Examining placebo effects after a 3-week repeated-sprint training program under hypoxic conditions in recreationally trained subjects: a randomized controlled trial

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Abstract:

Repeated-sprint training in hypoxia (RSH) has been suggested to significantly enhance anaerobic performance. However, the widespread belief in the benefits of altitude training raises questions about potential placebo effect. The aim of this study was thus to investigate the physiological and placebo effects of normobaric hypoxia combined with repeated-sprint training on performance. Twenty-nine moderately trained participants were randomly assigned to normoxia (RSN), placebo (RSN-P), or hypoxia (RSH) groups. Participants in RSN-P group were led to believe they were training at simulated altitude (between 2500 and 3500 m), while participants in the RSN and RSH groups knew they were training at sea level and at altitude, respectively. Repeated-sprint training involved six cycling sessions over three weeks, consisting of three sets of 8 x 6-s sprint with 24 s of recovery. There was no difference in the estimation of the altitude level to which participants from the RSN-P and RSH groups thought they had been exposed. There was a main significant effect of training on mean power output during Wingate (+7.9%; $p < 0.001$; $\eta p^2 = 0.47$) and repeated-sprint ability tests (+7.7%; $p < 0.001$; $\eta p^2 = 0.55$). However, contrary to our hypotheses, the enhancement among the three groups did not differ. The lack of greater improvement in the RSH group compared to the other groups raises questions about the added value of hypoxia in these conditions. In conclusion, neither real nor perceived hypoxia enhanced training adaptations following repeated-sprint sessions.

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Key words:

belief; cycling; Wingate test; repeated-sprint ability

1. Introduction

Combining hypoxia with different modalities of exercise training has been widely tested over the last decades. Performing maximal sprints under moderate hypoxia (commonly near 3000 m above sea level) has been proposed to improve repeated sprint ability (RSA), and this improvement has been observed even with very few training sessions and a short time spent under hypoxic stimulus (Beard et al., 2019; Birol et al., 2024; Brocherie et al., 2017). The physiological mechanisms proposed to explain the greater effects of repeated sprint training in hypoxic vs. normoxic conditions are enhanced muscle fiber perfusion, improved phosphocreatine resynthesis and/or higher glycolytic activity (Faiss et al., 2024). While this type of training has generated considerable enthusiasm, some studies have not replicated similar results (Brocherie et al., 2015; Goods et al., 2015; Montero and Lundby, 2017), prompting further reflection on the reasons for these discrepancies.

One methodological issue that is difficult to control in the field is the impact of the placebo effect. The importance of the placebo effect in sports performance has already been demonstrated. For instance, studies on beliefs related to nutrition displayed enlightening results. In fact, while carbohydrate ingestion had no effect on the power output over a time trial lasting ≈1h, telling the participants that they had ingested carbohydrate (while they had receive a placebo) significantly enhanced their performance (Clark et al., 2000). Similarly, running sprint performance was improved following ingestion of a factice energy drink in a group that was told that the drink augments running performance (De La Vega et al., 2017). Lastly, both caffeine and placebo significantly increased performance during a maximal incremental test and led to alterations in cerebral oxygenation compared to the control condition (Pires et al., 2018). Altogether, these results show how the belief into an intervention can trigger physiological alterations and positively impact exercise performance. Given the positive beliefs regarding the effects of hypoxia on exercise training (Turner et al., 2019), it is not unlikely that individual expectations can influence the physiological effects of this training. To determine whether training using repeated sprint in hypoxia (RSH) leads to adaptations larger than the potential placebo effect, it is thus necessary to include a placebo group in the protocol, as previously

done by others (e.g. (Brechbuhl et al., 2020; Faiss et al., 2013; Goods et al., 2015; Montero and Lundby, 2017)). However, for the placebo group to be meaningful, it seems essential to ensure that the participants in this group maintain a favorable belief in hypoxia until the end of the protocol. This can be done by asking participants to estimate the altitude at which they worked at the end of the protocol. To the best of our knowledge, ten studies have performed such a control at the end of the protocol (Brechbuhl et al., 2018a; Brocherie et al., 2015; Faiss et al., 2013; Galvin et al., 2013; Gatterer et al., 2015; Goods et al., 2015; Hamlin et al., 2017a; Montero and Lundby, 2017; Brechbuhl et al., 2020; Lanfranchi et al., 2024). Of these studies, four provide insight into the proportion of participants who were deceived or detected the deception (Faiss et al., 2013; Gatterer et al., 2015; Goods et al., 2015; Montero and Lundby, 2017). Out of these four, only one study was conducted in which all participants (both hypoxia and placebo groups) believed they were in hypoxia (Gatterer et al., 2015). However, including participants who recognized the deception (placebo group) or believed they were being deceived (hypoxia group) in the analyses may be questionable. To date, no study has focused on measuring the potential placebo effect in RSH training. To do so, it is crucial to include a control group in addition to the hypoxia and placebo groups, as recommended by Kienle and Kiene (Kienle and Kiene, 1997). This control group should follow the same training as the other two groups, but under normoxic conditions, and the participants should be aware of this condition (normoxia). Therefore, it seems relevant to conduct additional studies on this promising training under experimental conditions allowing the measurement of the potential placebo effect.

Besides, another unresolved question regarding the effects of RSH training on performance is the optimal timing of post-tests. In most studies, the post-tests were scheduled during the first week following the last training session. While some studies suggest that peak performance occurs within the first week consecutive to a RSH training (Gatterer et al., 2018; Trincat et al., 2017; Woorons et al., 2024), other findings suggest that a longer period may be required (Brocherie et al., 2023; Camacho-Cardenosa et al., 2017; Gutknecht et al., 2022). For instance, a recent case study on an elite triathlete observed that his peak performance was observed 21 days after completing the RSH protocol

(Gonzalez-Custodio et al., 2024). Conducting two post-tests sessions could provide insights into this unresolved question.

