Effects of caffeine on prospective duration judgements of various intervals depend on task difficulty

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The effects of caffeine on prospective duration judgements were investigated in two double-blind placebo-controlled experiments. After taking either 200 mg of caffeine or a placebo, participants performed a task that demanded considerable attention, driving a car in a simulator (Experiment 1) or a task that demanded relatively little attention, watching a videotaped scene from a driven car (Experiment 2). Each participant made duration judgements of three target intervals: 15 s, 60 s and 300 s. Actively driving participants in the caffeine condition judged it as shorter than did those in the placebo condition. Caffeine had no effect on duration judgements following passive viewing. When people must perform a relatively difficult task, caffeine causes participants to allocate relatively more of their attentional resources to the task and relatively less to duration timing. Although caffeine may increase the pacemaker rate of an internal clock (via dopamine D_1 agonism), when external events are attention-demanding, caffeine mainly influences the relative allocation of attention to external events or to time (via dopamine D_2 agonism) in cerebral areas subserving the executive control of attention. Copyright © 2005 John Wiley & Sons, Ltd.

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INTRODUCTION

Caffeine, arguably the most widely used stimulant, is known to alter a person's ability to estimate short time durations and consequently alter responses to environmental stimuli in adaptive ways. It is important, therefore, to understand as much as possible about the ways in which caffeine affects duration judgement and to assess any effects across tasks that vary in difficulty and intervals that vary in length.

Psychopharmacological effects of caffeine

Caffeine has many pharmacological, physiological and psychological effects (Snel and Lorist, 1998; Spiller, 1998; Fredholm *et al.*, 1999). For example, caffeine may enhance long-term memory (Hameleers *et al.*, 2000), alleviate age-related decrements in information processing (Horgevorst *et al.*, 1998), attenuate

impairments of working memory and long-term memory (Riedel *et al.*, 1995) and maintain various cognitive and psychomotor functions (Hindmarch *et al.*, 2000). The psychostimulant effects of caffeine have been ascribed mainly to cholinergic and dopaminergic mechanisms and, to a lesser extent, noradrenergic ones (Baldwin and File, 1989; Rammsayer *et al.*, 2001).

At typical human doses of caffeine (as well as at the dose used in the present study), the effects of caffeine on the brain are attributed mainly to blocking of adenosine A_1 and A_{2A} receptors. Adenosine A_1 receptors are co-localized with dopamine D_1 receptors, and adenosine A_{2A} receptors are co-localized with dopamine D_2 receptors (Daly *et al.*, 1994; Garrett and Griffiths, 1997; Lorist and Tops, 2003). However, the effects of similar doses of caffeine can be mimicked by a selective A_{2A} receptor antagonist, but not by a selective A_1 receptor antagonist (Svenningsson *et al.*, 1999). Thus, A_{2A} receptors are implicated more than are A_1 receptors in the effects of caffeine at common doses. When A_{2A} receptors are blocked, there is an agonistic effect on D_2 receptors (Ferré *et al.*, 1992; Garrett and Griffiths, 1997; Fuxe *et al.*, 1998). As a result,

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several researchers concluded that the main central effect of caffeine at typical doses is 'the enhancement of postsynaptic dopamine D2 receptor transmission' (Lorist and Tops, 2003, p. 83).

Caffeine and time estimation

A few early researchers investigated the effects of caffeine on various aspects of psychological time (Sterzinger, 1938; Joerger, 1960; Kostenko, 1968). However, until recently no experiment revealed an effect on duration judgement. Botella *et al.* (2001) found that caffeine affected duration judgements in the prospective paradigm. In this paradigm, a person is aware during a duration that time estimation is salient (relevant and important). Their subjects were asked to press a key when they estimated that 10 s had elapsed after a beep. Women who had taken 300 mg of caffeine made shorter estimates than did those who had taken a placebo, 75 mg of caffeine, or 150 mg of caffeine. Men showed no significant effect of caffeine on duration estimates. However, the method that Botella *et al.* used complicates the interpretation of their findings (Gruber and Block, 2003).

Gruber and Block (2003) found that 200 mg of caffeine decreased prospective duration judgements when participants performed an active information-processing task, but it did not affect judgements in the retrospective paradigm (in which a person is not aware during a duration that time estimation is relevant and important). They proposed that caffeine increases arousal (Smith and Tolla, 1998; Mikalsen *et al.*, 2001), which led participants to narrow their focus of attention to more salient information at the expense of less salient information (e.g. Callaway and Dembo, 1958; Easterbrook, 1959; Tracy *et al.*, 2000). In Gruber and Block's study, the nontemporal task was probably more salient than the temporal task. One limitation of all extant studies of caffeine effects on time estimation is that they have used relatively short durations (15 s or less). Many daily activities in which a person estimates time intervals involve durations longer than 15 s.

