

Ergogenic Effects of Low Doses of Caffeine on Cycling Performance

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The purpose of this experiment was to learn whether low doses of caffeine have ergogenic, perceptual, and metabolic effects during cycling. To determine the effects of 1, 2, and 3 mg/kg caffeine on cycling performance, differentiated ratings of perceived exertion (D-RPE), quadriceps pain intensity, and metabolic responses to cycling exercise, 13 cyclists exercised on a stationary ergometer for 15 min at 80% $\dot{V}O_{2peak}$, then, after 4 min of active recovery, completed a 15-min performance ride 60 min after ingesting caffeine or placebo. Work done (kJ/kg) during the performance ride was used as a measure of performance. D-RPE, pain ratings, and expired-gas data were obtained every 3 min, and blood lactate concentrations were obtained at 15 and 30 min. Compared with placebo, caffeine doses of 2 and 3 mg/kg increased performance by 4% (95% CI: 1.0–6.8%, $p = .02$) and 3% (95% CI: -0.4% to 6.8%, $p = .077$), respectively. These effects were ergogenic, on average, but varied considerably in magnitude among individual cyclists. There were no effects of caffeine on D-RPE or pain throughout the cycling task. Selected metabolic variables were affected by caffeine, consistent with its known actions. The authors conclude that caffeine preparations of 2 and 3 mg/kg enhanced performance, but future work should aim to explain the considerable interindividual variability of the drug's ergogenic properties.

Keywords: ergogenic aid, perceived exertion, pain, cycle ergometry

Caffeine is known to enhance prolonged exercise performance (Spriet, 1995). More specifically, caffeine doses of 3–13 mg of caffeine per kilogram of body weight (mg/kg) improve exercise performance by an average magnitude of 0.41 *SD* (Doherty & Smith, 2004). Doses of less than 3 mg/kg have received less attention, but some studies suggest that low doses of caffeine are effective for performance

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enhancement. For example, after a 2-hr moderate-intensity cycling pretest, caffeine doses of 1.3 mg/kg and 1.9 mg/kg, ingested in the form of a carbonated soft drink, reduced the time to complete a laboratory time trial lasting ~30 min by ~3% (Cox et al., 2002). In addition, doses of ~2.1 mg/kg and ~3.2 mg/kg administered in the form of a carbohydrate-electrolyte sports drink were ergogenic for a cycling time trial of ~1 hr duration (Kovacs, Stegen, & Brouns, 1998). Despite these interesting findings, however, there have been no investigations of the ergogenic effects of similar doses of anhydrous caffeine alone.

Reduced perception of effort is commonly experienced during submaximal exercise after caffeine ingestion. A meta-analysis found that caffeine ingestion reduces ratings of perceived exertion (RPE) by an average of 0.47 *SD* compared with placebo and that 29% of the variance in the ergogenicity of caffeine was explained by changes in RPE (Doherty & Smith, 2005). There is evidence that the underlying physiological mechanism for reduced RPE is the drug's antagonism of adenosine receptors (Davis et al., 2003; Fredholm, Battig, Holmen, Hehlig, & Zvartau, 1999), which also appears to account for hypoalgesia of naturally occurring muscle pain during dynamic exercise (Motl, O'Connor, & Dishman, 2003; O'Connor, Motl, Broglio, & Ely, 2004). To date, however, the implications of attenuated RPE and muscle pain during exercise for enhanced performance remain largely unstudied (Doherty & Smith, 2005). Furthermore, it is unknown whether low doses of caffeine affect perceptual responses to exercise and subsequently enhance exercise performance.

The effect of caffeine on RPE has been assessed primarily by the use of undifferentiated ratings (Borg, 1974). A model of differentiated ratings of perceived exertion (D-RPE) has been described that incorporates three components of effort sense (Pandolf, 1978, 1982). Central-nervous-system (CNS) factors such as motivation, drive, and task aversion determine the overall perception of effort (RPE-O). Local factors such as strain, force sensation, and fatigue in the working muscles determine the perception of effort in the legs (RPE-L). Cardiorespiratory factors such as increased heart rate and depth and rate of breathing determine "chest" perceived exertion (RPE-C). The effects of caffeine on these three components of perceived exertion are not yet understood. Assessment of effort sense using the D-RPE model could provide clarification of the complex effects of caffeine on perceptual responses to exercise. In addition, there is evidence that caffeine in doses of 5 and 10 mg/kg reduces sensations of naturally occurring leg-muscle pain during dynamic exercise (Motl et al., 2003; Motl, O'Connor, Tubandt, Puetz, & Ely, 2006; O'Connor et al., 2005). The authors reasoned that hypoalgesia might partially explain some of the drug's ergogenicity; hence, they encouraged future researchers to incorporate examinations of both hypoalgesic and ergogenic properties of caffeine.

Against this background, the purposes of this experiment were to determine whether caffeine in doses of 1, 2, and 3 mg/kg enhances cycling performance and alters D-RPE and quadriceps pain ratings in conjunction with improvements in performance. We hypothesized that these doses of caffeine would enhance performance and reduce D-RPE and pain during exercise.

