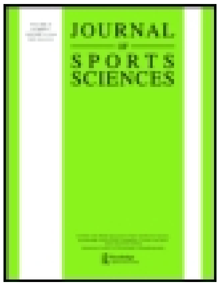

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The impact of 100 hours of exercise and sleep deprivation on cognitive function and physical capacities

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Abstract

In this study, we examined the effect of 96–125 h of competitive exercise on cognitive and physical performance. Cognitive performance was assessed using the Stroop test ($n = 9$) before, during, and after the 2003 Southern Traverse adventure race. Strength (MVC) and strength endurance (time to failure at 70% current MVC) of the knee extensor and elbow flexor muscles were assessed before and after racing. Changes in vertical jump ($n = 24$) and 30-s Wingate performance ($n = 27$) were assessed in a different group of athletes. Complex response times were affected by the race (16% slower), although not significantly so ($P = 0.18$), and were dependent on exercise intensity (less so at 50% peak power output after racing). Reduction of strength ($P < 0.05$) of the legs (17%) and arms (11%) was equivalent ($P = 0.17$). Reductions in strength endurance were inconsistent (legs 18%, $P = 0.09$; arms 13%, $P = 0.40$), but were equivalent between limbs ($P = 0.80$). Similar reductions were observed in jump height ($-8 \pm 9\%$, $P < 0.01$) and Wingate peak power ($-7 \pm 15\%$, $P = 0.04$), mean power ($-7 \pm 11\%$, $P < 0.01$), and end power ($-10 \pm 11\%$, $P < 0.01$). We concluded that: moderate-intensity exercise may help complex decision making during sustained stress; functional performance was modestly impacted, and the upper and lower limbs were affected similarly despite being used disproportionately.

Keywords: *Adventure racing, functional performance, Stroop test, prolonged exercise*

Introduction

The ability of humans to perform cognitive and physical tasks across more than one day of sustained exercise and sleep deprivation has received little research attention. Adventure racing provides a means to examine stress sustained across multiple days. Athletes' power output drops substantially during this very prolonged (~100 h) and sustained exercise strain (Lucas et al., 2008), although it is unclear whether this coincides with reductions in strength or power capabilities. Furthermore, adventure race competitors commonly report hallucinations and overwhelming tiredness that imply cognitive performance could be altered by this type of stress.

Sleep deprivation appears to adversely alter perceived exertion, mood, and cognitive function (Angus, Heslegrave, & Myles, 1985; Bonnet, 1980; Martin, 1981; Souissi, Sesboüé, Gauthier, Larue, & Davenne, 2003; VanHelder & Radomski, 1989). However, the effects of sleep deprivation on physical or physiological performance are less conclusive and often conflicting (Bulbulian, Heaney, Leake, Sucec, & Sjoholm, 1996; Souissi et al., 2003). Some researchers have reported no ill-effects (Guezennec, Satabin, Legrand, & Bigard, 1994; Hackney, Shaw, Hodgdon, Coyne, & Kelleher, 1991; Symons, VanHelder, & Myles, 1988). Others have reported selective decrements (Nindl et al., 2002; Reilly & Deykin, 1983; Takeuchi, Davis, Plyley, Goode, & Shephard, 1985) in, for example, mean but not peak anaerobic power output after 72 h of sustained military operations (Nindl et al., 2002). The diverse findings may reflect the variety of exercise modes, intensities, frequencies, and durations used, and different evaluation procedures (Symons et al., 1988). In addition, most studies induce only 1–3 days of sleep deprivation and typically include periods of rest and/or naps during each 24-h period. Furthermore, exercise stress has been incorporated in few such studies and typically only intermittently (Angus et al., 1985; Rodgers et al., 1995; Scott, McNaughton, & Polman, 2006).

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Military-based studies (e.g. Nindl et al., 2002; Opstad, Ekanger, Nummestad, & Raabe, 1978; Symons et al., 1988) provide a useful comparison to the stress of an adventure race, as soldiers have been studied during programmed military-type exercises over similar sleep-deprived periods. However, the severe calorie restriction, heavy pack loads (> 20 kg), externally constrained schedules, as well as the lower absolute exercise volume and duration in these studies mean that the stress of multi-day military training may be different to that of adventure racing.

In the adventure racing context, humans' ability to perform physical and cognitive tasks across multiple days of sustained and competitive exercise appears not to have been systematically examined. The purpose of this study was to assess cognitive performance at rest and during exercise, and selected physical capacities, before, during, and after prolonged (∼100 h) and sustained competitive exercise. It was hypothesized that cognitive performance (speed and accuracy of decision making) and short-duration strength and power would be impaired, but peak strength and power would not.