Attentional-gate model of prospective timing

The attentional-gate model of prospective timing (Block and Zakay, 1996; Zakay and Block, 1996) includes a pacemaker and emphasizes the importance of attentional allocation. The duration-judgement paradigm and the duration-judgement method strongly influence time estimates. The main effects occur in the prospective paradigm, in which a person must divide attentional resources between nontemporal information processing and temporal information processing. Arousal influences the pacemaker rate (i.e. the subjective time rate), and attentional allocation influences the attentional gate. If arousal increases or if a person allocates more attentional resources to temporal information processing (i.e. attending to time), more pulses are accumulated (in an accumulator, or cognitive counter), and the person will make a longer duration estimate. However, to the extent that a nontemporal (stimulus) information-processing task demands relatively more attentional resources, fewer resources are available for temporal information processing, and a person will make a shorter duration estimate.

Psychopharmacology of the attentional gate

Dopamine D_1 agonists increase the pacemaker rate of a hypothetical internal clock (Meck, 1996). However, opposing effects on timing have been seen with various dopaminergic agonists. Buhusi (2003) found that dopamine agonists increase the pacemaker rate, but some of them also reduce attentional resources allocated to the timing component of the task. He proposed that the pacemaker and attentional effects of dopaminergic drugs may relate to their affinity to D_1 and D_2 receptors, respectively. Drugs that activate both D_1 and D_2 receptors (e.g. metamphetamine) may affect both the pacemaker and the attentional component, whereas drugs that selectively affect D_2 receptors (e.g. quinpirole), may only affect the attentional component, leading to a reduction of attentional resources allocated to the timing component of a task. Although caffeine may increase the pacemaker rate as a result of D_1 agonism, its primary effect may be on the allocation of attentional resources as a result of its D_2 agonism.

Purpose of study

The present experiments investigated the effect of caffeine on prospective duration judgements of information-processing tasks lasting several seconds to several minutes. A short interval (15 s) was used because we wanted to see if our original results (Gruber and Block, 2003) were replicable and because short intervals are commonly used when studying duration judgements (Zakay, 1993). A medium interval (60 s) and a long interval (300 s) were used because people often need to time such intervals in everyday situations.

In our previous study (Gruber and Block, 2003), a relatively difficult task (haptic exploration of a 17-sided polygon) was used because information-processing task difficulty affects prospective duration judgements. People experience durations as being relatively short if they are actively processing a more complex stimulus (Zakay, 1993), and processing difficulty is an important moderator of prospective duration judgements (Block and Zakay, 1997). Therefore, the present study investigated the effect of caffeine on target intervals that involved either a relatively difficult, active information-processing task (Experiment 1) or a relatively easy, passive informa-tion-processing task (Experiment 2). For the relatively difficult information-processing task in Experiment 1, automobile driving was chosen, being a task that requires considerable mental workload (Brookhuis and de Waard, 2001).

EXPERIMENT 1

METHOD

Participants

A total of 60 people (41 women and 19 men) consented to participate in the experiment. They ranged in age from 22 to 77 years old (M = 45.3, SD = 12.3), and they reported a mean weight of 64.7 kg (SD = 13.0). They all were licensed to operate an automobile. Women and men were assigned sepa-rately at random to one of two conditions: placebo or caffeine.

Apparatus

The apparatus was a video game, Midtown Madness 2 (Microsoft Corporation, 2000). It consisted of a steer-ing wheel, a gas pedal, a brake pedal and a program that displayed simulated street scenes on a computer monitor. The monitor also displayed the speed of the vehicle. By controlling the gas and brake pedals, the participant could drive an automobile through a simu-lated city. Good driving required the avoidance of lamp poles, other cars and pedestrians. Although the density of traffic and pedestrians was set to the lowest level, there was significant road activity to compel the participant to attend actively to driving.

Procedure

Each potential participant was asked if he or she was willing to take a pill that may or may not contain caf-feine and to participate in an experiment involving driving and time estimation. Those who consented were given a pill (either 200 mg caffeine or a placebo) and instructed to take it 1 h prior to arriving for the experiment on a subsequent day. Both the participant and the experimenter were unaware of whether any particular participant had been given caffeine or a pla-cebo. Because the effects of caffeine can vary with time of day (Anderson and Revelle, 1994), all testing was conducted at approximately the same time of day (the afternoon). Participants were instructed to abstain from caffeine for 4 h prior to the experiment and to not eat or drink anything for 1 h before arriving.

When each participant arrived, age, body weight and average daily caffeine intake were solicited. Caf-feine intake was recorded as the number of servings/ day of espresso, coffee, tea and cola.