Methods

Participants

Twenty-one male cyclists were recruited by word of mouth, flyers, and e-mail lists of local cycling teams and clubs. Of these, eight either did not meet inclusion criteria ($n = 2$) or withdrew before starting the experimental trials for personal reasons ($n = 6$). The final sample size, $N = 13$, was determined a priori to be adequate to detect moderate ergogenic and perceptual effects of 0.4 *SD* (Doherty & Smith, 2004, 2005), assuming a mean test–retest correlation of .9 for preloaded work-based protocols (Jeukendrup, Saris, Brouns, & Kester, 1996), with 80% statistical power at the conventional α level of .05 (Potvin & Schutz, 2000).

Participants completed physical activity and dietary-caffeine recall questionnaires to assess training volume and caffeine consumption. They cycled 207 ± 31.5 km/week ($M \pm SEM$) and were habitual consumers of caffeine (132 ± 41 mg caffeine/day). None of the participants indicated any history of medical conditions that would predispose them to injuries or risks of negative side effects associated with strenuous exercise or caffeine ingestion, as assessed by medical history and caffeine-sensitivity questionnaires (Motl et al., 2003). Selected characteristics of the 13 cyclists are presented in Table 1. The institutional review board approved the procedures of this experiment, and all participants provided written informed consent.

Preliminary Procedures

Baseline Measures. Height and weight were measured, and seven skinfold thicknesses were assessed to estimate body density (Jackson & Pollock, 1978), from which body fatness was estimated using Siri's (1993) equation. Participants provided urine samples to confirm adequate hydration. Urine specific gravity was measured using a refractometer (Atago Co., Ltd., Bellevue, WA, model URC-PN) as a marker of hydration status (Armstrong et al., 1994). Testing was rescheduled if urine specific gravity was ≥ 1.021 (Armstrong et al.). On completion of preliminary measurements, participants performed a 10-min warm-up at a low intensity (100–125 W), followed by a graded exercise test (GXT) to exhaustion on an

Table 1 Participant Characteristics

| Variable | <i>M</i> \pm <i>SD</i> |
|--|--------------------------|
| Age (years) | 26.3 \pm 6.8 |
| Height (cm) | 179.9 \pm 4.5 |
| Weight (kg) | 76.6 \pm 11.9 |
| Body fat (%) | 11.8 \pm 4.9 |
| VO _{2peak} (L/min) | 4.2 \pm 0.5 |
| VO _{2peak} (ml \cdot kg ⁻¹ \cdot min ⁻¹) | 55.2 \pm 7.2 |
| 80% VO _{2peak} power output (W) | 260.4 \pm 34.9 |

electrically braked cycle ergometer to determine peak oxygen uptake ($\text{VO}_{2\text{peak}}$; Lode Excalibur Sport 2000, Lode B.V., Groningen, The Netherlands). The GXT began at a power output of 200 W, increasing 25 W every 2 min until participants reached volitional exhaustion. VO_2 , carbon dioxide production (VCO_2), pulmonary ventilation (V_E), and respiratory-exchange ratio (RER) were determined by indirect calorimetry using a Parvo Medics TrueOne 2400 metabolic measurement system (Parvo Medics, Inc., Salt Lake City, UT). Heart rate (HR) was monitored continuously using a Polar Vantage XL HR monitor (Polar Electro, Inc., Woodbury, NY, model 145900). Undifferentiated RPE was obtained at the end of every stage using the 10-point Borg category scale with ratio properties (Borg, 1982). Three minutes after the GXT, a capillary blood sample was obtained for determination of peak blood lactate concentration [La] (Lactate Pro blood lactate test meter, Arkray, Inc., Kyoto, Japan). All 13 cyclists met at least two of the following criteria of maximal effort: increase in VO_2 between the last two stages of less than half the expected increase (0.135 L/min), $\text{RER} \geq 1.10$, $[\text{La}] \geq 7.0$ mmol/L, or $\text{RPE} \geq 9$ on the Borg CR-10 scale.

D-RPE and Leg-Muscle Pain-Rating Instruction. During recovery from the GXT, participants were given detailed instructions as to how the D-RPE and leg-muscle pain scales were to be used in the experimental trials. The instructions for the pain scale were as described previously (Cook, O'Connor, Eubanks, Smith, & Lee, 1997). D-RPE instructions were developed from Pandolf's (1978) model. D-RPE was obtained using the 10-point Borg category scale with ratio properties (Borg, 1982), chosen because of its similarity to the quadriceps pain-intensity scale (Cook et al.). To ensure that participants understood the procedure, they were asked to explain the D-RPE and pain scales and instructions to the investigators in their own words. We were especially careful to ensure that participants understood the differences between RPE-L and sensations of quadriceps pain (i.e., that RPE-L involves sensations of muscle strain, force, and perceptions from all working muscles of the legs, whereas pain ratings solely indicate the degree of hurt felt in the quadriceps; Cook et al.; Pandolf, 1978).

Protocol Familiarization. After this instruction, participants performed a practice ride to familiarize themselves with the exercise tasks of the remaining trials and to verify the cycling intensity prescription of 80% $\text{VO}_{2\text{peak}}$. In addition, they were asked to periodically give D-RPE and pain ratings, so as to become familiar with assessing their perceptual responses to the exercise. For 15 min, they cycled at the work rate estimated to elicit 80% $\text{VO}_{2\text{peak}}$, which was calculated using the American College of Sports Medicine (2000) metabolic equation for gross VO_2 during cycle ergometry:

$$\text{VO}_2 = (10.8 \times W^{-1} \times M^{-1}) + 7$$

where VO_2 is gross O_2 consumption ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), W is power output in watts, and M is body mass in kg. After 4 min of active recovery (unloaded cycling), participants performed a 15-min cycling protocol during which they were instructed to maintain the highest possible intensity. For this ride, the ergometer was set to the linear mode, whereby the work rate increased linearly as a function of pedaling cadence. Participants were instructed to maintain as high a cadence (i.e., perform as much work) as possible.