Methods

The cognitive and physical performance tests reported here represent the final component of an extensive study designed to assess how humans responded to the stress of an adventure race. The 2003 Southern Traverse adventure race took place in Eastern Otago, New Zealand, near the University of Otago. It is an annual event and the world's second oldest adventure race; the 2003 race was the twelfth, and required teams of four athletes to navigate a novel 411-km course through stages of jogging/trekking, kayaking, coasteering (moving around the coastline below the high-tide mark), and mountain biking for ∼100 h in segments and order illustrated in Figure 1. Testing in this setting was limited by the fact that it took place before, during, and after an international adventure race. The experimental design required tests that were conducive to facilitating participant numbers and that minimized imposition on competitors during preparation for and participation in the event.

Participants

Two groups of participants were recruited for this study. The primary group consisted of three teams (Teams A, B, and C; collectively called "science teams") that took part in testing twice before (2–5 weeks and 22–24 h) the race and at the end of the race. These participants ($n = 9$) undertook cognitive performance tests, strength and strength endurance tests 2–5 weeks before and within 3 h of the end of the race. Participants in this group also completed the cognitive tests during the race. A separate group (referred to as "racing control") was recruited at pre-race registration, 36–48 h before the race, for a series of pre- and post-race tests that included vertical jump ($n = 24$) and 30-s Wingate ($n = 27$) tests. Participants from both groups underwent anthropometric measurements either 36–48 h ($n = 40$) or 22–24 h ($n = 9$) before the race as well as within 60 min of the end of the race. This project was approved by the University of Otago Ethics Committee, and all participants provided written informed consent.

Measurements and protocol

Cognitive performance. Cognitive performance was assessed using a speed and accuracy decision-making task in three situations (see Figure 1): (1) while completing a standardized cycling stress test (8-min consecutive blocks of rest and cycling at 25 and 50% peak power output); (2) while seated in a controlled

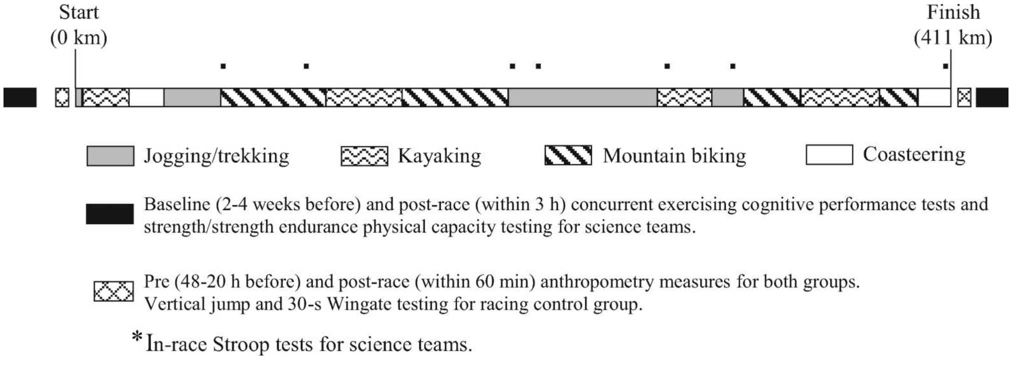

Figure 1. Schematic representation of the different stages of the 2003 Southern Traverse adventure race. The figure also shows the points where cognitive performance testing (Stroop test) was undertaken across the race (not all teams tested at each point), as well as testing before and after the race for physical characteristics and capacities and Stroop tests during standardized stress tests.

laboratory environment (in a quiet room) 15 min following the standardized exercise test; and (3) periodically in the field, often at exercise mode transition stages during the race.

The decision-making task was administered using a computer-adapted Stroop test (Stroop, 1935). This test was modified to include levels of complexity to compare performance on simple and more complex tasks, and was shorter in duration to encroach minimally on athletes' racing time. The test involved four blocks of 20 trials in which the participant responded by pressing the left or right arrow keys of a laptop computer. Each block became more complex. The initial two blocks measured response time to identify the word or colour of non-coloured words and coloured rectangles. The final two blocks required participants to differentiate between the "name of the word" and the colour that the word was displayed in, responding to the colour that the word was displayed in, thus creating a conflict between colour and word recognition. For example, if the word "GREEN" was presented in yellow, the correct response was "yellow". Participants were instructed to "attempt each trial as quickly and accurately as possible". Timing started with the first key press and ended with the last in each block, thus the first trial of each block was not included in the analysis.

Response time for each trial and number of incorrect answers were calculated using a macro function within Microsoft EXCEL®. All participants completed at least one familarization test before data collection (at rest for the baseline standardized cycling stress test). If participants fell asleep during the task, the researcher woke them by calling their name aloud. This was sufficient to rouse the participant, who then returned to the task.