The participant was told that the experiment involved driving and time estimation and was asked to remove any watch and to sit comfortably in front of the monitor. The experimenter indicated the gas pedal, the brake pedal, the speedometer and the steer-ing wheel. A 120-s practice trial followed, which involved driving through the city streets, staying in the far right lane, and traveling at a speed of 7– 10 mph. If the car came to a stop sign or a stoplight, the participant was told to make a right-hand turn and to continue driving. After the practice session, the par-ticipant was told that after completing each trial, he or she would be asked to estimate duration of that trial, but was told not to count in order to time the duration.

Each participant judged three target intervals (TIs): 15 s, 60 s and 300 s. The onset and termination of each TI was marked by two buzzes (each 0.5 s). The order of the three TIs was randomized for each participant. After each TI, the participant first made an analog duration estimate on a sheet of paper that contained two parallel 26 cm horizontal lines separated by 3 cm. The left half (13 cm) of the upper line was a thick 1 mm bold face line, whereas the right half was thin. The entire lower line (along which the esti-mate of the TI was to be drawn) was thin. Participants were told that the left half of the upper line repre-sented a duration of 10 s for the 15-s TI, 45 s for the 60-s TI, and 180 s for the 300-s TI. The lengths of the lines provided equal probabilities for the partici-pants to estimate the TI as being shorter or longer than the verbally defined line. Participants were asked to mark a line length on the lower line that represented the duration of the TI. Those few participants who said that the TI was greater than the entire length of the bottom line (i.e. greater than 20 s, 90 s or 360 s, respectively) were permitted to draw a third line
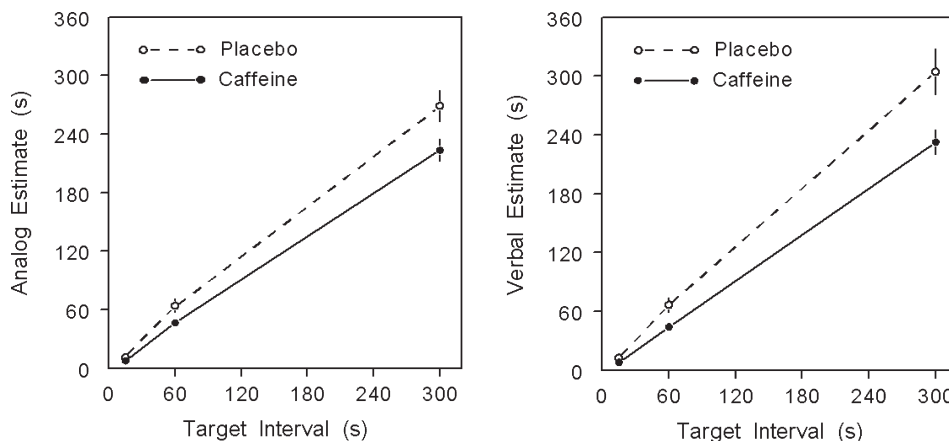
Figure 1. Mean analog (left panel) and verbal (right panel) duration judgement as a function of target interval and drug condition (caffeine vs placebo) in Experiment 1. Each error bar is a standard error of the mean

parallel to the second line. Next, the participant was asked to give a verbal duration estimate of the TI in seconds or minutes (and fractions thereof). Each participant also rated the extent to which he or she felt any effects from the pill taken before the experiment, using a three-point scale (*no*, *maybe* or *yes*). Finally, the experimenter subjectively rated each participant's driving skill on the simulator, using a three-point scale (*poor*, *fair* or *good*) because psychotropic drugs are known to affect driving (Hindmarch, 1988).

Thus, a 2 (drug condition: placebo vs caffeine) × 3 (TI: 15 s vs 60 s vs 300 s) mixed-model design was used, with drug condition a between-subjects variable and TI a within-subjects variable. Data from the analog and verbal duration estimates were analysed separately.[†]

RESULTS

Each participant's reported caffeine intake in servings was converted to the number of milligrams of caffeine per day by using approximations from Center for Science in the Public Interest (1997; cf. Gruber and Block, 2003; Stine *et al.*, 2002). The conversion assumes that a serving of espresso contains 170 mg of caffeine, a serving of coffee contains 120 mg, a serving of tea contains 46 mg, and a serving of cola contains 45 mg. The overall mean daily caffeine intake

was 186.6 mg/day (SE = 29.0), with a range from 0 to 1290 mg/day.

The random assignment of participants to drug condition was successful in that there were no significant differences between the placebo and caffeine participants in age, body weight, daily caffeine intake, or rated driving skill (all $p > 0.23$).

Duration estimates

The analog estimates were analysed by measuring the lower-line length in millimeters and determining the number of seconds of subjective duration that length represented for each of the three TIs. The raw verbal estimates (in seconds) were analysed also. The positive correlation between analog and verbal duration estimates was significant at the 15-s TI, the 60-s TI and the 300-s TI ($r_{(59)} = 0.89$, 0.90 and 0.89, all $p < 0.001$). The 2 (drug condition) × 3 (TI) mixed-model ANOVAs were conducted separately for the analog and verbal estimates. To analyse the main effect of the within-subjects variable (TI) and the interaction of TI and drug condition, planned contrasts (trend tests) were performed investigating a linear trend. (The weights were −22, −13 and +35 for TIs of 15 s, 60 s and 300 s, respectively; see Keppel and Wickens, 2004, for statistical details.)