Experimental Procedures

Research Design and Protocol. A double-blind, placebo-controlled, repeated-measures experimental design was employed in which all participants were tested under all treatment conditions. As described previously, participants refrained from strenuous exercise for 24 hr and from caffeine for 48 hr before testing and completed 24-hr history and 7-day caffeine recall forms to assess compliance with pretest instructions. Urine specific gravity was measured to confirm euhydration. With 450 ml water, participants ingested a pill containing a placebo (white flour) or one of three treatments: 1, 2, or 3 mg/kg caffeine. After ingestion, participants sat quietly for 60 min to allow for peak blood caffeine concentrations to be reached (Kalmar & Cafarelli, 2004).

After the 60-min quiet rest, participants performed a cycling protocol identical to the familiarization session. The first portion of the preloaded exercise test was 15 min of cycling at a work rate estimated to elicit 80% $\dot{V}O_{2peak}$. During the ride, $\dot{V}O_2$, $\dot{V}_{E'}$, and RER were continuously measured via open-circuit spirometry as described previously. At 3-min intervals (Minutes 3, 6, 9, 12, and 15), participants were asked for the D-RPE ratings (RPE-L, RPE-C, RPE-O) and intensity of quadriceps pain. After the 15 min of exercise, a blood sample was obtained via finger stick and was analyzed for [La].

After 4 min of active recovery (unloaded cycling), participants were instructed to ride as hard as possible for 15 min to simulate an extended all-out effort at the end of a race. This procedure was identical to the one practiced on the preliminary visit. This method of assessing performance in prolonged exercise is preferred over time-to-exhaustion protocols because of the ecological validity associated with work-based performance tests (Jeukendrup et al., 1996); that is, a protocol in which cyclists perform the greatest amount of work possible closely replicates competitive situations. Work production on this ride was expressed relative to participants' body weight (kJ/kg), which was used as the measure of cycling performance. The physiological and perceptual measures for the performance-test portion of the ride are identical to the methods described previously for exercise at the constant work rate. A finger stick was performed to determine [La] on completion of the ride.

Success With Blinding of Treatment. On completing all experimental trials, participants were asked to guess the order in which they had received the treatments. From this we determined the number of participants who correctly named the placebo trial, the number of participants who attributed the greatest dose of caffeine with the trial in which they produced the most work, and the number of participants who correctly guessed the sequence of treatments.

Statistical Analysis

A one-way repeated-measures analysis of variance (ANOVA) was used to test the significance of mean differences among treatments in work (kJ/kg) performed during the performance ride. A two-way repeated-measures ANOVA was used to test for an effect of order (i.e., independent of treatment) on performance. Physiological (% $\dot{V}O_{2peak}$, $\dot{V}_{E'}$, RER, and HR) and perceptual (RPE-L, RPE-C, RPE-O, and ratings of pain intensity) outcomes were analyzed using a 4 × 5 (Treatment × Time) ANOVA with repeated measures on both factors. Differences among treatments in [La]

obtained after each bout of exercise were analyzed using a one-way ANOVA with repeated measures. The constant-load and performance-ride portions of the exercise were analyzed separately for all variables. The Greenhouse–Geisser adjustment to degrees of freedom was used for all repeated-measures ANOVA tests in the event that the sphericity assumption was not met. If the omnibus test revealed a significant F ratio, paired-sample two-tailed t tests were used to test mean differences between treatments. Effect sizes are presented as partial eta-squared (η_p^2) to express the amount of total variance attributable to caffeine treatments, and differences between treatments are expressed as 95% confidence intervals (CI) and as standardized differences in the means (Cohen's d ; Cohen, 1988). All analyses were performed using SPSS v. 13.0 for Windows (SPSS, Inc., Chicago).

Results

Effects of Caffeine on Cycling Performance

The performance data are presented in Figure 1. Work performed ($M \pm SEM$) relative to body mass was 2.96 ± 0.16 , 2.94 ± 0.12 , 3.08 ± 0.16 , 3.05 ± 0.17 kJ/kg for placebo and 1-, 2-, and 3-mg/kg caffeine treatments, respectively. The omnibus one-way repeated-measures ANOVA revealed a significant main effect, $F(3, 36) = 3.7$, $p = .02$, $\eta_p^2 = .23$. Analysis of mean differences indicated that 2 mg/kg resulted in a 3.9% (95% CI: 1.0–6.8%, $p = .02$, $d = .2$) increase in performance compared with placebo. Caffeine in 3 mg/kg elicited a 2.9% (95% CI: -0.4% to 6.8%, $p = .077$, $d = .14$) mean increase in performance compared with placebo. There was no effect of 1 mg/kg on performance compared with placebo (95% CI: -4.4% to 3.4%, $d = -.01$, $p = .80$). The observed statistical power of the ANOVA on performance was .75. The interindividual range for performance change with caffeine compared with placebo was -7.9% (1 mg/kg) to 17.8% (2 mg/kg). There were