Physical characteristics. Anthropometry (height, mass, sum of seven skinfolds, and limb girth) measurements were obtained before (36–48 h or 22–24 h) and within 60 min of finishing the race. Nude body mass (accuracy ± 0.01 kg) was measured using electronic scales (D1-10, Digi, Teraoka Seiko Ltd., Japan) behind a privacy screen. Height was measured using a stadiometer (School of Physical Education, University of Otago). Skinfold thicknesses were measured using skinfold calipers (C-136, Harpenden, UK) at seven right-side locations: triceps, biceps, subscapular, supraspinale, abdominal, front thigh, and medial calf (accuracy ± 0.2 mm). Waist and three limb girths were measured using a plastic measuring tape: calf, waist, bicep (tensed), and bicep (relaxed). Measurements were made in accordance with the procedural guidelines of the International Society for the Advancement of Kinathropometry, by ISAK-accredited assessors.

Physical capability tests. Explosive power was measured using a vertical jump tester (Swift yardstick, Hart Sport, New Zealand). Participants performed three standing jumps, with countermovement, with the highest taken as their maximum vertical jump. The vertical jump tester was standardized to stand-and-reach height for each participant before their first jump.

The 30-s Wingate cycle sprints were performed on a calibrated Repco cycle ergometer (Exertech EX10, Repco Cycle Company, Australia). After completing a 3-min warm-up (females 100 W, males 150 W) on a Monark cycle ergometer (Monark 824E, Ergomedic, Sweden), the participants performed the 30-s sprint with instruction and sustained encouragement. Peak, mean, and end power were converted using a MacLab/4e (ADInstruments, Australia) analog-to-digital converter, and subsequently recorded and displayed using a personal computer with Chart 4.2 software (ADInstruments). The ergometer was calibrated using the Repco electronic interface control unit.

Strength and strength endurance of the knee extensor and elbow flexor muscles for the participants in the science teams were measured before (2–5 weeks) and after (within 3 h) the race. Strength was assessed from three maximal voluntary contraction (MVC) efforts, while strength endurance was measured as the time to failure at 70% of the current MVC force for each muscle group. Participants were seated with torso and right leg strapped in the accessory chair of a Biodex Isokinetic Dynamometer (Biodex Corporation, USA). The participants then performed three warm-up isometric contractions ($\sim$25, $\sim$50, $\sim$80% of MVC) before completing the three MVCs, with 30 s between contractions. After a 2-min recovery following the third MVC, participants contracted the knee extensor muscles to produce a force equal to 70% of their highest MVC and were instructed to hold this force for as long as they could (without verbal encouragement). They received verbal instruction to either start ("go") or finish ("relax") the contraction, and directional feedback ("a little more" or "a little less") for force production during the strength-endurance task. Knowledge of incorrect force was primarily given by high (too much force) and low (insufficient force) tones that indicated when the 70% target force was less than 70% (low pitched tone) or greater than 80% (high pitched tone) of MVC force production. The point of failure was when participants either voluntarily stopped or were instructed to do so when the low tone sounded continuously for 3 s. Participants were familiarized with this feedback system prior to testing.

A force transducer (PST250 load cell, Precision Transducers Ltd., Australia) attached to the foot plate of the chair was used to transduce the force produced during isometric knee extension. Force was converted to digital signal using a MacLab/8e (ADInstruments) and recorded at 1 Hz using Chart 4.2 software (ADInstruments) onto a PC-based computer. Event Manager for Chart was used to monitor force output and provide audio feedback.

The same protocol was used to measure elbow isometric flexion force. The device comprised a hand grip connected to a steel rod attached to a force transducer (PST250 load cell) mounted in a custom-built, adjustable support structure. Participants sat on an adjustable office chair at a comfortable height with their elbow on the centre of a foam pad, forearm perpendicular to the base, and pulled on the hand grip. The MVC and 70% MVC strength tasks were performed as described for knee extension. The heights of the chair and hand grip were replicated during post-race testing. The isometric force device was secured to a bench and the office chair was mounted to a secure baseboard (1 × 1 m).

Data analysis

Cognitive test. Mean response time, coefficient of variation [(standard deviation/mean) × 100], and percentage error were calculated for each block of trials for each of the four levels of complexity for each participant. Results for the simple level and most complex level are reported. If participants fell asleep during a block of trials and held down the arrow key, these data trials were removed so as not to misrepresent the mean and standard deviation (s) of that block of trials. The number of verbal prompts that participants received to rouse them from sleep was recorded. Performance during the controlled laboratory environment before the race was taken as ‘‘baseline’’. This baseline was compared with the post-race measure in the same setting for the across-race effect using a paired t-test.

Changes in response time and coefficient of variation are reported as absolute change and percent change. Error trials are reported as a percentage of the total number of trials performed. Change in response times during the race was assessed by averaging each of the three teams’ mean response times across all testing times and comparing this average to baseline performance. Linear regression was used to test the relation between error rate and race duration for the in-field tests. A repeated-measures analysis of variance (ANOVA) (SPSS) was used to assess the relationship between cognitive performance and concurrent exercise using Stroop test data collected during the standardized stress tests before and after the race. The baseline and post-race Stroop test results were added to this ANOVA to differentiate possible order effect from an exercise effect. Pairwise comparisons (Bonferroni-adjusted) were made to isolate the source of significant interaction effects.