Figure 1 displays the mean analog estimate (left panel) and the mean verbal estimate (right panel) in each combination of drug condition and TI. The linearly increasing trend across TI was significant for both analog and verbal estimates ($F_{(1,58)} = 562.5$ and 355.4, both $p < 0.001$, $d = 6.12$ and 4.87, both very large effects). The main effect of drug condition was

[†]A single mixed-model multivariate ANOVA was conducted, including duration estimate method (analog vs verbal) as a within-subjects variable. In this analysis, the main findings did not differ from those of the separate analyses, and for the sake of simplicity, the results of the separate ANOVAs are reported.

significant for both analog and verbal estimates ($F_{(1,58)} = 8.41$ and 10.68, $p = 0.005$ and 0.002, $d = 0.74$ and 0.83, both large effects). Analog and verbal estimates were larger in the placebo condition than in the caffeine condition. The TI $\times$ drug condition interaction was significant for both analog and verbal estimates ($F_{(1,58)} = 3.94$ and 5.61, $p = 0.05$ and $.02$, $d = 0.51$ and 0.60, both medium effects). The difference between estimates in the placebo condition and estimates in the caffeine condition increased as the TI lengthened (see Figure 1).

In order to investigate further the effect of TI, each estimate was converted to a duration-judgement ratio, dividing the subjective duration (in seconds) by the objective duration (in seconds). Figure 2 displays the mean analog ratio (left panel) and the mean verbal ratio (right panel) in each combination of TI and drug condition. The linear trend across TI was marginally significant for both analog and verbal ratios ($F_{(1,58)} = 3.37$ and 4.11, $p = 0.07$ and 0.05, $d = 0.47$ and 0.52, both medium effects). As shown in Figure 1, this marginally significant trend is mainly attributable to the relatively small ratio at the shortest duration (15 s). The main effect of drug condition was significant for both ratios ($F_{(1,58)} = 11.11$ and 13.29, $p = 0.002$ and 0.001, $d = 0.86$ and 0.94, both large effects), with larger ratios in the placebo condition (M = 0.91 and 0.99, SE = 0.12 and 0.13) than in the caffeine condition (M = 0.69 and 0.69, SE = 0.07 and 0.08). The TI $\times$ drug condition interaction was not significant for either ratio (both $F_{(1,58)} < 1$). The difference between ratios in the placebo and caffeine conditions remained approximately constant as the objective duration lengthened (see Figure 2).

Rated pill effect

Participants' ratings of effects of the pill correlated significantly with drug condition ($r_{(59)} = 0.39$, $p = 0.002$), indicating that participants in the caffeine condition detected effects of the caffeine. The rated pill effect was greater in the caffeine condition (M = 1.37, SE = 0.17) than in the placebo condition (M = 0.63, SE = 0.16), ($t_{(58)} = 3.19$, $p = 0.002$, $d = 0.83$, a large effect).

Rated driving skill

Although rated driving skill was slightly higher in the caffeine condition (M = 1.63, SE = 0.13) than in the placebo condition (M = 1.40, SE = 0.14), the difference was not significant ($t_{(58)} = 1.21$, $p = 0.23$, $d = 0.31$, a small effect). Rated driving skill was not correlated with either analog or verbal duration estimates (both $r_{(59)} < 0.07$, $p > 0.63$).

Multiple-regression analyses

Multiple-regression analyses were conducted to investigate variables and interactions that may predict overall mean analog and verbal duration-judgement ratios (cf. Figure 2). Potential predictor variables included the demographic variables (participant age, gender, body weight, daily caffeine intake, reported pill effect and rated driving skill), the main experimental variable (drug condition), and the two-way interaction between each of the variables. (Categorical variables were contrast-coded.) Only the drug condition $\times$ body weight interaction was a significant predictor of
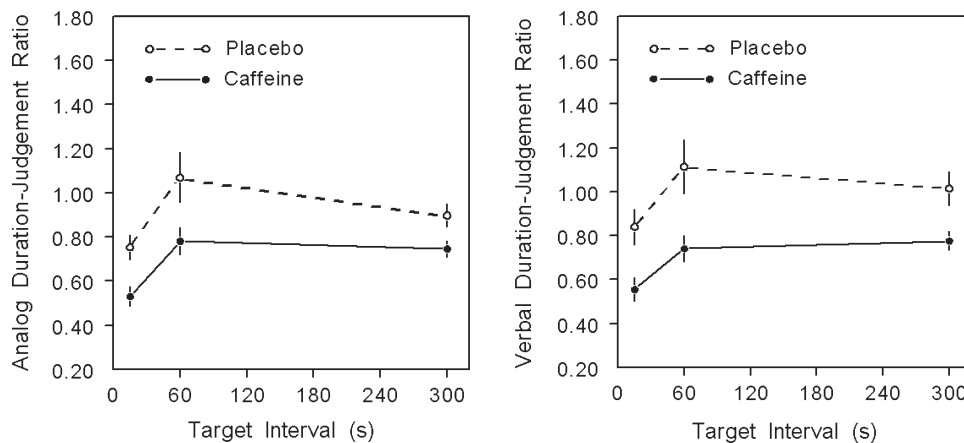

