Sleep Medicine 147 (2026) 109159

Contents lists available at ScienceDirect

Sleep Medicine

journal homepage: www.elsevier.com/locate/sleep

Do power naps save sleepiness? Cognitive benefits of brief sleep during a 100 miles ultramarathon

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ARTICLE INFO

Keywords:
Sleep deprivation
Cognitive function
Ultramarathon running
Circadian rhythm

ABSTRACT

Objectives: This study aimed to investigate the effects of short naps on perceived sleepiness and cognitive vigilance during extreme sleep deprivation in ultra-endurance racing. It tested whether baseline cognitive performance predicts nap decisions and if 20-min naps enhance objective cognitive function while reducing subjective sleepiness.
Design: An observational field study was conducted during the 2022, 2023, and 2024 editions of the Ultra-Trail du Mont-Blanc® (170 km; ~10 000 m elevation gain).
Methods: Sleep was recorded via wrist accelerometery for 52 completing runners (43.9 ± 8.3 years). Subjective sleepiness (Karolinska Sleepiness Scale, KSS) and reaction time (Psychomotor Vigilance Test, PVT) were assessed at five checkpoints (CP0–CP4). At CP1–CP3, participants chose between a 20-min sleep opportunity (nap group, NG) or remaining awake (awake group, AG). Measurements occurred at checkpoint entry (ENT) and 1 km post-checkpoint.
Results: Finishers slept an average of 28.4 ± 21.9 min. Linear mixed-effects models confirmed robust circadian modulation of both sleepiness and reaction times. Nap decisions were primarily driven by subjective sleepiness rather than objective vigilance deficits. While 20-min naps produced immediate reductions in KSS 1 km post-checkpoint, cognitive benefits (PVT) manifested more gradually, with significantly faster reaction times observed only at subsequent checkpoints.
Conclusions: Brief naps serve as an effective reactive strategy to reduce perceived drowsiness and provide partial protection against late-race performance decline without compromising overall race completion times.

1. Introduction

Sleep plays a fundamental role in maintaining global health and optimizing both physical and cognitive performance [1,2]. In modern societies, many safety-critical professions such as military personnel, firefighters, and healthcare providers are subjected to work schedules that impose severe sleep restriction [3–6]. The safety consequences of sleep restriction are significant, research has demonstrated that obtaining 5 h of sleep or less within a 24-h period doubles the risk of a motor vehicle accident [7]. Among athletes, chronic sleep debt is associated with an up to a 2.0-fold higher risk of musculoskeletal injuries [8]. A recent systematic review and meta-analysis further confirmed that sleep deprivation impairs multiple domains of athletic performance, with the largest adverse effects observed for skill control and aerobic endurance performance [9].

Over the past 20 years, the context of ultra-endurance has shifted from a niche activity to a rapidly growing international phenomenon. The number of participants has increased significantly, particularly for

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https://doi.org/10.1016/j.sleep.2026.109159
Received 9 April 2026; Received in revised form 12 July 2026; Accepted 21 July 2026
Available online 23 July 2026
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ultramarathons exceeding 42 km [10,11]. These events are characterized by extreme physical exertion in diverse and hostile environments, with races often winding through mountains, deserts, or other remote wilderness areas. Beyond the immense muscular and metabolic constraints, these athletes operate under severe sleep restriction, often staying awake for several consecutive days and nights.

In the field of extreme endurance sports, ultra-marathons represent an exceptional model for investigating the interaction between homeostatic sleep pressure (Process S) and circadian modulation (Process C), as defined by Borbély's two-process model [12]. During these events featuring extreme distances and elevation gains, runners voluntarily curtail rest to minimize total race time, exposing themselves to acute sleep deprivation that can exceed 40 h [13–15]. This extreme deprivation leads to marked cognitive impairments, including a significant increase in reaction times and the occurrence of auditory or visual hallucinations in approximately 25% of participants [14].