The present study involved three groups following a repeated-sprint protocol: a control group in normoxia, a placebo group (in normoxia but believing they are in hypoxia), and a hypoxia group. Two post-testing periods were conducted to discriminate the immediate and delayed effects of the intervention. Our hypotheses were that the placebo group would show greater performance improvement compared to the control group due to the participants' belief that they were in hypoxia, while the hypoxia group would show greater improvement due to the direct benefits of hypoxia.

2. Materials and methods

2.1. Participants

The required sample size was estimated with G*Power software (version 3.1.9.7, University of Düsseldorf, Germany). It resulted to a total of 27 participants for the following input parameters: within-between interaction, moderate effect size (partial $\eta^2 = 0.10$), α risk = 0.05 and power $(1 - \beta) = 0.90$. The CONSORT flow diagram is shown in Fig. 1. Participants declared 5-7 h/wk of moderate to vigorous physical activity (team sports, racket sports, combat sports). Four participants were unable to complete the study: three withdrew due to injury (unrelated to our protocol) and one withdrew due to illness. Thus, this study numbered a total of twenty-nine participants including one woman (age [mean ± SD] 21.3 ± 3.9 yr; weight 73.1 ± 8.8 kg; 178.7 ± 8.5 cm; BMI 22.9 ± 2.2 $kg.m^{-2}$) knowing that it has been recently shown that RSH induced similar adaptations in active males and females (Piperi et al., 2024).

Inclusion criteria were: no intolerance to moderate hypoxia, no stay at altitudes above 1500 m in the previous two months and being accustomed to intense exercise such as repeated sprints. All participants provided written informed consent before participating in the experimental protocol. The study was approved by the local ethics committee (IRB-EM 2201C, EuroMov-Montpellier) and adhered to the principles outlined in the Declaration of Helsinki.

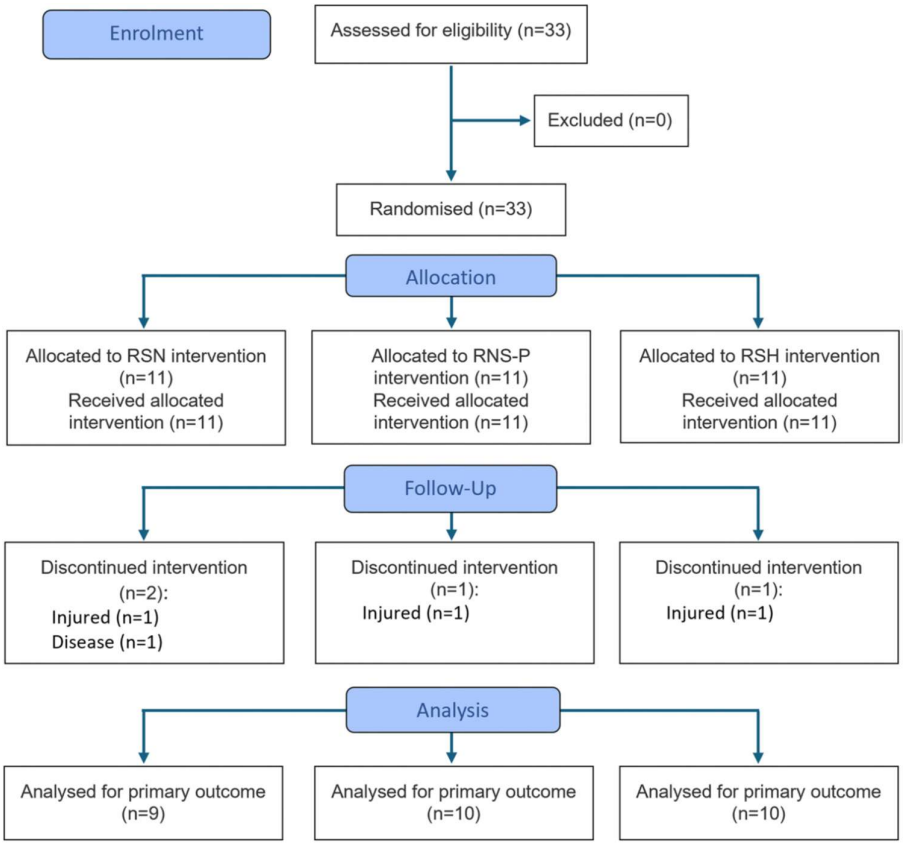

Fig. 1. CONSORT 2025 flow diagram. Flow diagram of the progress through the phases of the randomized trial. RS-N, repeatedsprint in normoxia; RSN-P, repeated-sprint in normoxia with placebo setup; RSH, repeated-sprint in hypoxia.

2.2. Experimental design & placebo control

This placebo-controlled study spanned a duration of 7 weeks, encompassing a total of 13 visits of approximately 45 minutes each. The training consisted of six sessions of repeated-sprint training over a three-week period on a friction-loaded cycle ergometer (Monark type 818E, Stockholm, Sweden) equipped with a strain gauge (interface MFG type, Scottsdale, AZ, USA). During the first visit, a preliminary round of Wingate testing was conducted to acquaint participants with the level of exertion required and to mitigate the risk of performance improvement on subsequent tests due to familiarization with the testing procedure. This familiarization was exclusively conducted for the Wingate test, as participants were not used to such an exertion, in contrast to the RSA-type exercise encountered in their sport practice. During the week preceding the training sessions, participants

performed a Wingate test and an RSA test. Subsequently, over the two weeks following the training, they repeated these assessments once per week (Fig. 2).