Figure 2. Mean analog (left panel) and verbal (right panel) duration-judgement ratio (i.e. subjective duration divided by objective duration) as a function of target interval and drug condition (caffeine vs placebo) in Experiment 1. Each error bar is a standard error of the mean

overall analog and verbal ratio ($R = 0.39$ and 0.43, $F_{(1,58)} = 10.4$ and 13.5, $p = 0.002$ and 0.001). This correlation was significant for participants in the caffeine condition (both $r_{(29)} = 0.44$, $p = 0.01$): those who weighed less tended to give a smaller ratio. The correlation was not significant for participants in the placebo condition ($r_{(29)} = 0.21$ and 0.28, $p = 0.26$ and 0.14).

Nonuser analyses

In order to determine the extent to which the duration estimates in the placebo and caffeine conditions represent a true caffeine effect, excluding a possible caffeine-withdrawal effect, only nonusers' data were analysed. Only a small number of participants (11) reported no daily caffeine intake. Therefore, *nonusers* were defined as participants who reported consuming less than 120 mg of caffeine per day (i.e. less than the equivalent of one cup of coffee per day). Nonusers in the placebo condition would not be experiencing much, if any, caffeine withdrawal; however, nonusers in the caffeine condition would be experiencing a caffeine effect. Compared with nonusers in the placebo condition, nonusers in the caffeine condition showed smaller mean analog and verbal duration estimates ($t_{(21)} = 2.17$ and 2.22, both $p = 0.04$, $d = 0.90$ and 0.92, both large effects), as well as smaller mean analog and verbal duration-judgement ratios ($t_{(21)} = 2.33$ and 2.40, both $p = 0.03$, $d = 0.97$ and 1.00, both large effects).

EXPERIMENT 2

METHOD

Participants

A total of 60 people (44 women and 16 men) consented to participate in the experiment. They ranged in age from 17 to 75 years old (M = 44.8, SD = 12.2), and they reported a mean weight of 62.5 kg (SD = 10.5). As in Experiment 1, women and men were assigned separately at random to one of two conditions: placebo or caffeine.

Apparatus

The apparatus consisted of a monitor playing a videotape of a car traveling along a highway at a speed of about 55 mph. The camera that videotaped this trip was placed on the dashboard of a car so as to record the highway from the driver's viewpoint. The participant was asked to sit on a chair approximately 1–1.5 m from the monitor. The task, an easy information-processing task, was to simply observe the scene as the car drove on the highway.

Procedure

The procedure was the same as in Experiment 1 except that participants were told that the experiment involved watching a videotape of a car on a highway. Participants were asked to remove their watches, sit comfortably in front of the monitor, and observe the car as it drove on highway. They were asked not to count in order to estimate time. The design and data analyses were the same as in Experiment 1, except that there was no simulated driving and therefore no rating of driving skill.

RESULTS

Using the same conversion as in Experiment 1, the overall mean reported caffeine intake was 206.5 mg/day (SE = 19.1), with a range from 0 to 570 mg/day.

The random assignment of participants to drug condition was successful in that there were no significant differences between the placebo and caffeine participants in age, body weight or daily caffeine intake (all $p > 0.38$). In addition, none of the demographic measures differed from those in Experiment 1 (all $p > 0.30$).

Duration estimates

The duration estimates were analysed as in Experiment 1. The positive correlation between analog and verbal duration estimates was significant at the 15-s TI, the 60-s TI, and the 300-s TI ($r_{(59)} = 0.94$, 0.91 and 0.78, all $p < 0.001$). Separate 2 (drug condition) $\times$ 3 (TI) mixed-model ANOVAs were conducted as in Experiment 1.[‡]

Figure 3 displays the mean analog estimate (left panel) and the mean verbal estimate (right panel) in each combination of drug condition and TI. The linearly increasing trend across TI was significant for both analog and verbal estimates ($F_{(1,58)} = 202.7$ and 409.6, both $p < 0.001$, $d = 3.68$ and 5.23, both very large effects). The main effect of drug condition was not significant for either analog or verbal estimates (both $F_{(1,58)} < 1$). The TI $\times$ drug condition interaction was not significant for either analog or verbal estimates ($F_{(1,58)} = 1.06$ and 0.01, respectively, $p = 0.31$ and 0.95).