Despite these risks, the literature identifies napping as a primary strategy for counteracting the harmful effects of sleep deprivation [14–18]. While earlier studies reported that 72% of runners did not sleep during the race [19], recent large-scale analysis reveals an evolution in practice, 77% of finishers now take at least one nap (average 76 min cumulative sleep over 165 km), mostly brief (82% last less than 30 min) and timed to the circadian nadir (midnight–5 a.m.) [20]. This is corroborated by a recent systematic review focusing specifically on ultra-endurance athletes, which found that both pre-race sleep quality and mid-race napping opportunities were positively associated with cognitive performance during competition [21].

However, a "performance paradox" persists: most runners still perceive napping as a competitive constraint threatening race completion within cut-off times [22], despite 80% reporting severe sleep-related symptoms (hallucinations, ataxia, falls) [20]. Scientific evidence confirms that short naps significantly reduce fall and accident risks by restoring alertness [23–25]. A hallmark of this management is the documented dissociation between perceived sleepiness (Karolinska Sleepiness Scale, KSS), which often dictates the decision to stop [4,16,26], and objective vigilance as measured by the Psychomotor Vigilance Test (PVT), considered as the gold standard to assess sustained attention [27,28]. However, the mechanisms underlying this dissociation and the potential restorative effect of short naps remain insufficiently understood in real-world ultra-endurance settings.

The aim of this study was to investigate the effects of short naps on perceived sleepiness and cognitive performance during prolonged sleep deprivation in ultra-endurance racing. Following a pilot study demonstrating improved reaction times after napping [16], these effects were further examined across multiple race editions. Specifically, two hypotheses were proposed: (1) baseline cognitive performance would predict nap decisions, and (2) brief naps (15–20 min) would enhance objective cognitive function while reducing subjective sleepiness relative to pre-nap levels.

2. Materials and methods

2.1. Study design

This study was conducted during the 2022, 2023, and 2024 editions of the Ultra-Trail du Mont-Blanc® (UTMB Mont Blanc®), a single-stage mountain ultramarathon starting and finishing in Chamonix, France, around the Mont Blanc massif (170 km; ~10 000 m elevation gain; 46.5 h time limit). Sleep was recorded continuously thought wrist accelerometry for all 52 completing runners from race start to finish line. Sleepiness (KSS) and reaction time (PVT) were assessed at five checkpoints: CP0 (Chamonix, km 0), CP1 (Courmayeur, km 82.6), CP2 (Champex-Lac, km 129.4), CP3 (Trient, km 145.9), and CP4 (Vallorcine, km 158).

At CP0 (2 h pre-race), baseline measurements were taken. At CP1-3, participants chose freely whether to take a 20-min sleep opportunity and informed researchers of their decision, allowing classification into nap group (NG) or awake group (AG). Measurements occurred at checkpoint entrance (ENT) and 1 km post-checkpoint (except CP4, where post-measurement was omitted due to proximity to finish line and low nap incidence) (see Fig. 1).

A power analysis (G*Power 3.1, α = 0.05, power = 0.95) indicated n = 176 participants were required to detect moderate between-group differences (d = 0.5) via independent t-tests. The study was approved by the UTMB® Medical Committee and CERSTAPS (IRB00012476-2022-17-06-189; June 22, 2022), conducted per Helsinki Declaration, with CNIL declaration N°2227560 v0. All participants provided written informed consent.

2.2. Participants

A total of 121 athletes were recruited for this study, which took place during the 2022, 2023, and 2024 editions of the UTMB®. Fifty-two participants aged 43.9 ± 8.3 years completed the entire protocol (5 women, 47 men).

The inclusion criteria were voluntary participants, registered for the UTMB and aged between 18 and 65. The exclusion criteria were runners undergoing medical treatment likely to affect alertness, as well as those who had crossed more than two time zones in the month preceding the race. No additional exclusion criteria were applied after enrolment; all data attrition reflects either race withdrawal or incomplete protocol completion, as detailed below. Of the 121 volunteers who started, 44 (36.4%) did not finish the race. This rate is consistent with the overall DNF rate of the UTMB® over the three studied editions (31.8–36.3%), indicating that attrition in this subgroup reflects the inherent difficulty of the event rather than a study-specific bias. A further 25 runners finished the race but did not complete the full testing protocol, due to withdrawal or malfunction of the actigraphy device, refusal or inability to perform the PVT at one or more checkpoints because of time pressure. These 25 participants were excluded from statistical analysis because incomplete checkpoint data precluded the longitudinal mixed-effects modelling approach.