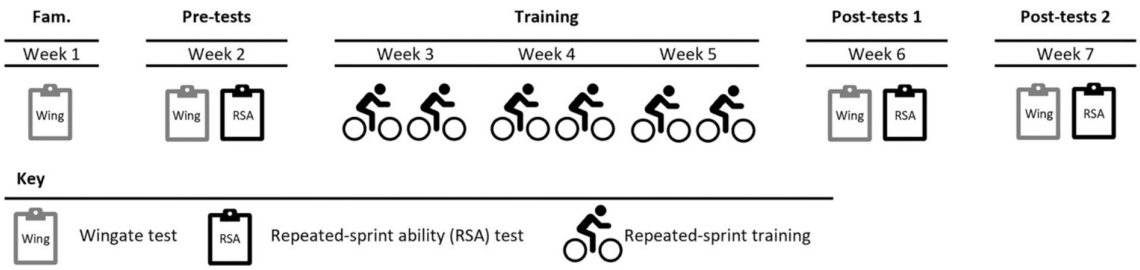

Fig. 2. Overview of the experimental schedule. Fam.: familiarization; each icon represents one session. Wingate test: 30 s all out cycling; repeated-sprint ability (RSA) test: 10 × 6 s cycling sprints interspersed with 24 s of recovery; repeated-sprint training: 3 sets of 8 × 6 s cycling sprints interspersed with 24 s of recovery.

The participants were randomly balanced into three groups based on the maximum and average power output relative to body mass (W/kg) recorded during the Wingate and RSA pre-tests. The three groups were: repeated-sprint in normoxia (RSN; n=9), repeated-sprint in normoxia with placebo setup (RSN-P; n=10), and repeated-sprint in hypoxia (RSH; n=10). The experimentation took place over three separated waves during the same year, with a balanced distribution between the three groups during each wave.

All sessions were conducted in Euromov laboratory with participants wearing a mask (Altitrainer®) covering the nose and mouth. For the RSN group, the mask was not connected to the hypoxic generator and participants were aware that they were breathing normoxic air (20.9% O_2). For the RSN-P and RSH groups, the mask was connected to a 150-L buffer bag itself connected to two hypoxic generators (Cloud 9, Sporting Edge, Basingstoke, England) to ensure sufficient airflow. Participants in the RSN-P group were kept in normoxia (fractional inspired oxygen (FiO_2) = 20.9%), while those in the RSH group were exposed to hypoxia (FiO_2 = 14.4%, equivalent to a simulated altitude of 3000 m). To test the potential placebo effect, it was necessary to ensure that each participant had an appropriate expectation of the hypoxic training. Participants were thus told that RSH training is known to promote greater performance gains compared to normoxia, and that the study aimed to determine the optimal

altitude for such training, explaining the concealment of the simulated altitude level. We informed the participants that they would be exposed to altitudes ranging from 2500 to 3500 m, a range chosen to avoid arousing suspicion about the question asked at the end of the protocol designed to assess blinding. All tests were conducted in double-blind fashion since neither the participants (from the RSN-P and RSH groups) nor the experimenter who encouraged them were aware of the actual condition of the participant. Testing sessions were carried out at an altitude of 75 m in an air-conditioned room where the ambient temperature was maintained at 21°C. At the end of the last visit, participants were asked to rate the altitude they had been exposed to on a scale from 0 to 4000 m.

2.3. Training sessions

The training sessions started with a 7-min warm-up aimed at achieving a power output of 100 W, featuring two progressive 10-s accelerations in the 5^{th} and 6^{th} min. Subsequently, following a 1-min period of passive rest, participants engaged in 3 sets of 8 repetitions of 6-s maximal sprints, interspersed with 24 s of passive recovery on the cycle ergometer. Resistance was set at 7.5% of BM for each session and participants were given very strong verbal encouragement. An LCD screen provided participants with information on the countdown timer and the number of sprints. Participants' heart rate (HR) and pulsed oxygen saturation (SpO_2) were recorded throughout all training sessions using a HR sensor (H10 Polar Electro, Kempele, Finland) and a 1 Hz frequency pulse oximeter (pulsox®-300i, Konica Minolta Inc., Osaka, Japan), respectively. The oximeter screen was concealed from both participants and experimenters to preserve blinding. Participants were reminded not to clench the hand connected to the oximeter to prevent artifacts in SpO_2 values. They were also instructed to rate their perceived exertion (RPE) on the Borg scale (from 6 to 20) after the warm-up and each of the three sets. To avoid influencing the RPE values, participants did not receive any direct feedback on their HR. All sessions were performed at an all-out intensity, except for the first one, during which participants were instructed to self-regulate their effort to complete the three sets. Mechanical power output (W) was recorded at a frequency of 1 Hz using PowerTap P1 pedals

(CycleOps, Madison, USA) connected to a watch (Fenix 3, Garmin). This setup was positioned in such a way that participants were unable to see the data.

2.4. Testing sessions

The pre- and post-tests were scheduled to take place either in the morning or in the afternoon, consistently at the same time of day (within a range of ± 1 hour) for each participant. This scheduling approach aimed to minimize potential bias arising from circadian fluctuations in performance (Knaier et al., 2019). The average intervals between the last training day and the Wingate tests were 4.7 ± 1.2 and 12.0 ± 2.1 days for post-tests 1 and 2, respectively. The RSA tests were 6.4 ± 1.3 and 14.4 ± 2.3 days after the last training session for post-tests 1 and 2, respectively. These intervals did not significantly differ between the three groups (group effect: $F=0.753$, $p=0.48$).