[‡]A single mixed-model multivariate ANOVA, including duration estimation method as a within-subjects variable, again agreed with the findings of the separate ANOVAs.
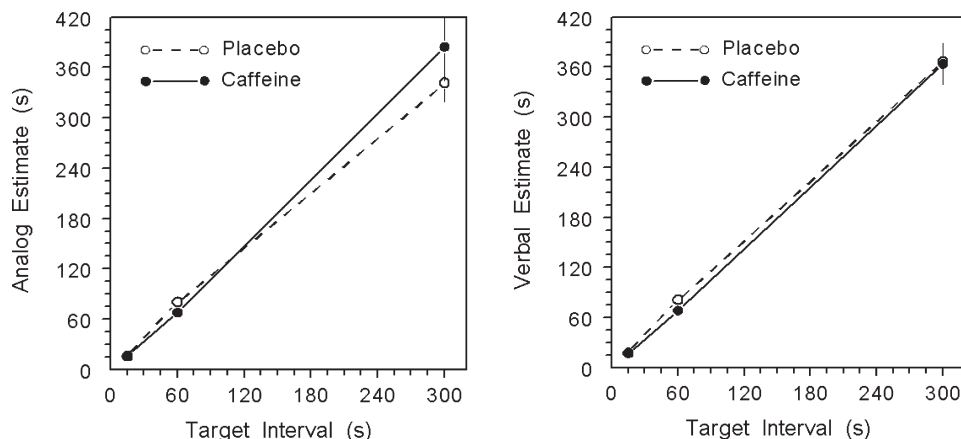
Figure 3. Mean analog (left panel) and verbal (right panel) duration judgement as a function of target interval and drug condition (caffeine vs placebo) in Experiment 2. Each error bar is a standard error of the mean

Each estimate was converted to a duration-judgement ratio as in Experiment 1. Figure 4 displays the mean analog ratio (left panel) and the mean verbal ratio (right panel) in each combination of TI and drug condition. The linear trend across TI was not significant for either analog or verbal ratio (both $F_{(1,58)} < 1$). The main effect of drug condition was not significant for either ratio (both $F_{(1,58)} < 1$). The TI × drug condition interaction was also not significant for either ratio ($F_{(1,58)} = 1.25$ and 0.47, $p = 0.27$ and 0.50).

Rated pill effect

As in Experiment 1, participants' ratings of pill effects correlated significantly with drug condition, ($r_{(59)} = 0.44$, $p < 0.001$), indicating that participants

in the caffeine condition detected effects of the caffeine. The rated pill effect was greater in the caffeine condition ($M = 1.50$, $SE = 0.13$) than in the placebo condition ($M = 0.73$, $SE = 0.16$), ($t_{(58)} = 3.70$, $p < 0.001$, $d = 0.96$, a large effect).

Multiple-regression analyses

Multiple-regression analyses were conducted as in Experiment 1. No demographic or experimental variable was a significant predictor of the analog duration-judgement ratio. However, the verbal duration-judgement ratio was significantly predicted ($R = 0.53$, $F_{(2,57)} = 6.60$, $p = 0.003$). Participant gender was a significant predictor ($\beta = 0.32$, $t_{(1)} = 2.68$, $p = 0.01$), with men giving slightly larger ratios than women.
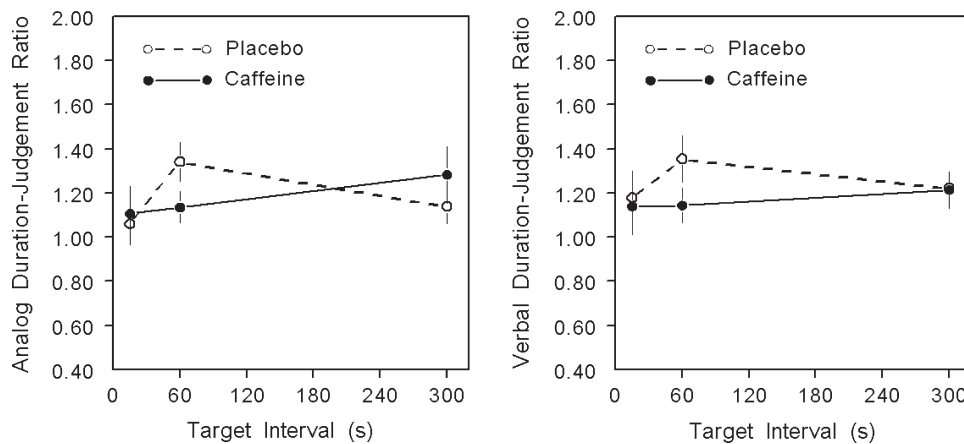

Figure 4. Mean analog (left panel) and verbal (right panel) duration-judgement ratio (i.e. subjective duration divided by objective duration) as a function of target interval and drug condition (caffeine vs placebo) in Experiment 2. Each error bar is a standard error of the mean

The drug condition × daily caffeine intake interaction was also a significant predictor ($\beta = 0.30$, $t_{(1)} = 2.51$, $p = 0.02$). Participants in the placebo condition showed a significant positive correlation between daily caffeine intake and the overall mean ratio ($r_{(29)} = 0.38$, $p = 0.04$): Those who reported more daily caffeine intake tended to give a larger ratio. Participants in the caffeine condition showed a marginally significant negative correlation ($r_{(29)} = -0.34$, $p = 0.07$): Those who reported less daily caffeine intake tended to give a larger ratio.