The 52 remaining participants (43.9 ± 8.3 years, 5 women, 47 men) completed the entire protocol and were included in statistical testing (Fig. 2).

2.3. Measurement

2.3.1. Sleep measurement

All participants wore an ActiGraph GT3X + triaxial accelerometer (TheActigraph©, Pensacola, FL, USA) on their non-dominant wrist. Participants were asked not to remove the device, even when showering. Accelerations were sampled at 30 Hz to account for the required recording time and to ensure that the battery would be sufficiently charged for the entire race. At the end of the study, the data were downloaded and extracted from the device's memory. The 30 Hz acceleration data were grouped into 60-s periods using ActiLife software (v. 6.13.4). The Cole-Kripke algorithm [29] was then used, considering a moving weighted average window, to classify the 60-s periods as "asleep" or "awake." It was not possible to reliably determine bedtimes, and only data on the start and end times of each sleep period were extracted. These two results were determined automatically by the

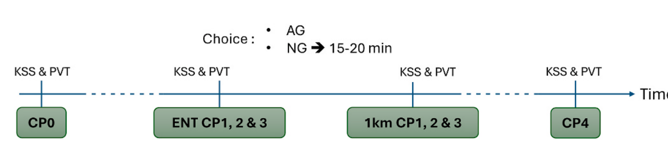

Fig. 1. This is a diagram of the measurement protocol for the various checkpoints (CP). For each checkpoint, volunteers choose whether to be in the awake group (AG) or the nap group (NG) and then take a 20-min sleep opportunity.

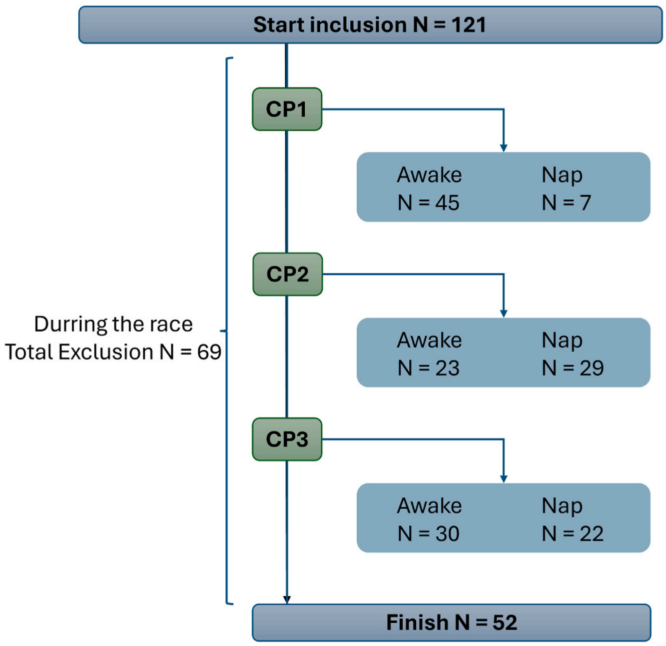

Fig. 2. Shema glove for distribution during the race.

Actilife analysis software.

2.3.2. Self-reported sleepiness

The Karolinska Sleepiness Scale (KSS) is a widely used measurement tool for assessing levels of sleepiness or fatigue [30]. The KSS consists of nine levels, ranging from 1 to 9, with each level associated with a description of the individual's state of alertness or sleepiness. The KSS was chosen for its ease of use. The KSS is used in a variety of contexts, including sleep research, sleep medicine, driving alertness studies, and the assessment of sleepiness in critical work environments. The KSS was performed using a paper form, with participants asked to point to their subjective feeling of sleepiness after being reminded of the entire scale.

