intriguing possibility that biologically active substances in tea may have independent psychopharmacological effects and/or modify the effects of caffeine in the body. One way of testing this hypothesis is to investigate whether the psychopharmocological effects of beverages such as tea and coffee are similar to those of equivalent doses of caffeine, per se.

There is considerable evidence that caffeinated beverages other than tea can produce an improvement in cognitive function and psychomotor performance (Barone and Roberts 1984; Smith et al. 1990; Zwyghuizen-Doorenbos et al. 1990; Kerr et al. 1991; Mitchell and Redman 1992; Jarvis 1993; Bonnet and Arand 1994; Rogers et al. 1994; Bonnet et al. 1995). Although results are sometimes inconsistent, the usual finding is that caffeine improves performance on a variety of tasks, particularly those requiring sustained effort or attention (e.g. Nicholson et al. 1984; Smith et al. 1990; Frewer and Lader 1991; Bonnet and Arand 1994; Lorist et al. 1994). It has been argued that caffeine simply restores degraded performance in those subjects under caffeine withdrawal, but there is evidence that it can also enhance non-degraded performance (Rogers et al. 1994). Furthermore, a highly significant positive relationship exists between habitual caffeine intake and psychomotor performance (Jarvis 1993). These effects occur in non-users of caffeine and in those with their preferred levels of caffeine, as well as in subjects deprived of their normal intake of caffeine. Performance differences are pronounced in the last group, particularly in vigilance tasks. For example, in caffeine deprived subjects, Starmer et al. (1995) showed that caffeine improved accuracy on a tracking task compared to placebo where performance deteriorated. Kerr et al. (1991) showed that caffeine also enhances performance and cognition in non-deprived subjects, on a range of tests including critical flicker fusion and choice reaction time. Similar results have been found by Barlow and Baer (1967) and Zwyghuizen-Doorenbos (1990), among others.

Vigilance (and cognitive performance) typically declines over the day, and it is therefore plausible that regular consumption of caffeinated beverages throughout the day may help prevent this performance decrement. The time course of these effects, however, has not been described.

The effects of caffeine tend to be dose and task-related. Moderate doses of caffeine improve psychomotor performance, whereas higher doses may not. Frewer and Lader (1991) found that attention and vigilance were improved by a 250 mg dose of caffeine compared to placebo. A higher dose (500 mg) of caffeine impaired performance at 45 min post-ingestion; however, at 165 min post-administration, 500 mg caffeine facilitated performance on this task. Improvements in reaction time performance were maintained in the high-dose group. Furthermore, tasks with a significant motor component are known to be more susceptible to the effects of caffeine (Chait and Griffiths 1983; Loke et al. 1985; Ghoneim et al. 1986; Foreman et al. 1989; Loke 1990; Frewer and Lader 1991). This emphasises the importance of studying the psychopharmacological effects of caffeine at doses relevant to normal consumption patterns.

Caffeine attains maximum plasma concentration (T_{max}) around 30–60 min post-consumption (Marks and Kelly 1973; Bonati et al. 1982; Blanchard and Sawers 1983; Passmore et al. 1987) and has an elimination half-life of between 3 and 6 h, though the latter can be affected by a range of factors, including smoking and oral contraceptives (Fagan et al. 1988; Lader and Bruce 1989; Snel 1993). Caffeine is a lipophilic substance that easily passes across the blood-brain barrier and a close relationship should exist between the pharmacokinetic and pharmacodynamic effects of the substance. It would be expected, therefore, that the cognitive and psychomotor effects of caffeine would be maximal around the T_{max}. For this reason, caffeine effects are often measured > 45 min post-administration (e.g. File et al. 1982; Lieberman et al. 1987; Zahn and Rapoport 1987a,b; Swift and Tiplady 1988; Corr et al. 1995), though a few studies have measured responses from 30 min post-consumption (e.g. Smith et al. 1994). Recent evidence suggests that effects may indeed occur 10–30 min after ingestion of caffeine on measures of skin conductance responses (SCR; Quinlan et al. 1997). Changes in SCR are used as a sensitive measure of autonomic nervous system activation and have recently been correlated with cerebral cortical activity (Lim et al. 1996). These findings therefore raise the intriguing possibility that caffeinated beverages may have more rapid effects on cortical function than hitherto described.