The composition of the two meals preceding the pre-tests was recorded, and participants were instructed to replicate the same menus before post-tests 1 and 2. Additionally, participants were advised to abstain from consuming caffeine or alcohol 24 hours before each test. However, for participants accustomed to regular coffee consumption, the quantity consumed was noted, and participants were encouraged to consume the same dose for the post-tests. Before each test, participants were required to complete the wellness questionnaire (comprising the following items: mood, sleep quality, energy level, muscle soreness, nutrition from the previous day and stress, each assessed on a scale from 1 to 5 in accordance with the recommendations of Hopper and Mackinnon (Hooper and Mackinnon, 1995) to assess their current wellness status. At the end of each test, they were invited to rate the perceived exertion (RPE) using the 6-20 Borg scale. During all tests, the participants received consistent and strong verbal support from the same experimenter, who remained unaware of the participants' assignment to one of the three groups. The verbal encouragements were positive: "come on," "push," "harder," "again," "all the way," "breathe well," "stay focused," and regularly included the participant's first name, as recommended by Midgley et al.

(Midgley et al., 2018). Mechanical power output (W) was recorded at a frequency of 1 Hz with the same device as for the training sessions.

2.4.1. Wingate Test

The warm-up prior to the Wingate test comprised a 6-minute period during which participants cycled at a target power output of 100 W. Following a 2-min passive recovery period, participants were instructed to exert maximal mechanical power over the 30-s duration of the test, with the resistance adjusted to 7.5% of their BM, while remaining seated on the saddle. To avoid any pacing strategy, participants were not provided with any temporal information during the test. Peak and mean power outputs were used to assess anaerobic power and capacity, respectively (de Poli et al., 2021). During the Wingate sessions (pre-test and post-test 1 only), a micro-blood sample was taken from the participants' fingertip at rest and 6 min after exercise completion. Lactate concentration and base excess (a proxy for buffering capacity) were determined using an iSTAT (Abbott, Abbott Park IL) and an Abbott CG4 + cartridge.

2.4.2. Repeated Sprint Ability Test

The RSA test was conducted 48 h apart from the Wingate test. The warm-up consisted of a 5-minute period during which participants were required to pedal at a target power output of 100. Additionally, two 4-s maximal sprints were performed at the 3rd and 5th min with a resistance offset to 5% of BM. Following a 2-min recovery period, participants engaged in 10 maximal sprints lasting 6 s each, with a resistance set to 7.5% of BM. These sprints were interspersed with 24 s of passive rest. Participants were encouraged to exert maximal effort during each sprint and were not informed of the total number of sprints to prevent pacing strategies (Billaut et al., 2011). We determined mean power, indicating the average power output throughout the entire test, and mean peak power output (PPO), computed as the average of peak powers across each of the 10 sprints. The fatigue index was assessed

using the percentage decrement score formula: $100 \times \frac{\text{mean power}}{10 \times \text{best sprint}} - 100$ where 'best sprint' denotes the mean power output during the 6 s of the top-performing sprint (Glaister et al., 2008). Additionally, the number of sprints performed above 85% of the best performance (NbS 85%) was recorded.

2.5. Training load

The training load of participants was calculated via the Robust Exponential Decreasing Index (REDI) which allows more weight to be given to the last training sessions compared to those performed a few days earlier (Moussa et al., 2019). Participants were asked to note the duration (min) and their RPE (CR10 scale) for each extra-protocol session. Then, the REDI was calculated on the 7 days preceding each test by setting the value of λ to 0.2 (Moussa et al., 2019).

2.6. Statistical analyses

Values are presented as means ± standard deviations or median (interquartile range). The sphericity and the equality of variance assumptions were tested with Mauchly's and Levene's tests, respectively. Greenhouse-Geisser correction was applied when sphericity was not met. The altitude estimation was analyzed using a Student's t-test. Data from training sessions (heart rate, RPE, power output) were analyzed using a one-way ANOVA with group (RSN, RSN-P, RSH) as the between-subject factor. Data from tests (wellness, RPE, REDI, power output, Sdec) as well as blood markers (lactate and base excess) were analyzed using a two-way repeated-measures analysis of variance (ANOVA) with time (pre-test, post-test 1, post-test 2) as the within-subject factor and group (RSN, RSN-P, RSH) as the between-subject factor. NbS 85% and SpO_2 data did not meet the assumption of homoscedasticity; therefore, Kruskal-Wallis (SpO_2) and Friedman (NbS 85%) tests were applied. Tukey's post hoc was used when ANOVA was significant. The level of significance was set to 0.05 for all tests. Effect sizes (ES) for the ANOVA were calculated using partial eta squared (ηp^2) for group, time, and interaction of these two

factors. ES was considered small when $0.01 < \eta p^2 \leq 0.06$, medium when $0.06 < \eta p^2 \leq 0.14$, and when large $\eta p^2 > 0.14$. For comparison of two groups, Cohen's d was calculated with 0.2 to 0.5 being considered as a small effect, 0.5 to 0.8 as moderate and > 0.8 as large. All statistical analyses were performed using the Jamovi Project software (version 2.3.18.0).

3. Results

3.1. Efficacy of the blinding procedure

The placebo setup allowed the RSN-P group to have no statistical difference belief as the RSH group (2605 ± 425 m and 2500 ± 445 m, respectively, *p*=0.557; Fig. 3). Furthermore, none of the participants reported feeling as if they had trained under normoxic conditions, thought 3 participants in each group reported lower to 2500 m (range 1700-2300 m).