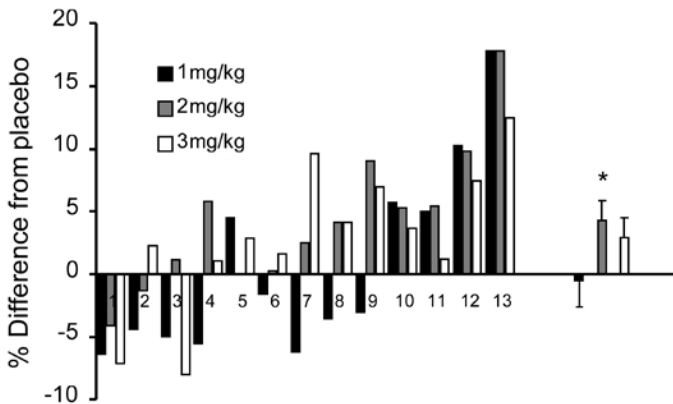


Figure 1 — Effect of caffeine on cycling performance for individual participants (numbered 1–13). Treatment $M \pm SEM$ are shown at right. *Significant at the .05 level.

no differences among treatments in the effect of order of visit on performance, as indicated by the lack of a Treatment \times Order interaction effect, $F(9, 108) = 0.883$, $p = .543$, $\eta^2_p = .069$.

Effects of Caffeine on Perceptual Responses to Exercise

Perceptual responses to exercise are summarized in Figure 2 (D-RPE) and Figure 3 (pain). During cycling at 80% VO_{2peak} , there was no Treatment \times Time interaction effect on RPE-C, RPE-L, RPE-O, or quadriceps pain-intensity ratings. Analyses of marginal means revealed no treatment main effect on RPE-C, RPE-L, RPE-O, or quadriceps pain-intensity ratings. There was a significant time effect for all variables ($p < .05$).

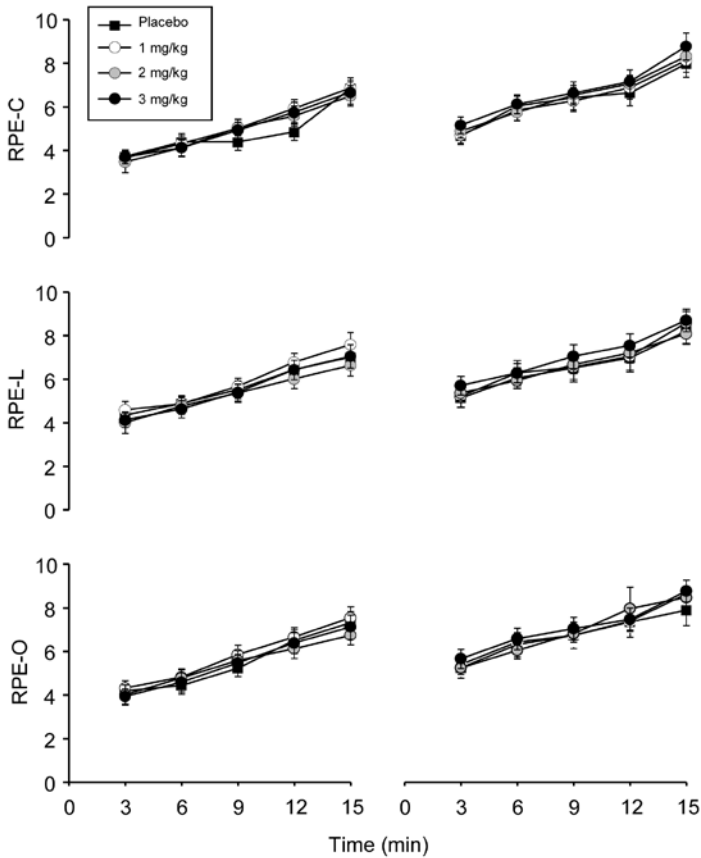


Figure 2 — Differentiated ratings of perceived exertion (RPE) during 80% VO_{2peak} (left column) and performance ride (right column). The y axes are RPE-chest (RPE-C), RPE-legs (RPE-L), and RPE-overall (RPE-O).

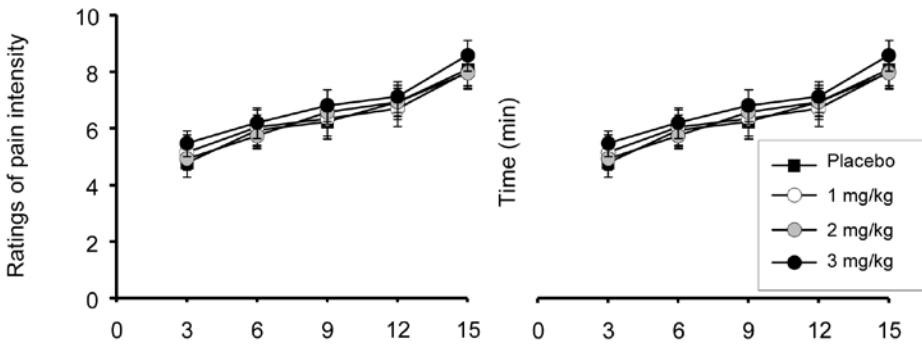


Figure 3 — Ratings of quadriceps pain intensity during cycling at 80% $\text{VO}_{2\text{peak}}$ (left) and performance ride (right).

During the performance ride, there was no Treatment \times Time interaction effect on RPE-C, RPE-L, RPE-O, or quadriceps pain-intensity ratings. Analysis of marginal means revealed no treatment effect on RPE-C, RPE-L, RPE-O, or quadriceps pain-intensity ratings on the omnibus two-way repeated-measures ANOVA. There was a significant effect of time on all variables ($p < .05$).