The present study had three aims: first, to determine the time course of the cognitive and psychomotor responses to hot caffeinated beverage ingestion, second to determine whether regular consumption throughout the day affected either the pattern of response or the tonic level of the dependent measures, and third to determine whether the effects of black tea and coffee consumption could be explained entirely by the presence of caffeine in the beverage. A 2 × 2 factorial design with caffeine (0, 100 mg) and beverage vehicle (water, tea) was employed, with coffee (100 mg caffeine) as the positive verum. The strength of the black tea and coffee used in this study was manipulated to deliver 100 mg caffeine per 400 ml serving to allow comparisons of the caffeine effect between beverages.

Materials and methods

Subjects

Ten female and nine male, non-smoking volunteers completed the study. Their mean age was 29.2 years (± 6.07). All subjects were in good physical and mental health, and free from concomitant medication. All subjects were fully trained on the psychometric test battery. Approval was obtained from the University of Surrey Ethics Committee. Subjects provided their written informed consent.

Design

This study employed a within subject, complete five-way crossover design, in which each subject acted as their own control. Allocation of treatments was based upon four sets of randomised 5 × 5 Latin square arrangements, where rows represented subjects and columns the order of presentation of the treatments. The five treatment conditions were: black tea (with caffeine); black decaffeinated tea; coffee (with caffeine); water with caffeine; water (no added caffeine).

Beverages

All drinks were 400 ml (at a temperature of 55°C) and prepared from a larger sample, a proportion of which was analysed for its caffeine content. The black tea and decaffeinated black tea were freeze dried tea solids prepared from a standard blend by T.J. Lipton Inc., Englewood Cliffs, N.J., USA, and contained 7.18% and 0.54% caffeine, respectively. Decaffeination was performed using supercritical carbon dioxide as solvent. The freeze dried coffee granules (Maxwell House Gold Blend) contained 2.97% caffeine. Caffeinated beverages were prepared such that each 400 ml serving contained 100 mg caffeine, giving a total consumption of 300 mg during the day.

Assessments

Critical flicker fusion (CFF)

CFF is an objective means of measuring the subjects' ability to distinguish discrete sensory data (Hindmarch 1982; Parrott 1982) and is used as an index of overall CNS activity (Hindmarch and Subhan 1983). Subjects were required to discriminate flicker fusion in a set of four light emitting diodes held in foveal fixation at 1 m. Individual thresholds were determined by the psychophysical method of limits on three ascending and three descending scales (Woodworth and Schlosberg 1958). The mean of the six values was the response measure recorded.

Choice reaction time (CRT)

CRT is a measure of sensorimotor reaction to a critical stimulus (Frewer and Hindmarch 1988). Subjects were required to extinguish one of six equidistant red lights, illuminated at random, by touching the appropriate response button. This test provides three measures: recognition reaction time (RRT), motor reaction time (MRT), and their sum, total reaction time (TRT). The response measure used was the mean reaction time for 20 stimulus presentations.

Short term memory task (STM)

The STM task (Sternberg 1966, 1975) measures high speed scanning and retrieval from short term memory. Subjects were required to judge whether a test (probe) digit presented on the computer monitor was contained in a set of digits held in short term memory. Subjects responded by pressing the buttons on a computer mouse. Reaction time was recorded.

Line analogue rating scale (LARS)

Subjective ratings of treatment effects were obtained from a series of 100 mm line analogue rating scales (LARS). The mean score of ratings of tiredness, drowsiness and alertness (which were included amongst a number of distracter scales) was taken as a measure of subjective sedation (Hindmarch and Gudgeon 1980).