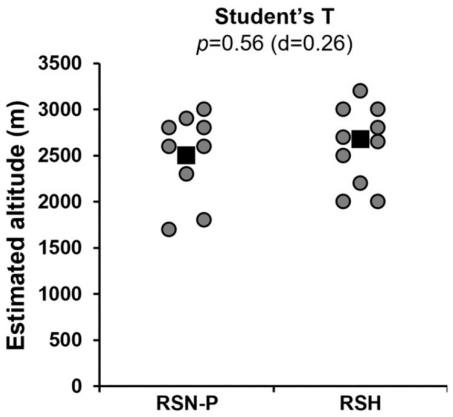

Fig. 3. Estimation of hypoxia severity by participants in the repeated-sprint in normoxia with placebo setup (RSN-P) and repeated-sprint in hypoxia (RSH) groups. Circles and squares represent individual and mean data, respectively.

3.2. Training sessions

As expected, SpO_2 during training sessions did not differ between the RSN and RSN-P groups, but was significantly reduced in the RSH group (Table 1). The mean %HR (relative to the peak of HR reached during the RSA test) was 5.2 ± 1.9% (*p*=0.02) and 5.7 ± 1.8% (*p*=0.01) higher in the RSH compared to

the RSN and RSN-P groups, respectively (Table 1). A similar result was observed on the absolute HR values. RPE tended to reach statistical significance with slightly higher values RSH group displaying (p=0.072; large ES) (Table 1). However, no group effect is observed for the mean power output sustained over all training sessions (Table 1).

Table 1. Average psycho-physiological responses during the 6 sessions of repeated-sprint training in normoxia (RSN and RSN-P) or in hypoxia (RSH).

				ANOVA *p* values (ES)
	RSN	RSN-P	RSH	*Group*
SpO_2 (%)	95.8 ± 0.6	96.0 ± 0.7	85.5 ± 2.6	**K-W <0.0001**
HR				
(bpm)	133 ± 12	126 ± 9	145 ± 11	**0.001 (0.41)**
(%)	79.2 ± 3.2	78.6 ± 5.6	84.8 ± 3.2	**0.005 (0.33)**
RPE	15.8 ± 1.0	15.8 ± 0.9	16.6 ± 0.8	0.072 (**0.18**)
Power output				
(W/kg)	10.6 ± 0.76	10.2 ± 1.2	9.8 ± 1.2	0.296 (0.09)
(W)	756 ± 87.9	782 ± 121	699 ± 136	0.291 (0.09)
(%)	94.7 ± 8.5	90.0 ± 7.3	91.9 ± 8.6	0.452 (0.057)

SpO_2: pulsed O_2 saturation; HR: heart rate; RPE: rate of perceived exertion; K-W: Kruskal-Wallis. Heart rate and power output are expressed as absolute values and as percentages of the peak RSA pre-test values. P-values and effect sizes are bold when significant and of large magnitude, respectively.

3.3. Tests sessions

We assessed an overall view of the participants' well-being before each test using the Wellness questionnaire, and analyses revealed a main effect of time for the RSA tests. Indeed, participants felt better during the second RSA post-test compared to the pre-test (+8.8%; *p*=0.001; Table 2). No other differences were found for the wellness score during either the RSA or the Wingate test sessions. A main effect of time was also observed for the RPE during the RSA but not the Wingate tests, with RPE being greater for the post 1 compared to the pre-test session (+8.4 ± 10.1%; *p*=0.038; Table 2). No main effect of group was observed for the RPE during either the Wingate or RSA test sessions.

Quantification of training load (REDI) also showed a main effect of time with a greater load in the 7 preceding days for the post 1 session compared to pre and post 2 for the RSA tests (+ 19.8 ± 38.4%; p= 0.001), and for the post 1 session compared to the pre session for the Wingate test (+ 199 ± 341%; p<0.001; Table 2). There was no interaction between time and group for any of the data presented in Table 2.

Table 2. Psychological and physical fitness status for the tests.

	RSN			RSN-P			RSH			ANOVA *p* values (ES)		
	Pre	Post 1	Post 2	Pre	Post 1	Post 2	Pre	Post 1	Post 2	*Time*	*Group*	*T x G*
Wellness												
(0 to 30)												
Wingate	23.1 ± 2.21	22.6 ± 2.91	21.4 ± 3.08	23.3 ± 2.02	23.6 ± 2.61	24.5 ± 2.87	23.2 ± 2.85	23.1 ± 2.86	22.8 ± 1.87	0.85 (0.01)	0.387 (0.07)	0.169 (0.12)
RSA	21.9 ± 4.19	23.3 ± 2.43	24.9 ± 2.42	23.2 ± 1.65	24.2 ± 4.24	24.9 ± 2.18	22.4 ± 3.37	22.2 ± 2.97	23.7 ± 2.21	**0.002 (0.24)**	0.539 (0.06)	0.624 (0.06)
RPE												
(6 to 20)												
Wingate	16.4 ± 1.81	17.3 ± 1.35	16.7 ± 1.60	17.1 ± 1.79	18.1 ± 1.30	17.2 ± 1.48	16.8 ± 1.32	17.6 ± 2.78	17.5 ± 2.59	0.118 (0.09)	0.612 (0.04)	0.91 (0.02)
RSA	15.9 ± 2.04	16.7 ± 1.60	16.1 ± 1.10	15.9 ± 1.95	17 ± 1.85	16.6 ± 1.18	16.1 ± 1.36	17.3 ± 1.03	17.7 ± 0.96	**0.011 (0.2)**	0.39 (0.09)	0.558 (0.07)
REDI												
Wingate	204 ± 160	464 ± 277	325 ± 252	246 ± 268	459 ± 160	382 ± 236	278 ± 173	386 ± 117	371 ± 181	**0.003 (0.24)**	0.91 (0.01)	0.726 (0.04)
RSA	304 ± 147	442 ± 279	324 ± 278	294 ± 126	522 ± 254	431 ± 271	295 ± 135	401 ± 147	359 ± 174	**<0.001 (0.27)**	0.702 (0.03)	0.595 (0.06)

RSA: repeated-sprint ability; RPE: rate of perceived exertion; REDI: robust exponential decreasing index is a score without units. P-values and effect sizes are bold when significant and of large magnitude, respectively.