Ancillary finding

Participants in the placebo condition of Experiment 2 gave significantly larger overall mean analog and verbal duration estimates than did those in the placebo condition of Experiment 1 ($t_{(58)} = 2.99$ and 2.26, $p = 0.004$ and 0.03, $d = 0.77$ and 0.58, both medium effects).

Nonuser analyses

As in Experiment 1, only nonusers' data were analysed in order to determine the extent to which the duration estimates in the placebo and caffeine conditions represent a caffeine-withdrawal effect instead of a caffeine effect. *Nonusers* were defined as in Experiment 1. Nonusers in the caffeine and placebo conditions showed no significant difference in overall mean analog and verbal duration estimates ($t_{(13)} = 0.93$ and 0.97, $p = 0.37$ and 0.35), as well as no significant difference in overall mean analog and verbal duration-judgement ratios ($t_{(21)} = 1.30$ and 1.29, both $p = 0.22$).

DISCUSSION

Taken together, the results of the two experiments replicate and extend our earlier research (Gruber and Block, 2003) on the effects of caffeine on prospective duration judgements. In Experiment 1, people performed an active and relatively difficult information-processing task (driving a simulated car in city traffic). Those who had taken caffeine estimated the duration of the task as being shorter than those who had taken a placebo. In Experiment 2, people performed a passive and relatively easy information-processing task (watching a videotape of the scene as a car was driven on a highway). Those who had taken caffeine estimated the duration of the task as being about the same as those who had taken a placebo.

The major finding of Experiment 1—people who performed an active and relatively difficult information-processing task made shorter prospective duration estimates of duration in the caffeine condition than in the placebo condition—replicates the findings of our previous study (Gruber and Block, 2003). Caffeine affects prospective timing; more specifically, caffeine decreases the experienced duration of an attention-demanding information-processing task. In the previous study, a similar effect of caffeine was found on the duration judgements of participants who were given a 15-s target interval during which they were asked to perform an active and relatively complex information-processing task.

The present findings also reveal that this caffeine effect does not depend on the target duration; instead, the difference between the caffeine and placebo conditions is relatively constant per unit of target duration (see Figure 2). The data in Figure 1 show an interaction only because the caffeine effect had accumulated over more objective seconds at the 60-s and 300-s target intervals than at the 15-s target interval. In other words, caffeine had as much effect on experienced duration during the first minute as during the last of 5 minutes of a task.

The major finding of Experiment 2—caffeine did not affect prospective duration estimates when participants performed a passive and relatively easy information-processing task—clarifies the findings of Gruber and Block (2003) and the present Experiment 1. This finding may be explained by noting the importance of attentional resources in Experiment 1 compared with Experiment 2. If a task demands the allocation of relatively few attentional resources, as in the passive-viewing situation (Experiment 2), there is no significant effect of caffeine on duration judgements. We previously discussed several potential explanations for why caffeine may shorten prospective duration experience (Gruber and Block, 2003). One explanation for these findings is that caffeine increases arousal and attentional resources, and the increased arousal leads to a narrowing of the focus of attention to the primary (nontemporal) task at the expense of the secondary (temporal) task.

Considered along with Experiment 1, Experiment 2 suggests that the effect of caffeine on prospective duration judgements cannot be explained in terms of the arousal effects of caffeine without considering its effect on attentional allocation. Any explanation requires the assumption that caffeine affects the allocation of attentional resources. In Experiment 1, the increased arousal of participants in the caffeine condition apparently resulted in a focusing of attention on

the attention-demanding primary task, active driving; and it interfered with performance of the secondary task, prospective timing (Brown, 1997; Gruber and Block, 2003). On the other hand, the primary task in Experiment 2, passive viewing, was so easy that participants in the caffeine condition apparently did not need to allocate much attention to it; and as a result it did not interfere with performance of the secondary task, prospective timing. Thus, the caffeine effect was negligible in Experiment 2.

Data from control (placebo) participants in the two experiments reveal that those who were actively driving (Experiment 1) gave shorter duration judgements than those who were passively viewing (Experiment 2). This finding replicates the findings of many studies showing that task difficulty (i.e. attentional demands) affects prospective timing. Specifically, to the extent that a nontemporal information-processing task (e.g. active driving) requires attention, it also decreases prospective duration judgements (e.g. Brown, 1997; Block and Zakay, 1997).