Spielberger state anxiety inventory (STAI)

The STAI index (Spielberger et al. 1970) was completed by subjects on the morning of each study session prior to beverage administration (0730 hours) and again at the end of the day (2100 hours).

Procedure

Subjects arrived at the study centre having been told to abstain from caffeine-containing drinks and foods from the previous evening. They completed a baseline test battery at 0730 hours.

On each visit, subjects consumed the appropriate beverage at 0900, 1400 and 1900 hours. They performed CFF and LARS just before the first drink, then at 10 and 20 min following each beverage (thus: 0855, 0910, 0920, 1410, 1420, 1910 and 1920 hours).

Subjects completed the full test battery (CFF, CRT, STM and LARS) at 0930, 1000, 1100, 1300, 1430, 1500, 1600, 1800, 1930, 2000 and 2100 hours.

Subjects left the study centre after the final test battery, at around 2115 hours.

Statistical analyses

The data collected from each experimental session can be considered as coming from a double-repeated measures study, one repeat from the chronic effect of drinking three beverages over a day and the second repeat from the acute effect surrounding each beverage occasion. Two statistical analyses were conducted to estimate separately the chronic effect and acute (with the interaction between acute and chronic) effect, respectively.

The chronic effect of beverage ingestion was estimated from the three measurements taken prior to receiving a beverage, the analysis estimated the effect due to consuming a beverage (since nothing had been consumed prior to the first drink), and its orthogonal effect due to consuming a total of one or two drinks. (Hence, the assumption of sphericity was automatically satisfied, since the repeated measures factor with three time points was split into two orthogonal contrasts each with 1 degree of freedom).

The acute effect of beverage was estimated from the five measurements taken after each beverage was consumed, by a univariate repeated measures analysis of variance (that estimated the Greenhouse-Geisser epsilon adjustment) with the measurement taken prior to a beverage used as a covariate. The acute analysis was able to estimate the interaction between the acute and chronic effects.

In both the chronic and acute analyses, the between-session effect Beverage was included (with its interaction with the within-session factor Time) and all effects were adjusted to take account of the between-session blocking factors Subject and Session order. The effect of beverage was analysed as a 2 × 2 factorial plus control, with caffeine at levels (0, 100 mg) and beverage vehicle at levels (water, tea) and coffee as the positive internal control.

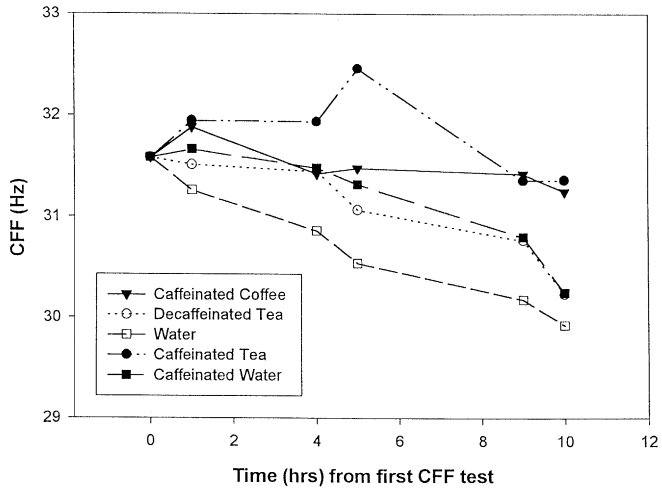

Fig. 1 The effects of beverage consumption on CFF thresholds through the day; a higher score indicates improved performance on the test. The 0, 4 and 9 h timepoints represent the 0855, 1300 and 1800 hour samples used in the chronic analysis. The 1, 5 and 9 h values represent the average of the overall change in CFF following ingestion of the first, second and third beverage, respectively. There was a main effect of beverage type (tea versus water) on the chronic CFF changes ($P = 0.034$), but no effect of caffeine