3.4. Performance during tests

3.4.1. RSA

Repeated sprint training had a main positive and large effect (p<0.001; ηp^2 = 0.41) on the mean power sustained during the RSA tests (Fig. 4A). Post-hoc analysis showed significant differences between pre-test and post-test 1 (+5.1 ± 5.4%; p<0.001), as well as between pre-test and post-test 2 (+5.9 ± 6.8%; p=0.002). However, no group effect or group x time interaction was observed (Fig. 4A). No effect was found regarding the mean of the 10 peak power outputs (mean PPO) or the fatigue index expressed via the power decrement (P_{dec}) (Table 3).

The number of sprints above 85% of the best mean power output generated during the pre-test were 7 (4), 9 (3) and 7 (4) for RSN, RSN-P and RSH groups, respectively. These values were not significantly improved in post 1 and post 2 for either RSN (9 (1) and 7 (4); $\chi^2_{Friedman}$=1.04, p=0.595), RSN-P (10 (1) and 10 (2); $\chi^2_{Friedman}$=3.13, p=0.209) or RSH group (7 (4) and 9 (5); $\chi^2_{Friedman}$=0.897, p=0.639).

3.4.2. Wingate

As for RSA test, mean power output during the Wingate test was significantly improved (p=0.004, ηp^2=0.25) with greater values during post 1 (+4.8 ± 9.1%; p=0.048) and post 2 (+5.4 ± 7.1%; p=0.002) compared to pre-test performances (Fig. 4B). However, neither group factor nor group x time interaction displayed a significant effect on mean power output. No effect was found regarding the peak power output (PPO) or the fatigue index (P_{dec}) (Table 3).

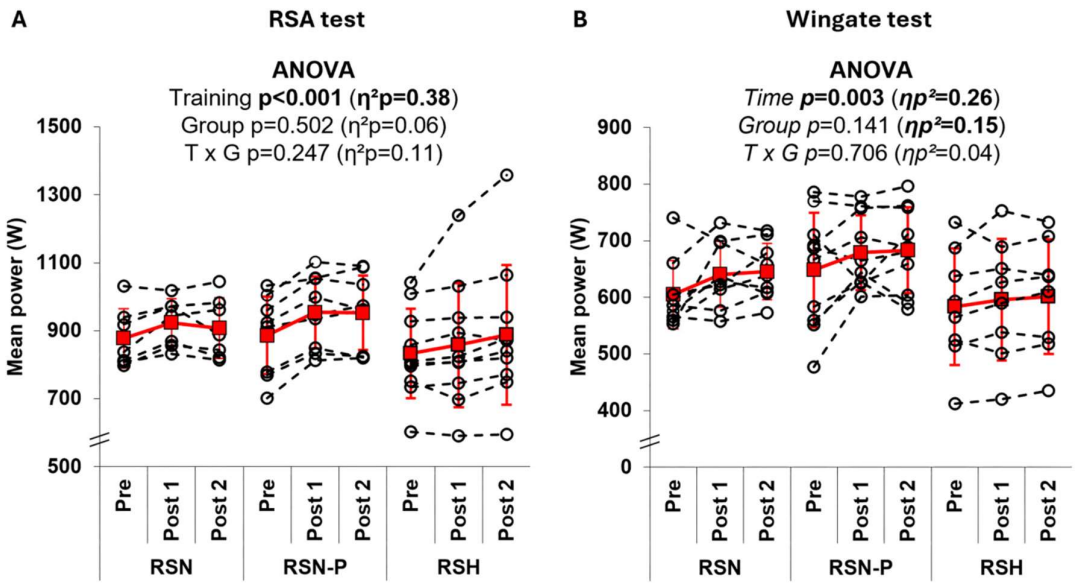

Fig. 4. Individual and average values of the mean power output during the repeated-sprint ability (RSA) and Wingate tests. Mean power during the RSA (A) and 30 s Wingate (B) tests. Circles and squares represent individual and mean data, respectively. The values of P and effect sizes are bold when significant and of large magnitude, respectively. G × T: group × time interaction.

Table 3. Sprint performance parameters during test sessions.