Effects of Caffeine on Cardiorespiratory and Metabolic Responses to Exercise

The physiological responses to cycling at 80% $\text{VO}_{2\text{peak}}$ are presented in Table 2. The two-way repeated-measures ANOVA revealed no Treatment \times Time interaction effect on % $\text{VO}_{2\text{peak}}$, V_E , RER, or HR. Analysis of marginal means revealed no treatment effect on % $\text{VO}_{2\text{peak}}$, RER, or HR. V_E was increased by caffeine, $F(3, 36) = 2.84$, $p = .05$, $\eta^2_p = .19$, at the 3-mg/kg dose by 5.7 ± 1.9 L/min (95% CI: 1.4–10.0 L/min, $p = .01$, $d = .36$) and by 6.7 ± 2.5 L/min (95% CI: 1.4–12.1 L/min, $p = .01$, $d = .36$) at 12 and 15 min, respectively. For all variables, there was significant time effect (all $p < .05$). The one-way repeated-measures ANOVA revealed a significant treatment effect on [La], $F(3, 36) = 3.8$, $p = .04$, $\eta^2_p = .24$, as the 3-mg/kg treatment elicited an increase of 1.6 mmol/L (95% CI: 0.16–2.9 mmol/L, $p = .03$, $d = .61$).

The metabolic responses to the performance ride are presented in Table 3. The omnibus ANOVA revealed no Treatment \times Time interaction effect on % $\text{VO}_{2\text{peak}}$, V_E , RER, or HR. Analysis of marginal means revealed a significant treatment effect on % $\text{VO}_{2\text{peak}}$. Comparisons of mean differences indicated that % $\text{VO}_{2\text{peak}}$ was elevated with 2 mg/kg caffeine compared with placebo by $5.2 \pm 1.2\%$ (95% CI: 2.6–7.8%; $p = .001$, $d = .71$), $5.1 \pm 1.6\%$ (95% CI: 1.6–8.6%; $p = .008$, $d = .81$), and $7.3 \pm 2.2\%$ (95% CI: 2.5–12.2%, $p = .005$, $d = .93$) at 9, 12, and 15 min, respectively. The omnibus test indicated a significant treatment effect on V_E , $F(3, 36) = 6.55$, $p = .004$, $\eta^2_p = .35$. Caffeine in 2 mg/kg increased V_E at 9, 12, and 15 min by 8.3 ± 2.02 L/min (95% CI: 3.9–12.7 L/min, $p = .001$, $d = .38$), 8.7 ± 2.8 L/min (95% CI:

Table 2 Physiological Responses to Cycling at 80%VO_{2peak}, *M* ± *SEM*

| Variable | Treatment | Time (min) | | | | |
|----------------------------|----------------------|-------------|-------------|-------------|-------------|--------------|
| | | 3 | 6 | 9 | 12 | 15 |
| %VO _{2peak} | Placebo | 80.3 ± 1.0 | 86.2 ± 1.1 | 88.4 ± 1.3 | 89.1 ± 1.1 | 89.9 ± 1.3 |
| | 1 mg/kg | 80.5 ± 1.0 | 86.6 ± 1.0 | 87.7 ± 1.4 | 89.1 ± 1.4 | 89.7 ± 1.4 |
| | 2 mg/kg | 81.4 ± 1.2 | 86.1 ± 1.4 | 88.4 ± 1.4 | 90.1 ± 1.8 | 91.3 ± 1.9 |
| | 3 mg/kg | 80.4 ± 1.0 | 87.5 ± 1.2 | 89.2 ± 1.2 | 90.8 ± 1.3 | 91.5 ± 1.3 |
| V _E (L/min)* | Placebo | 73.9 ± 3.5 | 84.4 ± 3.3 | 90.7 ± 3.7 | 94.1 ± 4.1 | 97.9 ± 4.8 |
| | 1 mg/kg | 75.3 ± 3.9 | 86.0 ± 3.6 | 91.2 ± 4.2 | 95.1 ± 5.0 | 99.0 ± 5.8 |
| | 2 mg/kg | 76.0 ± 4.0 | 86.5 ± 4.9 | 92.8 ± 4.9 | 96.8 ± 5.7 | 101.1 ± 6.0 |
| | 3 mg/kg ¹ | 75.8 ± 4.2 | 88.7 ± 4.1 | 94.0 ± 4.5 | 99.8 ± 4.7† | 104.7 ± 5.5† |
| RER | Placebo | 1.05 ± 0.01 | 1.02 ± 0.01 | 1.00 ± 0.01 | 0.99 ± 0.01 | 0.99 ± 0.00 |
| | 1 mg/kg | 1.04 ± 0.02 | 1.01 ± 0.02 | 0.99 ± 0.01 | 0.98 ± 0.01 | 0.98 ± 0.01 |
| | 2 mg/kg | 1.03 ± 0.02 | 1.01 ± 0.01 | 1.00 ± 0.01 | 0.98 ± 0.01 | 0.98 ± 0.01 |
| | 3 mg/kg | 1.05 ± 0.02 | 1.03 ± 0.01 | 1.01 ± 0.01 | 1.00 ± 0.01 | 0.99 ± 0.01 |
| HR (beats/ min) | Placebo | 155 ± 5.8 | 167 ± 2.8 | 173 ± 3.0 | 176 ± 3.1 | 179 ± 3.1 |
| | 1 mg/kg | 153 ± 5.1 | 167 ± 3.2 | 172 ± 3.1 | 176 ± 3.1 | 178 ± 3.3 |
| | 2 mg/kg | 154 ± 6.1 | 168 ± 3.4 | 174 ± 3.4 | 177 ± 3.5 | 180 ± 3.6 |
| | 3 mg/kg | 158 ± 3.7 | 168 ± 3.4 | 174 ± 3.4 | 178 ± 3.2 | 181 ± 3.4 |
| [La] (mmol/L)* | Placebo | | | | | 8.2 ± 0.7 |
| | 1 mg/kg | | | | | 9.0 ± 0.7 |
| | 2 mg/kg | | | | | 9.0 ± 0.8 |
| | 3 mg/kg | | | | | 9.7 ± 0.7† |