2.3.3. Reaction times

The Psychomotor Vigilance Test (PVT [31] is widely used to measure the decrease in vigilance due to sleep loss [32]. The PVT is a simple reaction time task with an inter-trial interval that varies between 2 and 10 s. The task was performed on a laptop computer, with a fixed task duration of 3 min per trial session. The measurements recorded are the mean reaction time (RTm) in milliseconds, the number of lapses (responses >500 ms), the number of false starts (responses prior to the stimulus), and the variability of reaction times in the test. This test is considered to be very sensitive to the cumulative effects of sleep deprivation and circadian fluctuations in attention [28].

2.4. Statistical analysis

Descriptive statistics (means, standard deviations) were calculated for participants' age, total cumulative sleep time during the race, and geographical distribution of naps (CP or in the field). The normality and homogeneity of the data were verified using the Shapiro–Wilk ($\alpha = 0.05$) and Levene tests, respectively, allowing the use of paired Student's t-tests or Wilcoxon were used to compare pre-nap (ENT) and post-nap (1 km) KSS and RTm (mean reaction time) scores. Unmonitored (out-of-checkpoint) sleep occurring in the intervals preceding CP3 and CP4 was compared between groups using Mann–Whitney U tests.

Longitudinal changes in subjective sleepiness (KSS) and mean reaction time (RTm; PVT) were analysed using linear mixed-effects models (LMMs). Fixed effects included group (NG vs AG), checkpoint (CP), their interaction (Group×CP), cumulative sleep time prior to each checkpoint (min), elapsed race time (TPS, hours) to capture homeostatic sleep pressure (Process S), as well as 24-h sinusoidal terms $\cos\left(2\pi \times \frac{TPS}{24}\right)$ and $\sin\left(2\pi \times \frac{TPS}{24}\right)$ to model circadian modulation (Process C: $\sin\left(2\pi \times \frac{TPS}{24} + \varphi\right)$). Continuous predictors were mean centered prior to analysis to facilitate model convergence. Random effects accounted for subject-specific intercepts and individual differences in the effect of TPS (1+TPS|Subject). This modelling approach allowed estimation of inter-individual variability in baseline performance and time-on-task effects, while circadian phase (acrophase/bathyphase) was inferred from the fitted sinusoidal components.

All analyses were conducted in R (version 4.4.1) via RStudio (v. 2024.12.1). The significance threshold was set at $\alpha = 0.05$.

3. Results

Among the 52 runners who completed the entire protocol in a race time of 41:50 ± 2:56 (2022: n = 18; 2023: n = 17; 2024: n = 17), 41 (78.8%) showed at least one significant trace of sleep (>1 min total) and completed the race in 42:04 ± 02:51.

Among these 41 runners, the cumulative duration of sleep recorded throughout the race was 28.4 min (±21.9) on average. The breakdown by edition is as follows.

- UTMB 2022 (n = 18): 29.2 ± 20.0 min,
- UTMB 2023 (n = 17): 35.3 ± 28.1 min,
- UTMB 2024 (n = 17): 23.1 ± 18.3 min.

The proportion of total nap time spent outside the three selected checkpoints (CP1, CP2, CP3) was 26.1% (Table 1). This unmonitored sleep did not differ significantly between groups in the intervals preceding CP3 (AG: 0.44 ± 1.63 min; NG: 0.76 ± 2.63 min, p = 0.89) or CP4 (AG: 0.0 ± 0.0 min; NG: 0.4 ± 2.0 min; p = 0.32). These additional episodes took place either in the field or at the Checkpoints not included in the measurement protocol.

3.1. Sleepiness (KSS)

At CP0, the KSS of the 52 runners was low (KSS = 2.25 ± 1.44). The KSS increased by 0.075 units for each additional hour spent in the race ($t(333) = 10.14$; $p < 0.001$) (Fig. 3).

At CP1, there was no change in KSS between or within groups at ENT and 1 km (Fig. 4).

At CP2, there was a significant difference between ENT and 1 km for the NG ($t(66) = 6.32$, $p < 0.0001$) and a significantly higher KSS for NG compared to AG at ENT ($t(50) = -4.13$, $p = 0.00014$), At 1 km, this difference disappeared (Fig. 4).