Physical characteristics and capabilities. Post-race physical characteristics and capabilities were compared with the baseline measures using paired t-tests. Changes in leg versus arm strength and strength endurance were analysed using repeated-measures ANOVA. Statistical significance for each analysis was set at $P < 0.05$.

Results

Race duration among all finishing teams ranged between 96 and 125 h. Race duration for the three science teams was distributed in accordance with their respective adventure racing experience (96 h, 108 h, and 116 h) and although the latter represented the time spent by the teams on a shortened course, their heart rate profiles were equivalent to competitors in the other teams (Lucas et al., 2008). As reported elsewhere (Lucas et al., 2008), exercise intensity averaged ~64% of aerobic power range across the first 12 h, but settled to ~41% by day 2 and remained at this level until the end of the event (inclusive of sleep periods). The work stress was affected by adverse weather, including hail and snow storms. During racing, temperatures recorded at the closest meteorological stations within the course (albeit below 300 m) ranged from 2.6 to 22.3°C, and wind gusts of $71\ \text{km} \cdot \text{h}^{-1}$ were recorded (NIWA Science New Zealand). The course elevation ranged from 0 to 1170 m. Participants from the three science teams reported almost no sleep on the first night of racing (13 ± 12 min) and only 1 h 36 min (± 29 min) of sleep for each subsequent 24-h period (estimated from self-report logs).

Cognitive performance

Figure 2 shows the across-race effect (baseline to post-race) on response times for Stroop test performance together with test performances measured during the three exercise intensities within the standardized stress test. Data are presented in the order that the tests were undertaken at baseline and after the race.

Simple-level response time changed less than 2% from baseline to post-race (mean ± s: 863 ± 159 to 850 ± 157 ms; $P = 0.48$), and error rates remained below 2% (shown beneath response times in Figure 2). Consistency of simple-level response time deteriorated across the race, as the within-participant coefficient of variation increased by 29% (15% before to 19% after; shown above error bars in Figure 2), although not significantly so ($P = 0.16$).

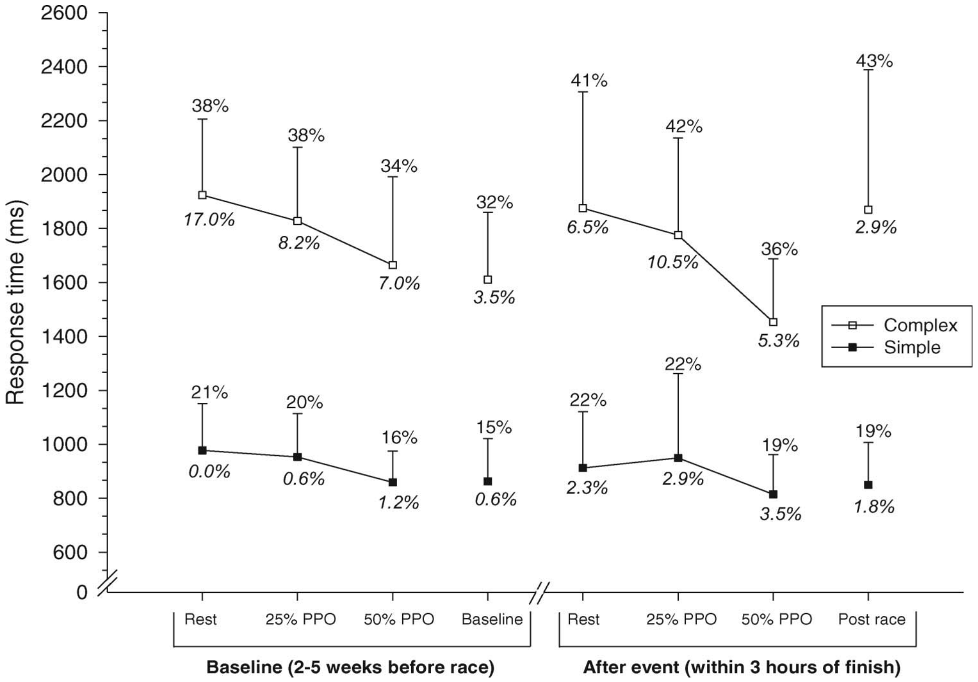

Figure 2. Response times ($n = 9$) for the simple and most complex levels of the Stroop test performed at rest, 25% and 50% peak power output (PPO) at baseline and after ~100 h of racing. The within-participant coefficient of variation and percentage of errors across all participants for each measure are reported above and below the mean response time, respectively.

Complex-level response time increased by 16% on average across the race (1610 ± 249 to 1869 ± 518 ms; Figure 2), although not significantly so ($P = 0.18$), and error rates were ~3% at baseline and post-race. Consistency of complex-level response time also deteriorated; the coefficient of variation increased by 34% (32% before to 43% after), although again not significantly so ($P = 0.13$).