Note. VO_{2peak} = peak oxygen uptake; V_E = pulmonary ventilation; RER = respiratory exchange ratio; HR = heart rate; [La] = blood lactate concentration.

*Significant omnibus *F* ratio. †Different from placebo at corresponding time point at the .05 level.

2.6–14.7 L/min, $p = .009$, $d = .31$), and 13.0 ± 4.7 L/min (95% CI: 2.8–13.2 L/min, $p = .02$, $d = .53$), respectively, and in 3 mg/kg at 6, 9, 12, and 15 min by 6.4 ± 2.5 L/min (95% CI: 0.9–11.8 L/min, $p = .03$, $d = .33$), 7.9 ± 2.8 L/min (95% CI: 3.9–12.7 L/min, $p = .1$, $d = .38$), 7.8 ± 2.7 L/min (95% CI: 2.0–13.6 L/min, $p = .01$, $d = .31$), and 13.2 ± 4.4 L/min (95% CI: 3.7–22.8 L/min, $p = .01$, $d = .53$), respectively. There were no treatment main effects on RER or HR. There was a significant time effect for each of these variables ($p < .05$). [La] was significantly increased with caffeine, $F(3, 36) = 4.34$, $p = .02$, $\eta^2_p = .27$, with 3 mg/kg being greater than placebo by 2.5 ± 0.5 mmol/L (95% CI: 1.3–3.6 mmol/L; $p < .001$, $d = .90$) and 2 mg/kg by 1.3 ± 0.6 mmol/L (95% CI: 0.1–2.5 mmol/L, $p = .04$, $d = .48$).

Table 3 Physiological Responses to Performance Ride, $M \pm SEM$

| Variable | Treatment | Time (min) | | | | |
|------------------------------------|----------------------|-------------|-------------|-------------|-------------|--------------|
| | | 3 | 6 | 9 | 12 | 15 |
| %VO _{2peak} * (L/min)* | Placebo | 80.4 ± 2.4 | 81.0 ± 2.1 | 79.1 ± 2.3 | 79.8 ± 1.9 | 83.6 ± 2.2 |
| | 1 mg/kg | 78.9 ± 1.5 | 79.8 ± 1.3 | 79.4 ± 1.2 | 80.9 ± 1.9 | 86.9 ± 1.2 |
| | 2 mg/kg | 84.2 ± 2.3 | 83.3 ± 1.9 | 84.3 ± 1.7† | 84.9 ± 1.6† | 90.9 ± 2.1† |
| | 3 mg/kg | 82.8 ± 2.4 | 83.0 ± 1.9 | 81.8 ± 2.1 | 81.8 ± 1.6 | 87.9 ± 1.7 |
| V _E (L/min)* | Placebo | 81.8 ± 5.2 | 85.5 ± 5.2 | 83.1 ± 5.8 | 83.7 ± 6.0 | 91.1 ± 6.5 |
| | 1 mg/kg | 78.7 ± 4.3 | 83.1 ± 4.3 | 81.3 ± 4.5 | 84.3 ± 5.2 | 97.7 ± 5.6 |
| | 2 mg/kg | 89.4 ± 6.0 | 89.5 ± 6.1 | 91.5 ± 6.3† | 92.3 ± 6.2† | 104.1 ± 7.0† |
| | 3 mg/kg ¹ | 88.1 ± 5.2 | 91.9 ± 5.4† | 91.1 ± 6.3† | 91.5 ± 6.0† | 104.3 ± 7.7† |
| RER | Placebo | 0.93 ± 0.02 | 0.94 ± 0.01 | 0.93 ± 0.01 | 0.93 ± 0.01 | 0.94 ± 0.01 |
| | 1 mg/kg | 0.90 ± 0.01 | 0.93 ± 0.01 | 0.92 ± 0.01 | 0.92 ± 0.01 | 0.96 ± 0.01 |
| | 2 mg/kg | 0.94 ± 0.02 | 0.94 ± 0.01 | 0.94 ± 0.01 | 0.93 ± 0.01 | 0.96 ± 0.01 |
| | 3 mg/kg | 0.94 ± 0.02 | 0.95 ± 0.01 | 0.94 ± 0.01 | 0.94 ± 0.01 | 0.97 ± 0.01 |
| HR (beats/min) | Placebo | 171 ± 2.6 | 175 ± 2.4 | 176 ± 2.5 | 177 ± 2.5 | 180 ± 2.5 |
| | 1 mg/kg | 170 ± 2.9 | 174 ± 2.4 | 175 ± 2.8 | 179 ± 2.4 | 183 ± 2.7 |
| | 2 mg/kg | 174 ± 2.0 | 177 ± 2.1 | 179 ± 2.3 | 180 ± 2.3 | 185 ± 2.5 |
| | 3 mg/kg | 174 ± 2.8 | 178 ± 2.5 | 178 ± 3.0 | 180 ± 2.8 | 184 ± 2.6 |
| [La] (mmol/L)* | Placebo | | | | | 7.5 ± 0.8 |
| | 1 mg/kg | | | | | 8.7 ± 0.8 |
| | 2 mg/kg | | | | | 8.8 ± 0.7 |
| | 3 mg/kg | | | | | 9.9 ± 0.7† |