At CP3 associated with CP4, as for CP2, there is a significant difference between NG and AG at ENT ($t(50) = -2.46$, $p = 0.017$), and no

Table 1
Total Sleep Time (TST) recorded by accelerometer during the UTMB race. Data represent mean ± standard deviation of TST (minutes) per participant at each Check Point ("AT CP") and between CP ("Before CP").

	Mean TST ± SD (min)	TST (min)	% TST
Before CP1	9.12 ± 2.51	92	7.9
At CP1	11.28 ± 4.22	149	12.8
Between CP1 and CP2	15.10 ± 5.29	182	15.6
At CP2	16.27 ± 9.15	477	40.9
Between CP2 and CP3	7.45 ± 1.06	31	2.6
At CP3	10.16 ± 5.13	226	19.4
At CP4	10.00 ± 0.23	10	0.8
Total		1167	100.0

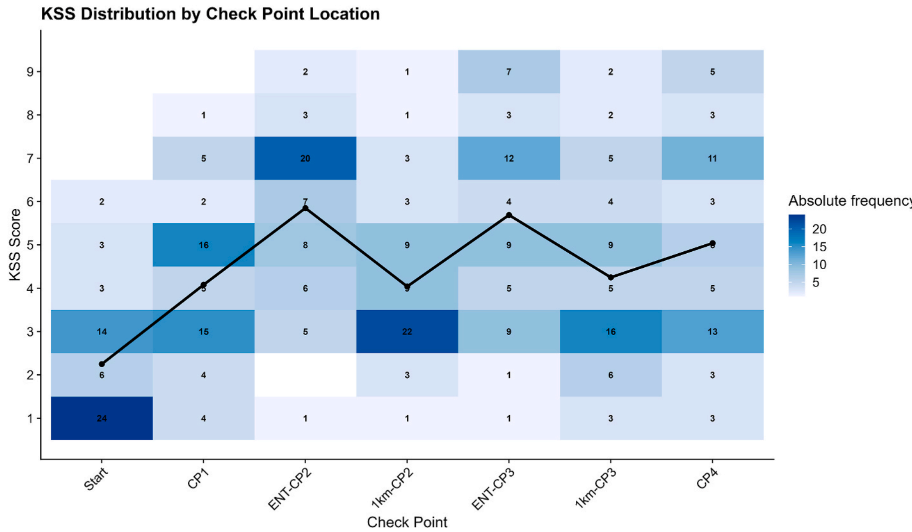

Fig. 3. Distribution of Karolinska Sleepiness Scale (KSS) scores by check point (CP) during the UTMB race among finishers. Heatmap tiles represent the number of observations for each KSS score (1-9) at each CP, with color intensity proportional to frequency (light blue = low, dark blue = high). Black line and points indicate the mean KSS score per CP. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