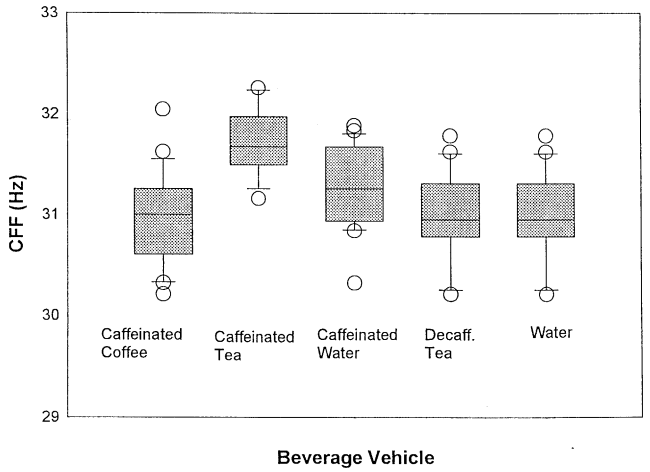

Fig. 2 The distributions of CFF threshold for each beverage. Data used were the means calculated across the 19 subjects participating in the study. The boundary of the box indicates the 25th percentile, a line within the box the median, and the line outside the box the 75th percentile. Outliers are represented by *circles*. Bartlett's test for variance homogeneity (using the equivalent method described by Box 1950) based on all subjects data (adjusted for the subject effect within each beverage) was $c_4^2 = 27.92$, $P < 0.001$

Results

Significant effects of both beverage type and caffeine were found in the data for CFF, significant effects for caffeine on subjective sedation (LARS) at both "acute" (in the time around beverage consumption) and "chronic" (over the course of the day) time points were also found. Similar trends were present in the reaction time data, but these were not statistically significant. No treatment effects were observed in the data for STM.

Chronic effects of beverage consumption

There was an overall difference between CFF performance from before the first drink compared to the two time points used in the chronic analysis taken later in the day ($F_{1,180} = 13.30$, $P < 0.001$) (Fig. 1). The general decline in performance accelerated during the day, as the CFF threshold at 1300 hours was 31.43 Hz, whilst at 1800 hours it was 30.71 Hz ($F_{1,180} = 19.38$, $P < 0.001$). A difference due to the type of beverage vehicle on CFF threshold was detected, with tea having a higher level of 31.38 Hz compared with water at 30.83 Hz, ($F_{1,180} = 4.59$, $P = 0.034$) (Fig. 2). A pairwise comparison between tea and coffee failed to attain significance ($P = 0.055$, sed = 0.372, $df = 68$).

The LARS assessment was affected by the amount of caffeine consumed. Decaffeinated beverages were associated with a higher LARS rating for sedation compared with caffeinated drinks ($F_{1,180} = 4.59$, $P = 0.033$, Figs. 3 and 4).

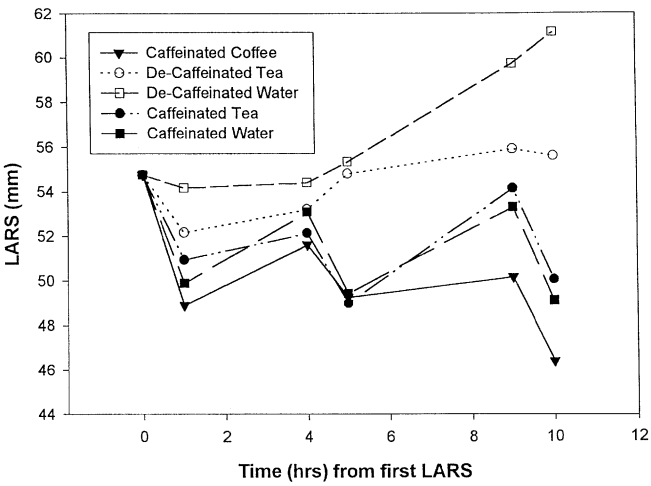

Fig. 3 The effects of beverage consumption on sedation score (LARS) through the day; a low score indicates a low level of sedation, i.e. higher alertness. The time points are as described in Fig. 1. There was a main effect of caffeine on the chronic LARS score ($P = 0.033$), but no effect of beverage type

Self-reported anxiety levels (STAI), measured at 0730 and 2100 hours were unaffected by caffeine level or beverage type (results not shown).