	RSN			RSN-P			RSH			ANOVA *p* values (ES)		
	Pre	Post 1	Post 2	Pre	Post 1	Post 2	Pre	Post 1	Post 2	*Time*	*Group*	*T x G*
RSA												
mean PO												
(W)	878 ± 87.3	924 ± 70.4	908 ± 89.6	886 ± 113	954 ± 106	953 ± 110	834 ± 132	858 ± 182	889 ± 206	**<0.001** **(0.38)**	0.50 (0.06)	0.25 (0.11)
(W/kg)	12.0 ± 0.5	12.6 ± 0.7	12.4 ± 0.9	11.7 ± 1.0	12.6 ± 0.8	12.6 ± 0.9	11.7 ± 1.0	12.1 ± 1.5	12.5 ± 1.8	**<0.001** **(0.41)**	0.85 (0.01)	0.22 (0.12)
mean PPO												
(W)	1066 ± 67.9	1047 ± 87.0	1027 ± 97.8	1075 ± 120	1080 ± 113	1068 ± 129	992 ± 161	957 ± 204	1001 ±234	0.33 (0.05)	0.40 (0.08)	0.16 (0.14)
(W/kg)	14.6 ± 1.2	14.3 ± 0.8	14.0 ± 1.0	14.2 ± 1.2	14.2 ± 0.9	14.1 ± 0.9	13.9 ± 1.2	13.4 ± 1.7	14.0 ± 2.1	0.21 (0.06)	0.69 (0.03)	0.10 **(0.15)**
P_{dec} (%)	-8.3 ± 3.8	-8.6 ± 3.0	-9.8 ± 4.3	-8.5 ± 3.2	-6.0 ± 2.3	-8.2 ± 3.6	-11.1 ± 2.7	-10.3 ± 4.5	-11.2 ± 5.9	0.18 (0.07)	0.09 (**0.18**)	0.68 (0.04)
Wingate												
mean PO												
(W)	605 ± 60.2	640 ± 58.2	645 ± 49.7	648 ± 101	679 ± 66.2	683 ± 76.0	583 ± 103	596 ± 107	601 ± 101	**0.003** **(0.26)**	0.14 **(0.15)**	0.71 (0.04)
(W/kg)	8.5 ± 0.5	8.8 ± 1.0	8.7 ± 0.6	8.5 ± 0.8	8.9 ± 0.7	9.0 ± 0.7	8.4 ± 0.7	8.6 ± 0.7	8.6 ± 0.6	**0.004** **(0.25)**	0.59 (0.04)	0.82 (0.03)
PPO												
(W)	975 ± 176	1046 ± 59.5	1073 ± 150	974 ± 194	1080 ± 232	1112 ± 168	948 ± 134	961 ± 222	903 ± 215	0.08 (0.10)	0.27 (0.10)	0.21 (0.11)
(W/kg)	13.7 ± 3.0	14.6 ± 1.8	14.8 ± 1.3	12.7 ± 2.2	14.0 ± 2.1	14.5 ± 1.8	13.6 ± 1.9	13.8 ± 2.8	12.9 ± 2.2	0.16 (0.07)	0.54 (0.04)	0.26 (0.10)
S_{dec} (%)	-35.8 ± 8.4	-37.7 ± 5.2	-38.2 ± 5.7	-31.5 ± 8.2	-34.5 ± 9.5	-37.1 ± 4.7	-37.3 ± 5.0	-35.5 ± 9.7	-31.0 ± 8.5	0.86 (0.00)	0.38 (0.07)	0.16 (0.12)

RSA: repeated-sprint ability; PO: power output; PPO: peak power output; P_{dec}: power decrement. Effect sizes are bold when significant and of large magnitude.

3.5. Blood parameters

Lactatemia was not modified by either training or the group x training interaction (Table 4). Blood lactate tended to be lower in the RSN-P group compared to the other two groups (group effect p=0.063; large ES). The main effect of time on base excess approached significance (p=0.055, large ES) with values tending to be lower after training. However, base excess did not differ between groups, and was not modified by the time x group interaction.

Table 4. Blood parameters measured 6 min after the Wingate test

	RSN		RSN-P		RSH		ANOVA *p* values (η_p^2)		
	Pre	Post 1	Pre	Post 1	Pre	Post 1	*training*	*Group*	*TxG*
Blood lactate (mM)	15.8 ± 1.3	16.1 ± 2.1	14.6 ± 2.4	14.9 ± 1.3	16.4 ± 1.2	15.9 ± 1.9	0.922 (0.00)	0.063 (**0.25**)	0.406 (0.09)
BE (mM)	-12.8 ± 1.6	-14.8 ± 2.2	-11.4 ± 2.2	-12.8 ± 2.3	-13.9 ± 1.9	-13.1 ± 3.1	0.055 (**0.19**)	0.120 (**0.21**)	0.161 (**0.18**)

BE: Base excess. Effect sizes are bold when significant and of large magnitude.

4. Discussion

This randomized placebo-controlled study aimed to determine the respective effects of thinking or being in hypoxia during repeated-sprint training on RSA and Wingate performance. The main conclusion of this study is that neither hypoxia nor the belief of being in hypoxia (placebo effect) provided any additional benefit to repeated sprint training under normoxia in recreationally trained adults. Performance enhancements (pre- vs. best post-test) were 7.9 ± 8.7% (p<0.001) for Wingate mean power output, comparable to those reported in previous studies (+6% for (Woorons et al., 2019), +4.4% for (Lanfranchi et al., 2024), and +11.9% for (Gutknecht et al., 2022). For RSA mean power output, we observed an average increase of 7.7 ± 7.3% (p<0.001), which is in line with the results of previous studies (+8.7% for (Kasai et al., 2019), +8.1% for (Gutknecht et al., 2022), +7.9% for (Lanfranchi et al., 2024), +10.8% for (Beard et al., 2019), and +5.4% for (Faiss et al., 2013)). The observed improvements were thus consistent with the findings of previous studies in the field. A potential reason why differences in performance gain between normoxic and hypoxic conditions are not observed could be a longer time required to reach peak performance after RSH training compared to RNS as observed by others (Brechbuhl et al., 2018b; Camacho-Cardenosa et al., 2017; Gonzalez-Custodio et al., 2024). We did not find any significant difference on performance between post 1 and 2 sessions, nor time x group interaction which would have suggested that one group displayed a specific response. However, analysis of qualitative variable using Chi^2 test with either P1 or P2 modality

to indicate whether peak performance was reached during post 1 or post 2 session revealed that the best mean power output for both RSA and Wingate tests was more frequent on the P2 session in RSH group compared to the other two (% of best performance during post 2 on RSA: 30, 20 and 90%; χ^2=11.5, p=0.003 and on Wingate: 30, 25 and 80%; χ^2=7.1, p=0.029 for RSN, RSN-P and RSH groups, respectively). This result may suggest that participants from the RSH group required a longer time to fully recover from the training, although the limited sample size for conducting such analysis invites us to temper this hypothesis.