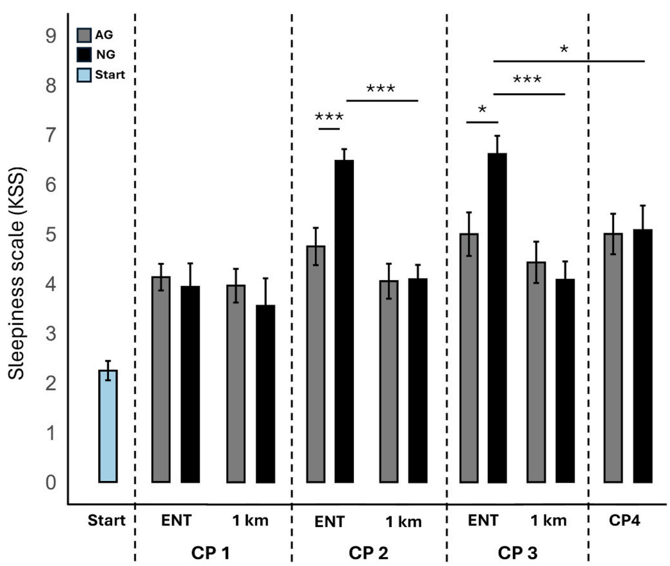

Fig. 4. Sleepiness scores (KSS) measured on entry to the checkpoint ("ENT") and 1 km after exit ("1 km") for CP0 (start), CP1, CP2, CP3 and CP4, by group (NG = nap group; AG = no-nap group; group allocation took place after the KSS assessment at each ENT). Inter-group comparisons (NG vs AG) at ENT and intra-group comparisons (ENT vs 1 km, or ENT vs CP4) were performed using Student's t-tests, with a significance threshold of $p < 0.05$. At CP1, there were no significant inter- or intra-group differences. At CP2, the NG group had a significantly higher KSS than the AG group at ENT ($t(50) = 4.13$, $p = 0.00014$) and a significant decrease between ENT and 1 km ($t(66) = 6.32$, $p < 0.0001$); the inter-group difference disappeared at 1 km. At CP3 (combined with CP4), the NG again differed significantly from the AG at ENT ($t(50) = 2.46$, $p = 0.017$), with no residual difference at 1 km or CP4; within the NG group, KSS decreased significantly from ENT to 1 km ($t(48) = 4.79$, $p < 0.0001$) and from ENT to CP4 ($t(48) = 2.20$, $p = 0.032$). Furthermore, linear mixed models including a circadian component revealed significant time-of-day modulation of KSS (acrophase 03:18, bathyphase 15:18), regardless of nap status.

difference at 1 km or CP4. There is also a significant difference for NG between ENT and 1 km and ENT and CP4 ($t(48) = 4.79$, $p < 0.0001$; $t(48) = 2.20$, $p = 0.032$, respectively). Conversely, there is no difference for AG between the stations (Fig. 4).

After including the circadian component, LMMs revealed significant time-of-day modulation for KSS: acrophase at 03:18 and bathyphase at 15:18 p.m.

3.2. Reaction time

At CP0, response times measured by the PVT were low (RTm = 307.25 ms ± 52.53). RTm increased by 1.30 ms for each additional hour of running ($t(330) = 5.55$; $p < 0.001$).

At CP1, CP2, and CP3, no intra- and inter-group changes in RTm were observed at ENT and 1 km points.

At CP4, those who slept at CP3 showed significantly better reaction times than the AG (Interaction CP3 – CP4: $\beta = -53.4$ ms, $t(103) = -2.28$, $p = 0.025$), independently of the cumulative sleep duration prior to CP3.

Despite the absence of a significant circadian effect, LMMs including the circadian component revealed an acrophase at 03:29 and a bathyphase at 15:29 for RTm.

4. Discussion

This study evaluated the effects of short naps on perceived sleepiness (KSS) and cognitive performance (PVT-measured RTm) during the Ultra-Trail du Mont-Blanc (UTMB®), an extreme endurance event characterized by acute sleep deprivation with a total course time up to the 46h30 cutoff. Building on a 2021 pilot study [16], we monitored 52 volunteer runners across three editions (2022–2024).

In this cohort, participants slept an average of 28.4 ± 21.9 min during a 162 km race completed in 41:50 ± 2:56, which is consistent with mean sleep durations reported by Hurdiel et al. [14] on the same event (23.4 ± 22.2 min).

During the first phase of the race (up to 82 km, at CP1), no significant group differences or patterns related to nap decisions were observed. Arrival at this checkpoint occurred between 7:00 and 13:00, during the first night of sleep deprivation. No significant between-group differences in KSS or RTm were observed at CP1 entry. This is consistent with recent evidence from ultra-endurance cycling showing that sleep strategies aligned with circadian and homeostatic drives, rather than purely reactive napping, are associated with better-preserved cognitive performance [33]. The sleep taken at this stage can therefore be considered prophylactic rather than recovery driven.