Acute effects of beverage consumption

The Greenhouse-Geisser epsilon adjustments for degrees of freedom estimated from the univariate repeated measures analyses of variance were 0.933 and

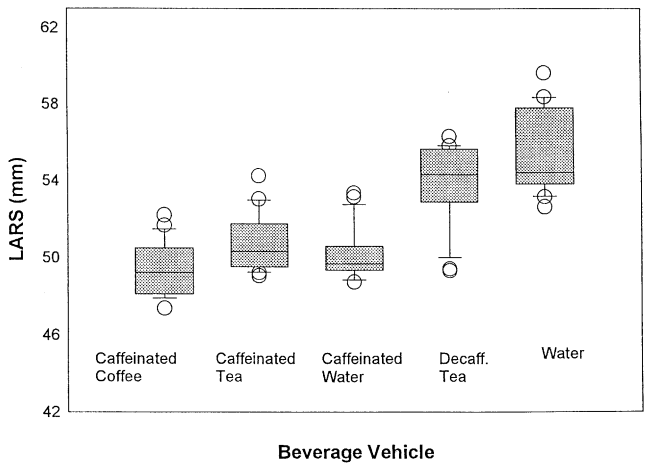

Fig. 4 The distributions of sedation scores (LARS) for each beverage. A low score indicates a low level of sedation, i.e. higher alertness. The box plot descriptions and analysis are as described in Fig 2. Bartlett's test for variance homogeneity based on all subjects data was $c_4^2 = 38.71$, $P < 0.001$

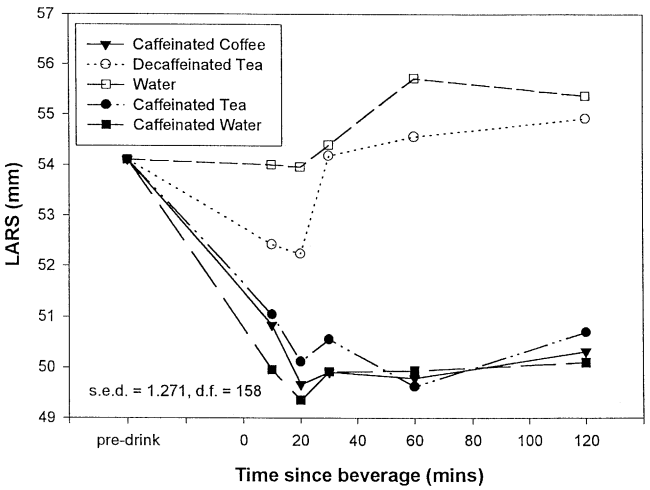

Fig. 6 The figure shows the change in sedation score (LARS) over the 3 h immediately following beverage ingestion, averaged over the three beverage occasions. There was a significant interaction between caffeine level and time ($P = 0.025$) but no effect of beverage type

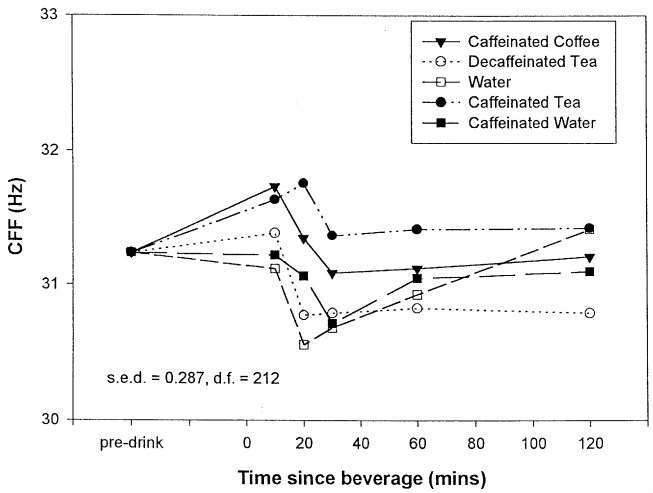

Fig. 5 The change in CFF threshold over the 3 h immediately following beverage ingestion, averaged over the three beverage occasions. There was a significant interaction between caffeine level and time ($P = 0.049$) and beverage type (tea versus water) and time ($P = 0.039$)