Standardized stress test

There was no significant three-way interaction among cognition level, order of tests, and phase of testing ($P = 0.18$). There was an interaction ($P < 0.01$) between cognition (simple and complex level) and order (rest, 25%, 50%, and baseline/post-race). Subsequent analysis revealed that the interaction effect was due to the response times at the complex level changing ($P < 0.01$) across the order of tests, while performance on the simple level was not different ($P = 0.22$). Pairwise comparisons for the complex level revealed that although rest, 25% peak power output, and baseline/post-race response times were not different from one another (all $P > 0.05$), response time at 50% peak power output was different from rest ($P < 0.01$) and 25% peak power output ($P = 0.04$), but not baseline/post-race ($P = 0.67$) performance. This effect was not altered by the race (phase effect; $P = 0.70$), so there was no evidence that learning influenced post-race response time performance. Not surprisingly, response time for the complex level was longer than the simple level (test level: $P < 0.01$).

During the race

Figure 3 shows response times and percentage errors for each of the three science teams from testing conducted periodically during the race. Compared with baseline, average response times across all participants and all test periods increased by 45 ms (5%; 863 to 908 ms) for the simple level and by 68 ms (4%; 1610 to 1678 ms) for the complex level. Consistency of responses was also affected; the coefficient of variation increased by 66% for simple (from 15 to 24%) and 17% for complex (from 33 to 37%). Individual differences were evident both within and between teams across the race (Figure 3). On average, accuracy of decision making was impaired at a rate of one additional error per day for the simple level, but improved by one less error per day for the most complex level. This change was inconsistent ($P = 0.90$ and $P = 0.20$ for simple and complex, respectively).

Prompting

Participants required no prompting during baseline testing or the first 24 h of racing. Two participants each received one prompt during testing after

~48 h of racing. On the fourth day of racing (72–77 h), four of nine participants required at least one prompt while completing the complex level of the Stroop test and six of nine participants required prompting during the complex level of the post-race test.

Physical characteristics and capacities

Anthropometric measures for all participants (including science teams) are given in Table I. On average, body mass decreased by 0.6 ± 1.3 kg ($P < 0.01$) across the race, standing height decreased by 1.2 ± 0.7 cm ($P < 0.01$), subcutaneous abdominal skinfold thickness decreased by 15 ± 15% ($P < 0.01$), and calf girth increased by 1.4 ± 3.9% ($P = 0.02$). Although all other girth measurements decreased, only relaxed bicep girth did so statistically ($P = 0.04$).

After the race, vertical jump height was reduced by 8% (from 47 ± 8 to 43 ± 7 cm; $P < 0.01$). In the 30-s Wingate test, peak power decreased by 7% (from 1006 ± 193 to 940 ± 230 W; $P = 0.04$), mean power by 7% (from 701 ± 109 to 651 ± 130 W; $P < 0.01$), and end power by 10% (from 542 ± 74 to 487 ± 77 W; $P < 0.01$). Individual differences were evident, with peak power dropping by 45% in one participant and increasing by 18% in another. Overall, 17 participants demonstrated a drop in peak power and 10 participants showed an increase.

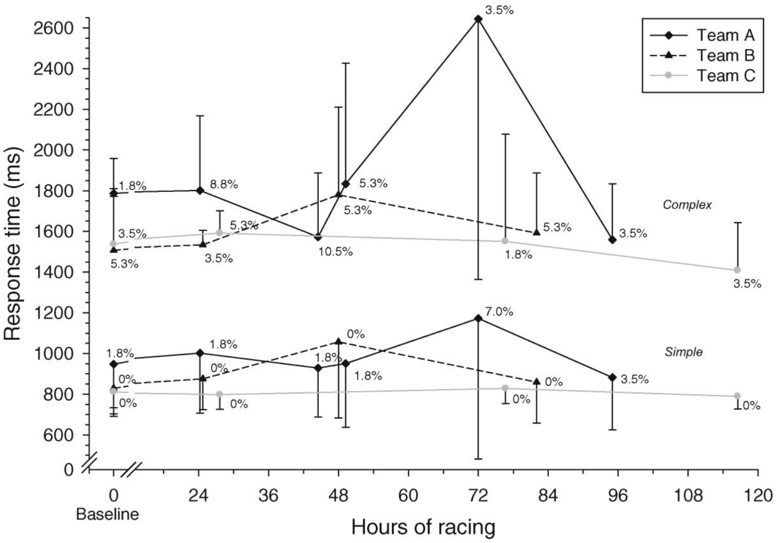

Figure 3. Mean (± *s*) response times for the simple and most complex levels of the Stroop test performed at baseline and periodically across 96–116 h of racing for each of the three teams. The percentage of errors across all team members is reported next to the mean team response time.

Table I. Anthropometric measurements for all participants taken either 36–48 or 22–24 h before as well as within 60 min after the race (mean ± *s*).