When participants decided to take naps at CP2 and CP3, they exhibited higher perceived sleepiness at checkpoint entry compared to non-nappers, confirming that napping served as a reactive strategy to manage acute exhaustion at these stages of the race, in contrast with the prophylactic pattern observed at CP1 (see above). This aligns with the pilot findings of heightened sleep pressure in nappers, though our larger cohort revealed higher KSS scores rather than isolated RTm prolongation: no significant RTm differences emerged between groups at the onset of CP2 and CP3, indicating that nap decisions were primarily driven by subjective sleepiness rather than objective deficits, a pattern partially validating our first hypothesis and replicating findings previously described by Hurdiel et al. [15] observations in ultramarathoners.

In contrast to the findings of our preliminary study the results of this larger cohort suggest that subjective sleepiness (KSS) was the primary factor differentiating nappers at the time of checkpoint entry. This suggests that, in situations of extreme fatigue, runners primarily utilise perceived sleepiness as a cue to initiate rest, thus demonstrating the decision-making process driven by perception as outlined by Lovato & Lack [26]. However, a clear dissociation in recovery kinetics persisted: while KSS values improved immediately post-nap, objective vigilance (RTm) gains appeared later, between CP3 and CP4. This lag highlights that the feeling of recovery may mask a lingering cognitive vulnerability in the first kilometers following awakening.

20-min nap opportunities across checkpoints proved sufficient to significantly reduce KSS 1 km post-checkpoint. Because the NG group also entered CP2 with higher perceived sleepiness than the AG group, part of this reduction may partly reflect a return toward pre-checkpoint levels rather than a purely nap-specific effect; the comparable reduction observed at CP3, however, occurred despite a similarly elevated baseline in the NG group, suggesting a more robust napping-related benefit at this later stage of the race Cognitive benefits, however, manifested more gradually, becoming evident at subsequent checkpoints (e.g., CP4 following CP3 naps). This temporal dissociation between rapid subjective recovery and delayed objective gains exemplifies a well-documented feature of brief naps [26,34]. Clinical studies [35] suggest short naps enhance mood, attention, and memory for up to 4 h post-awakening, warranting broader application in prolonged wakefulness scenarios.

Such short durations would likely effectively restore vigilance without substantial sleep inertia, as they would allow reaching stage N2 sleep, essential for cognitive benefits, while avoiding slow-wave sleep (N3), the primary source of post-nap grogginess [24,25,35–37].

These findings align closely with Borbély's two-process model, as the calculated acrophases (~03:15) and bathyphases (~03:15 p.m.) for both KSS and RTm trajectories precisely match circadian nadir/zenith predictions from Van Dongen & Dinges [38] and ultramarathon data [15]. This confirms the robustness of the circadian pacemaker (Process C), which remains stable and predictable despite extreme exertion and >40 h sleep deprivation. However, Process C cannot counteract the linear accumulation of homeostatic pressure (Process S), underscoring naps as essential modulators. The efficacy of brief naps (<20 min) further suggests an "Onset" (Process O) mechanism, where sleep initiation rapidly disinhibits wake-active neurons, restoring excitability before deep sleep onset [26].

Although naps provided measurable vigilance benefits, runners who napped did not compensate for total sleep time in relation to overall race duration nappers finished in 42:04 ± 2:51 compared with 41:33 ± 2:12 for non-nappers. In contrast to Poussel et al. [19] who reported that 72% of runners abstained from sleep viewing it as a non-competitive strategy despite its safety benefits, 78% of our participants opted to nap. This may reflect either a participation bias, volunteers aware of a sleep study being more inclined to nap, or a broader shift in attitudes over the seven years separating the two studies, suggesting a growing understanding of napping mechanisms as a means of maintaining safety while sustaining performance. In mountainous field, RTm degradation correlates with increased risk of falls and ataxia [23], compounded by hallucinations reported by ~25% of competitors after 40 h of wakefulness [14], further emphasizing the safety value of napping beyond mere performance considerations.