0.752 for CFF and LARS, respectively. The associated Box tests for symmetry of the covariance matrix were $c_{13}^2 = 41.09$ and $c_{13}^2 = 106.66$, indicating the need to adjust the degrees of freedom for the repeated measures treatment factor, time-since-beverage, and interactions with that factor.

The analysis of acute effects showed there was a difference in CFF performance due to caffeine intake, with caffeinated beverage consumption resulting in a higher CFF level than decaffeinated beverages ($F_{1,67} = 5.35$, $P = 0.024$). There was a weak indication of an interaction between caffeine level and beverage type ($F_{1,67} = 2.67$, $P = 0.089$), where the increase in CFF performance for caffeinated tea over caffeinated water was 0.49 Hz (sed = 0.21), but there was little change between the decaffeinated beverages (−0.03 Hz) (Fig. 5).

There was a highly significant effect of time, since beverage consumed for CFF ($F_{3.73,1007} = 7.18$, $P < 0.001$) and LARS ($F_{3.01,812.6} = 2.76$, $P = 0.041$) (Figs. 5 and 6). There were significant interactions between caffeine level and time for CFF ($F_{3.73,1007} = 2.45$, $P = 0.049$) and LARS ($F_{3.73,1007} = 3.13$, $P = 0.025$) indicating that the pattern of response over time changed depending on the amount of caffeine consumed (Figs. 5 and 6). For CFF, there was, in addition, a significant interaction between beverage vehicle and time ($F_{3.73,\ 1007} = 2.60$, $P = 0.039$).

The pattern or magnitude of the acute responses to beverage ingestion was not affected by time of consumption (0900; 1400 or 1900 hours).

Discussion

These results demonstrate that consumption of hot caffeinated tea results in rapid (within 10 min) and significant improvements in subjective alertness and cognitive function and that repeated administration in the morning, afternoon and early evening does not diminish this response. Furthermore, consumption of caffeinated, but not decaffeinated beverages, and of tea rather than water, largely prevented alertness and performance from declining through the day. Expectancy, sensory effects or the presence of biologically active substances besides caffeine may have contributed to the

effects of tea consumption, which were comparable to the effects of coffee in most respects. Although the present study showed no overall effect on memory, in keeping with previous research (Loke et al. 1985), it could be that the STM task used here was not sufficiently sensitive to small effects of the relatively low doses of caffeine administered in this present study.

Acute effects of caffeine ingestion

Consumption of hot caffeinated beverages was associated with rapid increases in CFF threshold and a decrease in sedation score (LARS) with effects apparent within 10 min of consumption (Figs. 5 and 6). These changes are indicative of an increase in cognitive function and alertness following caffeine ingestion and are consistent with recent psychophysiological data showing a rapid effect of caffeine (100 mg) ingestion on skin conductance, an index of sympathetic nervous system activity (Quinlan et al. 1997). These three measures, CFF, LARS and skin conductance, all show a similar speed of response following caffeine ingestion and have all previously been shown to be responsive to the effects of caffeine (Zahn and Rapoport 1987a,b; Swift and Tiplady 1988; Corr et al. 1995). It is therefore plausible that other cognitive and psychomotor measures previously shown to be sensitive to the effects of caffeine will show similar rapid response times.