	Pre-race	Post-race	Percent change	*P*-value
Body mass (kg) ($n = 46$)	75.7 ± 8.5	75.1 ± 8.7	−0.8	<0.01
Height (m) ($n = 36$)	1.75 ± 0.08	1.74 ± 0.08	−0.7	<0.01
Skinfolds (mm) ($n = 49$)				
Bicep	4.4 ± 2.1	4.3 ± 1.6	−1.5	0.66
Tricep	9.9 ± 4.8	9.4 ± 4.1	−4.3	0.02
Subscapular	9.5 ± 2.2	9.2 ± 1.7	−4.1	0.01
Supraspinale	7.4 ± 3.0	7.0 ± 2.4	−5.2	0.06
Abdominal	12.6 ± 4.6	10.7 ± 3.9	−14.7	<0.01
Front thigh	13.7 ± 7.5	13.3 ± 6.6	−2.7	0.19
Medial calf	8.2 ± 4.4	8.3 ± 4.3	2.1	0.37
Sum of 7 skinfolds	65.6 ± 22.0	62.2 ± 19.0	−5.1	<0.01
Girths (cm) ($n = 49$)				
Calf	39.2 ± 2.2	39.7 ± 2.7	1.4	0.02
Waist	79.2 ± 6.0	79.0 ± 6.1	−0.3	0.25
Bicep (tense)	32.4 ± 2.4	32.3 ± 2.3	−0.4	0.11
Bicep (relaxed)	30.5 ± 2.0	30.3 ± 2.1	−0.7	0.04

The force (MVC) produced during isometric knee extension and elbow flexion (see Figure 4a) after the race fell significantly (leg by 17%, $P = 0.02$; arm by 11%, $P = 0.01$). These reductions were not different from one another (time × limb interaction, $P = 0.17$). Similarly, time to failure at 70% MVC (Figure 4b) decreased by 18% ($P = 0.09$) for knee extension and by 13% ($P = 0.40$) for elbow flexion isometric contractions, with the decreases being equivalent between limbs ($P = 0.80$).

Discussion

These data form part of the first comprehensive report of actual strain and the consequences of very prolonged, competitive exercise and sleep deprivation characteristic of international adventure races. The main findings reported here are:

- only complex decision making was impaired by the race, yet the impairment was attenuated while exercising at moderate intensity (50% peak power output);
- physical capability was only modestly impacted (all means <20%), at least relative to the extent of decrease in pace that occurs in these races;
- strength and strength endurance of the upper and lower limbs were affected similarly despite being used disproportionately.

Cognitive performance

Impaired cognitive performance for both simple and choice reaction time tasks has been reported previously in sleep-deprived and exercise-stressed studies (Opstad et al., 1978; Reilly & Deykin, 1983; Scott et al., 2006). Therefore, stability of the simple response times across this ~100-h race was unexpected. The 16% (259 ms) increase in complex-level response times was consistent with previous studies (6%: Reilly & Deykin, 1983; 22%: Scott et al., 2006) for a two-choice reaction task, although less than the 30% slowing in four-choice reaction times reported by Opstad et al. (1978). Stability of the simple level response times could have been due to the length of test protocol, typically ~30 s for each level, which may not have been long enough to show sleep deprivation decrements. Dinges (1992) emphasized the importance of context on sleep-deprived cognitive performance (contextual dependence hypothesis). This hypothesis predicts that the greater the physiological sleepiness brought on by sleep loss, the more dependent the brain becomes on the local environment to maintain wakefulness and the more vulnerable it becomes to environmental monotony. Motivation and incentive can contribute to, or override, this environmental effect, but for a limited time (Dinges, 1992). It is possible that the stability of response time at the simple level may reflect the short duration of the task combined with the ability of participants to maintain their motivation through this early stage of the test and the novelty of taking such a test in an adventure race environment. The average increase in response time variation, although not significant, together with the observation that lapses (tendency to fall into brief microsleeps; Williams, Lubin, & Goodnow, 1959) only occurred during the latter levels of the test, supports the early stage null effect. Furthermore,