Study limitations include unaccounted confounders such as nutrition (major glycemic variability, [39]), supplementation, and alternative therapies (homeopathy, herbal medicine, hypnosis, aromatherapy, and yoga [20]), alongside marked inter-individual variability. Sleep deprivation vulnerability represents a stable genetic trait [2,40] explaining why some runners can endure extended periods without sleep while others cannot. Moreover, 26.1% of total sleep time occurred outside monitored checkpoints, limiting our ability to capture all sleep episodes across the race. However, this unmonitored sleep was minimal and did not differ significantly between groups in the time windows preceding our two main checkpoint-specific findings (CP2–CP3: 0.44 vs 0.76 min, $p = 0.89$; CP3–CP4: 0 vs 0.4 min, $p = 0.32$), indicating that it is unlikely to confound the reported effects. Future research could integrate location–scale modeling to capture minute-by-minute vigilance fluctuations, which are critical for understanding fatigue risk dynamics in extreme endurance contexts.

5. Conclusion

In ultra-endurance runners, cumulative sleep seems to ease but not erase fatigue during the race. The present data demonstrate that naps were principally reactive responses to heightened subjective sleepiness, rather than a preventive strategy. These short sleep episodes provided immediate relief from perceived drowsiness and were associated with more stable reaction times toward the end of the race, suggesting partial protection against performance decline.

Despite the fact that subjective and objective indices did not always evolve in parallel, the utilisation of brief, strategically timed naps may assist in the preservation of sustained attention in demanding environments. Such observations highlight the importance of individualized sleep strategies adapted to each athlete's profile and experience. Future work should further integrate dynamic models of sleep–wake regulation to guide evidence-based management of sleep and safety in endurance and other high-demand contexts.

6. Perspective

This study demonstrates that in ultra-trail runners, the decision to nap is primarily driven by subjective sleepiness rather than objective cognitive deficits. While existing literature, including works by Hurdiel et al. and Kishi et al., highlights the severe risks of sleep deprivation such as falls, ataxia, and hallucinations, many athletes still perceive napping as a competitive constraint. Our findings bridge this gap by showing that 20-min naps provide immediate relief from perceived drowsiness and delayed protection against late-race vigilance decline without compromising overall completion times.

The clinical and sporting impact is significant: the observed dissociation between rapid subjective recovery and gradual objective cognitive gains suggests that brief naps are an essential reactive safety measure. In sports medicine, these results advocate for individualized sleep strategies to mitigate the neurobehavioral risks inherent in extreme endurance. Integrating "fatigue management" protocols can enhance athlete safety and sustained attention in high-demand environments, moving beyond the "performance paradox" that often leads runners to ignore critical exhaustion cues.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the UTMB® Medical Committee and CERSTAPS (IRB00012476-2022-17-06-189; June 22, 2022)

Declaration of generative AI using

During the preparation of this work, the authors used generative AI tools for specific and limited purposes. Claude (Anthropic) was used to design and produce the graphical abstract submitted alongside this manuscript. NotebookLM (Google) was used as an AI-assisted writing support tool during the drafting process, notably to verify the accuracy of referenced concepts, cross-check bibliographic sources, and ensure the consistency of scientific notions discussed throughout the manuscript. After using these tools, the authors reviewed and edited all content as necessary and take full responsibility for the content of the published article.

Funding

This research was supported by Ultra Sport Science and AUM Bio Sync (no grant numbers available). The funding bodies had no role in study design, data collection, analysis, or the decision to submit the manuscript.

CRediT authorship contribution statement

Valentin Bourlois: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Antoine Boulagnon:** Formal analysis. **Charlotte Elsworth-Edelsten:** Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. **Maxime Ceugniez:** Investigation, Validation, Writing – review & editing. **Charlotte Claeyssen:** Investigation, Writing – review & editing. **Meg Smith:** Investigation. **Louise Comont:** Investigation. **Julie Clergue:** Data curation, Investigation, Software. **Pauline Baron:** Investigation, Methodology, Validation. **Charlotte Bonduelle:** Investigation. **Thierry Pezé:** Formal analysis, Writing – review & editing. **Rémy Hurdiel:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments & Funding

The authors express their sincere gratitude to the UTMB® organization for welcoming us during the 2022-2024 editions and facilitating access to checkpoints, which was essential for this study.

We are particularly grateful to all volunteer runners who participated despite extreme conditions.

Data availability

The data supporting the findings of this study have been deposited in Zenodo: https://doi.org/10.5281/zenodo.18630911.

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