It is likely that these early effects of caffeine simply reflect the speed of caffeine absorption following ingestion. Caffeine reaches $T_{max} \sim 45$ min post-consumption, but levels may already be $\sim 50\%$ of T_{max} within 10 min of consumption (Blanchard and Sawers 1983). This may be sufficient to trigger the rapid psychopharmacological responses seen in this study.

The pattern of the acute caffeine response was different for LARS and CFF. For the former, the caffeine effect was apparent from the first time-point following beverage consumption and was maintained for the 3 h post-consumption (Fig. 6). By contrast, the acute CFF response was transient, lasting a maximum of 20 min (Fig. 5), though over the longer term caffeinated tea and coffee did help prevent deterioration in CFF scores through the day (Fig. 1). The previously reported effects of caffeine on sympathetic nervous system activity (Quinlan et al. 1997) were also maximal in the 30 min post-consumption, though the effects were maintained for only 1 h. The reason for differences in the pattern of the LARS and CFF responses is not clear, but subjective (LARS) and objective (CFF) changes are not necessarily concordant.

There was no significant interaction of caffeine with time of beverage consumption, indicating that the immediate alerting effects of caffeine are similar whether the beverage is consumed in the morning, afternoon or evening. Thus consumption of a caffeinated beverage is an effective means of transiently increasing arousal levels regardless of the time of day. Caffeine ingestion has also been shown to improve cognitive and psychomotor performance when administered with either breakfast or evening meals (Smith et al. 1994). Since repeated administration of the caffeinated beverages produced similar effects, it is possible that the rate of change of caffeine concentration in the body, rather than the absolute level, was responsible for the initial rapid increase in arousal.

Ingestion of hot water alone had no effect on cognitive or psychomotor performance; indeed, the tendency was for CFF to decline following water ingestion (Fig. 5). In contrast, drinking hot water was found to stimulate sympathetic nervous system activity in the palmar sweat glands to about the same extent as caffeine (100 mg) during the first hour post-ingestion (Quinlan et al. 1997). Thus hot water ingestion has no effect on alertness and performance, but does stimulate peripheral physiological processes.

Chronic effects of caffeine consumption

Alertness and performance generally declined through the day, particularly after lunch. This decrease was most pronounced on occasions when subjects received decaffeinated beverages (Figs. 1 and 3). This may to some extent reflect the effects of abstinence following withdrawal from caffeine the previous evening. However, there was no effect of caffeine or beverage type on self-reported anxiety levels (STAI), which increased slightly on all treatments as the day progressed. The overnight caffeine withdrawal used in the current study is typical of normal consumer behaviour, but it is possible that continuation of this withdrawal in the decaffeinated beverage conditions was at least in part responsible for the observed performance decrement. This study cannot therefore directly address the issue of whether chronic caffeine administration attenuates performance decrements following withdrawal or produces real improvements in performance.

Caffeine administration did not significantly improve CFF scores with respect to baseline through the day (Figs. 1 and 2), but did result in a significant improvement in subjective alertness (i.e., a reduction in LARS sedation score, Figs. 3 and 4), however, caffeine treatments produced overall improvements in arousal relative to the control (water) treatment. Caffeine at doses up to 500 mg has been shown to increase CFF thresholds (Bruce et al. 1986; Kerr et al. 1991), although other studies report no effect (File et al. 1982; Nuotto et al. 1982; Swift and Tiplady 1988). The reason for these discrepancies may lie in personality differences with subjects high in sociability producing increases in CFF and subjects low in sociability showing no effect (Corr

et al. 1995). Nevertheless, caffeine was the main factor influencing the sedation score (LARS) throughout the day. Similar effects of caffeine on rating scales have been reported previously (Swift and Tiplady 1988). Caffeine maintained alertness at an overall higher level and significantly reduced the variance in LARS over time (Fig. 4). Thus the major effect of caffeine was to maintain a steady state of subjective alertness through the day.