Note. VO_{2peak} = peak oxygen uptake; V_E = pulmonary ventilation; RER = respiratory exchange ratio; HR = heart rate; [La] = blood lactate concentration.

*Significant omnibus *F* ratio. †Different from placebo at corresponding time point at the .05 level.

Success With Blinding of Treatment

Five of the 13 participants correctly identified the placebo trial, 8 attributed their best performance to the 3-mg/kg dose (2 of whom were correct), and no participants correctly guessed the sequence of treatments.

Discussion

We experimentally investigated the ergogenic, perceptual, and metabolic effects of low doses of caffeine (1, 2, and 3 mg/kg body weight). Caffeine in doses of 2 and 3 mg/kg increased cycling performance, on average, but did not affect perceptual

responses. These doses also increased $V_{E\max}$ and [La], consistent with known actions of the drug at higher concentrations (~6 mg/kg; Graham, 2001). These findings are important for athletes seeking to maximize performance gains from caffeine ingestion before a bout of training or competitive event.

Effect of Caffeine on Cycling Performance

The main finding of our experiment is that 2- and 3-mg/kg doses of caffeine elicited average ergogenic effects of 4% ($d = .20$) and 3% ($d = .14$) compared with placebo, respectively. Performance after ingestion of 1 mg/kg was not different compared with placebo, suggesting that the minimum threshold for performance enhancement might be between 1 and 2 mg/kg. These data are in general agreement with those of two studies that previously showed ergogenic effects of doses lower than 3 mg/kg. One investigation found that after a 2-hr bout of submaximal cycling, caffeine ingested in the form of Coca Cola, in concentrations of 1.3 mg/kg (Study A) and 1.9 mg/kg (Study B), enhanced cycling performance on a 7-kJ/kg laboratory time trial by ~3% (Cox et al., 2002), similar to the average magnitudes observed here. Kovacs et al. (1998) reported that a dose of ~2.1 mg/kg, ingested in the form of a carbohydrate-electrolyte sports drink, is ergogenic for a cycling time trial of ~1 hr duration. Our data extend these previous results by demonstrating performance enhancement after ingestion of similar amounts of anhydrous caffeine.

A somewhat surprising result of our study was that 3 mg/kg elicited slightly smaller and less consistent performance enhancement than did 2 mg/kg. A dose of 3 mg/kg has been shown to increase exercise time to exhaustion at 85% VO_{2peak} (Graham & Spriet, 1995) and decrease 8-km running time in a field setting (Bridge & Jones, 2006), and it is generally thought that 3 mg/kg is sufficient to enhance prolonged performances (Doherty & Smith, 2004). Using conventional criteria, the effect of 2 mg/kg achieved statistical significance ($p = .02$), and 3 mg/kg “approached” significance ($p = .077$). Lack of statistical significance of the 3-mg/kg dose might have been a result of the relatively small sample size and slightly low statistical power (75%). The athletes displayed considerable interindividual variation in response to caffeine, as depicted in Figure 1. On a case-by-case basis, 3 mg/kg was ergogenic for 11 of the 13 cyclists, with 2 nonresponders heavily influencing the mean and error terms. Because potential sources of error variance were carefully controlled in our experiment (e.g., double-blind/placebo-controlled design, familiarization session, etc.), it is likely that the somewhat smaller effect of 3 than 2 mg/kg primarily reflected individual variability.

Previous investigations have used sports drinks and cola beverages to determine the ergogenic effects of caffeine (Cox et al., 2002; Kovacs et al., 1998). The aim of our study, however, was to investigate the effects of caffeine per se; therefore, we chose pills as the vehicle of administration to isolate the effects of the drug itself. For this reason, we also chose shorter exercise duration than many previous experiments (Costill, Dalsky, & Fink, 1978; Cox et al.; Doherty & Smith, 2004; Graham & Spriet, 1995; Ivy, Costill, Fink, & Lower, 1979; Kovacs et al.), although the ergogenic effect of caffeine is apparent in as little as 15 min of exercise 60 min after caffeine ingestion (Ivy et al.). Had the duration been longer (e.g., ~45–60+ min), it would have necessitated delivering the caffeine in the form of a beverage or some other vehicle to counteract dehydration and glycogen depletion associated

with prolonged aerobic activity. We thus opted for a protocol that we judged short enough to preclude these phenomena yet long enough to be limited chiefly by the aerobic capacity of the participants. Certainly, duration of the performance protocol is a potentially important determinant of the ergogenic properties of caffeine (Graham, 2001), and it is possible that the doses used in the current investigation are more consistently effective when ingested in some other vehicle during more prolonged performances. This issue deserves attention of future investigators.