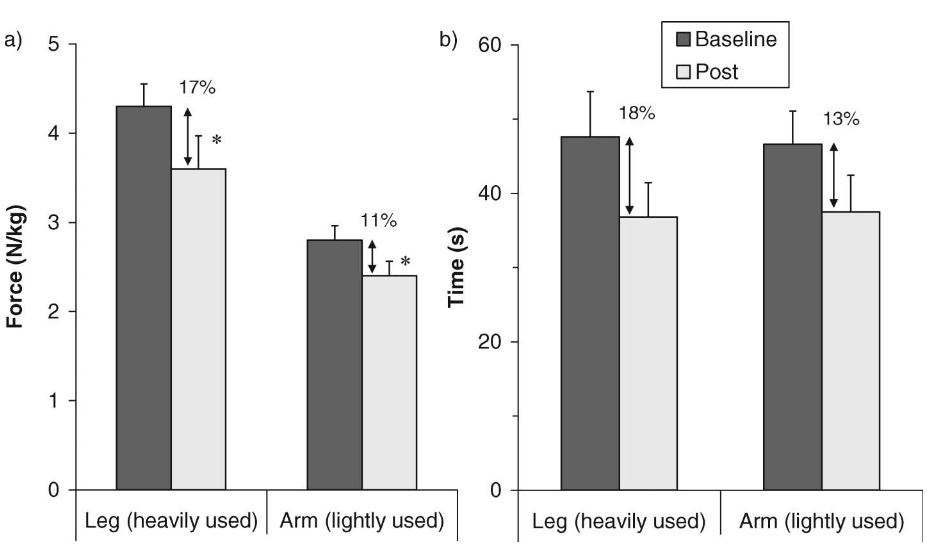

Figure 4. Relative strength (a) and strength endurance (b) of science team participants ($n = 9$) 2–5 weeks before (baseline) and within 3 h after the race (post). Measures were recorded from two muscle groups, one used extensively (knee extensors) and one used less extensively (elbow flexors) throughout the race. $^*P < 0.05$ compared with baseline measure.

these participants were falling asleep during a task that required less than 2 min of their attention. Thus, while we did not study cognition in relation to vigilance, the increase in lapses as the race continued is further indication of the reliable findings (Dinges et al., 1997; Lim & Dinges, 2008; Williams et al., 1959) that this domain of cognition is markedly impaired by sleep deprivation.

There has been limited investigation of the effect of concurrent exercise on sleep-deprived cognitive performance when participants have also been exercise stressed during the sleep-depriving period, and no studies have examined the effect of exercise sustained *throughout* the deprivation period on cognitive performance. Two studies examining sleep deprivation and exercise effects on cognitive performance reported conflicting observations (Reilly & Deykin, 1983; Scott et al., 2006). The first indicated a benefit of concurrent exercise, perhaps due its arousal effect (Reilly & Deykin, 1983), whereas the second indicated an impairment, perhaps because of its distracting influence (Scott et al., 2006). In our study, response time improved during exercise at 50% peak power output compared with rest and 25% peak power output, at the baseline and post-race measures. Despite participants practising the Stroop test at least once before the baseline standardized stress test, the high and decreasing error rate across the exercise intensities at the complex level (Figure 2) indicated that some learning or practice effect may also have contributed to the decreasing response times as the exercise intensities increased, but this could not explain these post-race results. Furthermore, response time returned to standardized stress test resting values at the ''post-race'' measurement (~30 min later), which was a different pattern to that at baseline measures (Figure 2). This is consistent with Dinges' (1992) contextual dependence hypothesis, in that moderate-intensity exercise provides arousal and lessens monotony of the stimulus environment. Additionally, to prevent them falling asleep while undertaking the Stroop test, some participants required prompting more regularly in the latter stages (Day 3+) and during the post-race measurements. Prompting was not required during the baseline tests or during standardized-intensity exercise periods post-race. Thus, our findings from athletes under very prolonged exercise and sleep-depriving stress support Reilly and Deykins' (1983) observations of the positive arousing effect of exercise on cognitive performance when sleep-deprived.

An important consideration and possible limitation of this study is the variation in the time-of-day that performance was tested. It has been suggested that executive functions of the brain, as needed for Stroop test performance, are not a unitary process but rather related to independent processes (Miyake et al., 2000), and that sleep deprivation and time-of-day appear to affect these components selectively (Jennings, Monk, & van der Molen, 2003). Consequently, inconsistent findings have been reported in the literature with regard to sleep-deprived complex cognitive task performance, especially for Stroop test performance (e.g. Binks, Waters, & Hurry, 1999; Lingenfelser et al., 1994). Sleep-deprived cognitive performance strategies may also be influenced by circadian rhythms (Blatter & Cajochen, 2007). Regardless of the contribution of these factors to cognitive performance variability, the ability to control for time-of-day for testing during an adventure race is constrained by the nature of adventure racing. Thus, findings may be confounded by circadian effects, which can be cumulative with prolonged disruption of the sleep–wake cycle (Blatter & Cajochen, 2007). Nevertheless, these reliability problems are countered by the opportunity to study effects on cognition of more severe exercise and sleep-deprivation stress than could be obtained in the laboratory.

Physical capabilities

Power output was reduced substantially during the race, most notably by one-third within the first 24 h (Lucas et al., 2008). Impaired exercise performance with sleep deprivation is thought to result from decreased motivation (Martin, 1981; Plyley, Shepherd, Davis, & Goode, 1987). The ''will to perform'' and ''mood state'' are considered to contribute to the sensation of fatigue (Nybo & Secher, 2004). The effects of sleep-depriving, sustained exercise stress on anaerobic performance are unclear; some researchers have reported no ill-effects (Guezennec et al., 1994; Hackney et al., 1991), whereas others have reported selective decrements (Nindl et al., 2002). Running time to exhaustion at 80% of maximum oxygen consumption decreased by 11% (Martin, 1981) and 20% (Martin & Chen, 1984), while cardiovascular, ventilatory, and metabolic variables were unchanged after 36 h and 50 h of sleep deprivation, respectively. This supports the notion that decreased exercise tolerance or willingness, or both, decreases exercise performance under such stress. Presumably, decreased motivation as a result of such prolonged wakefulness and strenuous exercise contributes to decreases in physical capacity after an adventure race.