Effect of beverage type

Consumption of tea versus water significantly influenced CFF threshold both immediately following consumption and over the whole day. In the chronic analysis, tea consumption was associated with a significantly higher score over the day compared to water. This effect was due primarily to caffeinated tea outperforming the caffeinated water treatment (Fig. 2), though there was no interaction between caffeine and beverage type. Similarly, during the first hour after consumption tea resulted in a significantly greater CFF threshold than water at both levels of caffeine (Fig. 5). However, these effects of tea versus water on CFF threshold were not accompanied by an effect of beverage type on subjective alertness ratings (LARS) either immediately following consumption or over the whole day (Figs. 3 and 6).

It is possible that the differences between tea and water ingestion were sensory and/or expectancy-mediated effects, though it is surprising that the subjective alertness ratings were not similarly affected. These differences in the effects of tea and water could be produced by a number of mechanisms. Firstly, the olfactory and gustatory properties (e.g., bitter taste) of tea and coffee may produce a rapid but probably short-lived effect on arousal. In support of this hypothesis, tea and coffee have been shown to stimulate sympathetic nervous system activity to a greater extent than water during the ingestion phase (independent of the effects of caffeine), with these effects attenuated by the addition of milk (Quinlan et al. 1997). Cephalic phase (i.e. pre-absorption) responses have been shown to occur after activation of the vagus nerve through food-related sensory stimulation (Teff et al. 1993), and it is plausible that similar responses are activated during fluid ingestion.

Secondly, it is possible that the tea/water differences may be a learned effect. Drinking coffee and tea is associated with certain psychological effects, and paired with particular experiences. In classical conditioning terms, the unconditioned stimulus is caffeine; the unconditioned response is the elevation of psychological function; the conditioned stimulus is the sensory properties of the drink and the conditioned response becomes the improvement in psychological function and/or mood.

Thirdly, tea and coffee may contain substances besides caffeine which can influence psychological processes either directly or via modulation of the effects of caffeine. This possibility is suggested by recent evidence demonstrating that green tea contains substances that can dampen the physiological stress response (Henry and Stephens-Larson 1984) and that flavonoids, which are present in both black and green tea, can interact with the benzodiazepine receptor (Medina et al. 1997). However, the specific flavonoids in tea have not been evaluated against this receptor, and it is unlikely that such effects would have been observed in the present study, as subjects were not exposed to anxiety-inducing or stressful scenarios.

Pairwise comparison of the caffeinated tea and coffee treatments indicated that there were no major differences in the psychopharmacological effects of these beverages when matched for caffeine content. However, caffeinated tea compared to caffeinated coffee was associated with a higher but not significantly so, CFF threshold in the chronic analysis ($P = 0.055$) and a significant reduction in the overall variance in this measure over the day (Fig. 2). Thus tea maintained the CFF threshold around the baseline levels throughout the day. This may be indicative of a subtle difference in the psychopharmacological effects of tea and coffee, though the use of focused test scenarios will be necessary to tease out such differences.

Coffee normally contains around twice as much caffeine as tea (Barone and Roberts 1996) which may influence the magnitude of the performance effects observed with these beverages under naturalistic conditions. However performance effects have been observed following ingestion of as little as 32 mg caffeine (Lieberman et al. 1987) and these improvements are often dose-independent (Lieberman et al. 1987; Hasenfratz and Battig 1994). Furthermore, higher doses can occasionally reverse performance improvements seen at lower doses (Frewer and Lader 1991), possibly as a result of task difficulty, a high trait arousal, and the effects of caffeine combining to push subjects beyond their optimal arousal state (Andersen 1994).

In conclusion, the present study demonstrates that tea and coffee ingestion are associated with rapid increases in alertness and performance, and that consumption throughout the day largely ameliorates diurnal patterns of performance decrements. The effects of tea and coffee consumption cannot be entirely explained as the acute effects of caffeine ingestion. Other factors either intrinsic to the beverage (e.g. sensory attributes or the presence of biologically active substances) or of a psychological nature (e.g. expectancy) may play a significant role in mediating these responses.

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