Ancillary findings

There were also some minor findings of both experiments concerning participants' gender, body weight and daily caffeine intake. In Experiment 1, the interaction of drug condition and body weight was a significant predictor of overall mean duration judgements. This finding can be explained rather simply. The caffeine was not administered in terms of milligrams per kilogram of body weight, as is usually done in drug experiments, but only as one 200 mg pill for all participants. The correlations reveal that lower-weight people in the caffeine condition showed a relatively smaller duration-judgement ratio. This is not surprising, because the same dose of caffeine is expected to affect a lower-weight person more than a higher-weight person.

In Experiment 2, gender was a significant predictor of overall verbal duration estimates. Men gave relatively larger duration judgements than women, perhaps because they found the passive task more boring than the women did and were attending to time more frequently than the women were. In addition, people in the placebo condition tended to show a larger verbal duration-judgement ratio if their daily caffeine intake was relatively high, whereas participants in the caffeine condition tended to show a larger verbal duration-judgement ratio if their daily caffeine intake was relatively low. The former finding may be interpreted in terms of a caffeine withdrawal effect, whereas the latter finding may be interpreted in terms of a caffeine effect (e.g. on the pacemaker rate).

Withdrawal symptoms from caffeine can potentially influence cognitive performance (Hogervorst et al., 1998). In habitual caffeine users, withdrawal symptoms occur within a short period of time following the last caffeine intake (Phillips-Bute and Lane, 1997). With 4 hours of caffeine deprivation, habitual coffee drinkers show significantly reduced blood pressure and increased fatigue. Thus, if people are performing an easy task (such as that in Experiment 2), those who are experiencing caffeine withdrawal may allocate more attention to time. This hypothesis might not apply if people are performing a difficult task, however, because there was no similar correlation between daily caffeine intake and overall mean verbal estimate in Experiment 1. The analyses of only non-users' data, however, seriously weaken an interpretation in terms of a caffeine withdrawal effect. Nonusers in the placebo condition would not be experiencing any caffeine withdrawal effect, whereas nonusers in the caffeine condition would be experiencing a caffeine effect. However, in Experiment 1 nonusers in the placebo condition gave shorter duration estimates than did nonusers in the placebo condition, just as was the case in the complete sample. In addition, in Experiment 2 nonusers in the placebo and caffeine conditions did not differ in their duration estimates, just as was the case in the complete sample. Thus, the main findings and ancillary findings cannot be explained in terms of a caffeine withdrawal effect.

Psychopharmacological implications

The present findings clearly support the view that caffeine affects duration judgements because of its effects on the way people allocate their attentional resources: when people must perform a relatively difficult information-processing task, they allocate relatively more attentional resources to the nontemporal information and relatively fewer resources to the temporal information. These findings also suggest a specific psychopharmacological and neuroanatomical mechanism. Although caffeine may increase the rate of the pacemaker of an internal clock (via dopamine D_1 agonism), our evidence suggests that it mainly influences the relative allocation of attention to external events or to time (via D_2 agonism; Buhusi, 2003). D_2 receptors modulate areas of the brain known to be involved in selective attention (Kähkönen et al., 2001). The main area identified as subserving the executive control of attention is the anterior cingulate cortex (ACC; Posner and Dehaene, 1994; Posner and Raichle, 1997), although some researchers have found that the pre-supplementary motor area (pre-SMA) is

also involved in time and attention (Coull *et al.*, 2004). The pre-SMA is adjacent to the ACC, and either area or both areas may be involved in the executive control of attention. Mesocortical D_2 inputs to the cingulate cortex and medial prefrontal cortex result in neuromodulation of these neural networks, which are involved in planning and attention (Seamans and Yang, 2004). Affinity for the D_2 receptor also predicts the magnitude of effects on timing (Frederick and Allen, 1996; Meck, 1996). Imaging studies reveal that dopamine function is markedly disrupted in drug-addicted subjects, and this is associated with reduced activity of the cingulate gyrus (Volkow *et al.*, 2004). Caffeine may influence prospective duration judgements by affecting D_2 receptors of the ACC, the pre-SMA, or both.

SUMMARY AND CONCLUSIONS

Considered together, the findings of the present experiments show for the first time that caffeine influences prospective timing if a person performs an active and relatively difficult task but not when a person performs a passive and relatively easy task. In the future, researchers may wish to investigate whether the effect of caffeine on prospective timing is attributable to the kind of task (active responding vs passive perception) or to the difficulty of the task (easy vs difficult) *per se*. The present findings clarify a major effect of caffeine in the brain, the dopamine D_2 agonism effect, as well as provide additional evidence supporting an attentional-gate model of prospective time estimation.

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