At post-race testing, the vertical jump and Wingate tests were repeated in the same order as baseline testing and completed within 60 min of crossing the finish line by all participants. The observed variability in performance between athletes was likely to be due to genetic (especially gender) and other factors, including age. The reductions in strength or power across the race were much smaller than the baseline variability between people. Only modest reductions in vertical jump height after the race (8%) were observed, conceivably due in part to foot ailments from racing, which may mean that explosive muscle power was even less impaired. The modest reduction is supported by the 7% reduction in Wingate peak power. The equivalently small impairment in both mean power and end power in the Wingate test was surprising given the volume of work completed over 4–5 days of racing. Stable or slight (5%) drops in Wingate peak and mean power have been observed following sustained military operations of shorter duration (up to 60 h) (Rodgers et al., 1995; Symons et al., 1988), and 96–120 h of military field operations (Hackney et al., 1991). Interestingly, despite Rodgers and colleagues' (1995) non-significant findings, the group that performed continuous physical work tasks during 48 h of sleep deprivation showed a similar average drop in peak (8%) and mean (6%) power during Wingate performance. In addition, peak and mean power recorded in the present study were higher than any reported in the military-based studies. The modest drop in Wingate performance in the present study is therefore consistent with findings from similar duration sustained military operations, and with the non-depleted (50%) muscle glycogen stores observed in participants in the science teams (Helge et al., 2007). One could speculate that the marked shift towards fat utilization observed in this setting (Helge et al., 2007) preserves the stores of glycogen to enable high-intensity power output if required, and that performance during an adventure race, at least for the latter part of it, is not limited by substrate availability (for muscle) or extracellular fluid availability (Lucas et al., 2008). Collectively, these findings may indirectly support the notion of a greater importance of psychological factors (e.g. motivation and perceived exertion) on the sensation of fatigue and resultant regulation of prolonged exercise performance (Nybo & Secher, 2004). Such a notion is supported by the increase in perceived exertion at standardized workloads observed at the conclusion of the race (Lucas et al., 2008). It is important to note that alterations in brain metabolism in response to activation by exercise are reportedly associated with central fatigue (Nybo & Secher, 2004; Secher, Seifert, & Van Lieshout, 2008). Glycogen depletion of astrocytes, and the accumulation of interleukin-6 (Nybo, Nielsen, Pedersen, Moller, & Secher, 2002), serotonin (Blomstrand, 2001; Davis, Alderson, & Welsh, 2000), and ammonia (Nybo, Dalsgaard, Steensberg, Moller, & Secher, 2005) in the brain could also form part of the explanation for the drop in power output during racing and for the post-race capacities.

Strength (assessed here by MVC) and strength endurance (time to failure at 70% MVC) of the knee extensors and elbow flexors provided a comparison of force production in a heavily used muscle group (legs, used for 63% of race duration; concentric and eccentric) to that of a relatively lightly used muscle group (arms, 27%; concentric); in addition, the final two stages (lasting 4–6 h) of the race were leg-based exercise modes (Figure 1). Strength and strength endurance of both muscle groups were affected similarly, perhaps indicating a centrally mediated reduction in force generation. This conflicts with the observations of Nindl et al. (2002), who reported that anaerobic (mean) power production for under- and over-utilized muscle groups after 72 h of sustained operations was differentially impacted. Interestingly, their results also showed that peak power output for both under- and over-utilized muscle groups in the anaerobic power tests was not affected by the sustained operations, while mean power was reduced by only 8% (compared with 17% and 11% reductions in MVCs and 18% and 13% reductions in time-to-fatigue observed here for knee extension and elbow flexion, respectively). This discrepancy may reflect increased exercise and sleep-depriving stress of an adventure race compared with sustained military operations.

In conclusion, complex decision making was affected by the very prolonged exercise and sleep deprivation of adventure racing, with the impairment attenuated by exercising at moderate intensity (50% peak power output). The observed effect of exercise interventions on cognition warrants further investigation. Explosive power and very high-intensity "anaerobic" power were modestly ($<10\%$) impacted. Strength and strength endurance of the upper and lower limbs were affected similarly despite being used disproportionately, indicating the involvement of centrally mediated fatigue. Although a 10–15% reduction in physical capabilities is not unimportant for sustained performance among elite endurance athletes, it additionally illustrates the remarkable capacity of humans to retain movement function under conditions of very prolonged exercise and sleep deprivation.

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