The current experiment must be considered in light of the recent finding that a placebo effect associated with caffeine administration might be ergogenic in itself (Beedie, Stuart, Coleman, & Foad, 2006). Cyclists increased power output during a simulated 10-km time trial by ~2–3% when they believed they had ingested caffeine compared with when they believed they had ingested a placebo, although no caffeine was actually consumed (all conditions were placebo). Beedie et al. suggest that even with a double-blind, placebo-controlled experimental design, some of the observed ergogenicity might be explained by participants' beliefs or expectations of caffeine's putative performance-enhancing effects, and these placebo effects might be erroneously interpreted as meaningful. On one hand, the blind was successfully retained in the current study, because none of the 13 participants correctly identified the order of their treatments. Eight of 13 cyclists, however, believed that they had received the highest dose of caffeine on the day that corresponded with their personal best performance, and only 2 of these 8 actually received 3 mg/kg on that day. We therefore cannot rule out the possibility that some portion of our observed increases in performance were a result of participants' belief that they had received caffeine and that this placebo-belief phenomenon explains a portion of the interindividual variability in our performance outcome.

Irrespective of our protocol or supposed placebo-belief effects, our findings are generally consistent with the known ergogenicity of greater caffeine doses. Future investigations should aim to tease out the causal components of interindividual variation in caffeine's performance-enhancing properties.

D-RPE and Quadriceps Pain Ratings

Caffeine had no effects on RPE-C, RPE-L, RPE-O, or quadriceps pain during cycling at 80% $\dot{V}O_{2peak}$. This finding is in contrast to the hypothesis that caffeine would attenuate these perceptual responses to exercise, perhaps because the intensity prescription of the constant-rate exercise was severe enough to reduce the likelihood of reduced D-RPE and pain. Caffeine is known to decrease effort sense and muscle pain via CNS adenosine-receptor antagonism (Fredholm et al., 1999), which appears to be the primary mechanism underlying the typically observed moderate ($d \approx .5$) reduction in RPE (Doherty & Smith, 2005). Adenosine is only one of several metabolites (e.g., H⁺ ions, bradykinin, substance P), however, associated with high-intensity exercise that contribute to sensations of discomfort and pain (O'Connor & Cook, 1999). Caffeine has no known effects on these noxious metabolites. In our experiment, adenosine-receptor antagonism apparently did not occur to the extent necessary to attenuate feelings of discomfort and pain. In addition, the deleterious effects of these other metabolites were probably present because of the severe intensity. The combined effects of high-intensity exercise and low caffeine doses likely reduced the possibility of attenuated sensations of

muscle effort, dyspnea, and quadriceps-muscle pain. An interesting and important finding of the current study is that 2 and 3 mg/kg caffeine elicited ergogenic effects without blunting these perceptual responses.

Three investigations have provided convincing evidence that caffeine attenuates naturally occurring leg-muscle pain during cycling exercise (Motl et al., 2003, 2006; O'Connor et al., 2004). In each of these investigations, the authors called for future research to investigate the possibility of concomitant hypoalgesia and ergogenicity, and here we have attempted to address this problem. We conclude that caffeine is not hypoalgesic in doses of 1, 2, and 3 mg/kg at 80% $\text{VO}_{2\text{peak}}$. Gliotoni and Motl (2008) recently found that 5 mg/kg caffeine is hypoalgesic during cycling at 80% $\text{VO}_{2\text{peak}}$. Therefore, it is possible that ~5 mg/kg is the minimum effective hypoalgesic dose, which might not be surprising in light of the evidence that this dose is consistently ergogenic (Doherty & Smith, 2004). Nonetheless, the question of whether hypoalgesia is partly responsible for ergogenic properties of caffeine has by no means been completely addressed. Future investigation of this important question is warranted.

Metabolic and Cardiorespiratory Outcomes

Caffeine has been repeatedly shown to increase [La] (Graham, 2001), perhaps because of altered hepatic lactate metabolism (Graham, Helge, MacLean, Kiens, & Richter, 2000). We found that 3 mg/kg increased [La] immediately after cycling at 80% $\text{VO}_{2\text{peak}}$, suggesting that 3 mg/kg might be a threshold to detect this effect. It is unlikely that effects of caffeine on [La] metabolism influence exercise performance (Graham), so it is improbable that this increase in [La] influenced work done during the 3-mg/kg trial. \dot{V}_E was increased with 3 mg/kg during the later portions of the pretest, consistent with previous data (Hadjicharalambous et al., 2006) and likely because of increased CNS stimulation (Fredholm et al., 1999; Graham; Kalmer & Cafarelli, 2004). The heightened rates of aerobic metabolism and \dot{V}_E during the performance test elicited by the 2- and 3-mg/kg preparations are consistent with the observed ergogenic effects. These doses were sufficient to augment the highest tolerable metabolic rate and consequently increase the total amount of work done during the performance test.

Conclusion

We conclude that anhydrous caffeine doses of 2 and 3 mg/kg enhance cycling performance under the conditions of this study. Ergogenic effects were consistent on average but heterogeneous in magnitude between individual cyclists. Contrary to our hypothesis, we did not find caffeine-induced reductions of perceived effort and leg-muscle pain. Future investigations should assess D-RPE and quadriceps pain to further elucidate caffeine's perceptual effects, specifically in light of concomitant ergogenicity. Effects of caffeine on metabolic parameters observed previously with greater doses were replicated at the lower doses used in our experiment. An important focus of future work should be to determine sources of interindividual variation in caffeine's ergogenic properties.

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