4.1. Physiological responses

As expected and consistent with previous studies, SpO_2 was lower in the hypoxia training group (Birol et al., 2024; Montero and Lundby, 2017), while power output during training did not significantly differ between the hypoxia group (RSH) and the normoxia groups (RSN and RSN-P) (Hamlin et al., 2017a). Participants training in hypoxia exhibited a higher % of peak HR compared to those in normoxia (+5.1% and +5.7% compared to RSN and RSN-P, respectively). These findings contradict results from other studies on the acute effects of RSH (Brocherie et al., 2017; Goods et al., 2015; Montero and Lundby, 2017). Indeed, it has been suggested that at altitudes below 3500 m, work intensity (heart rate, power output, RPE) does not differ significantly between normoxia and hypoxia conditions (Brocherie et al., 2017; Millet et al., 2019). In addition to the increase in HR with hypoxia, we observed a non-significant but large effect size indicating a rise in RPE compared to the RSN and RSN-P groups (p = 0.072; η_p^2= 0.183), which is consistent given the strong correlation between RPE and HR during exercise (Scherr et al., 2013). Thus, it is possible that RSH induces a slight increase in the relative exercise intensity (% peak HR) compared to RSN, although the absolute intensity (power output) remains unaffected. Based on these results and a previous study (Gutknecht et al., 2022), one may hypothesize that the slightly higher training load with hypoxia would require more time to reach the peak performance once the training was completed. Nevertheless, the results of the current study do not support this assumption.

In 2008, a study on repeated sprint training in hypoxia induced by voluntary hypoventilation demonstrated a 5.2% increase in blood HCO_3^- concentration at rest, indicating an improved buffering capacity (Woorons et al., 2008). However, the results of the present study on base excess (which characterizes buffering capacity) do not align with these findings, as no differences were found between the three groups. It is possible that hypercapnia induced by hypoventilation may have facilited this adaptation (Trincat et al., 2017). To shed more light into this topic, it would be beneficial to implement a protocol including, among others, an RSH group and an RSH group with hypercapnia induced by an $FICO_2$-adjusting device.

In the quest to find elements of response to the responder/non-responder concept, a hypothesis has emerged within the field of repeated sprint training in hypoxia: participants with a higher proportion of fast-twitch muscle fibers would demonstrate superior responsiveness (Millet et al., 2019). We tested indirectly this hypothesis by estimating a correlation between maximal performance over 6 s and the proportion of type II fibers, as previously proposed (Raberin et al., 2022). Pearson correlation analysis indicates that there is no statistically significant correlation between changes in all performance indicators and maximal power over 6 s ($|r| < 0.3$; $p > 0.11$). To confirm or refute this hypothesis, muscle biopsies are required to determine fiber typology.

4.2. Methodological concerns

The exercise-to-rest ratio and the sprint duration determine the respective contribution from glycolytic and oxidative metabolism, the second being more affected by hypoxia (Raberin et al., 2022). Therefore, one may wonder whether the lack of differences in performance improvement between the RSN and RSH groups could result from a design that was not the most appropriate. We identified six studies with exercise-to-rest ratio (1:4 to 1:5), sprint duration (5-7 s) and a number of training sessions close as ours (Brechbuhl et al., 2020, 2018a; Brocherie et al., 2017; Fornasier-Santos et al., 2018; Hamlin et al., 2017b; Kasai et al., 2017). Of these six studies, five showed greater improvement in the hypoxic condition. Consequently, it can be concluded that the experimental design employed here does not

constitute a significant factor that would account for the absence of differences between the hypoxic and normoxic conditions.

An important factor that could potentially influence the results, and therefore the interpretation of the treatment, is the placebo effect resulting from the participants' belief of being at altitude. For instance, one study conducted under rigorous scientific conditions—randomized, double-blind, crossover—retained 33% of its placebo group participants even though they were not deceived, and retained 33% of the participants in the hypoxia group who believed they were in normoxia (Montero and Lundby, 2017). This study, like the present one, did not identify any additional benefits of hypoxia. However, it is possible that including these participants who believed they were in normoxia masked potential differences in progress between the various conditions. In our study, as in those conducted by Gatterer, none of the participants believed they were in normoxia (Gatterer et al., 2015). Unfortunately, Gatterer's article lacks information on how participants were informed to reinforce the belief of being in hypoxia. In our study, providing false information ("You will train at a simulated altitude between 2500 and 3500 meters.") likely reinforced the deception. A meta-analysis of the placebo effect in sport indicates that deceptive administration yields more pronounced effects compared to allowing doubt to persist (Bérdi et al., 2011).

To the best of our knowledge, the present study represents the first attempt to quantify the potential placebo effect in this specific training modality. Surprisingly, the results indicated no discernible difference between the placebo group and the control group. This absence of distinction might be attributed to the significant variability in responses to the placebo effect, a phenomenon notoriously difficult to predict (Bérdi et al., 2011). Various hypotheses have been proposed regarding the determinants of placebo responders, including personality traits (Geers et al., 2007), social acquiescence (Fisher and Greenberg, 1997), and motivation (Jensen and Karoly, 1991). The present study only controlled for motivation using the Wellness test, and no differences were observed between the three groups, but it would have been relevant to measure the other parameters. Finally, the Pearson correlation analysis shows that the estimated altitude does not correlate with any changes

in the performance indicators of the placebo and hypoxia groups ($|r| < 0.12$; $p > 0.6$), which suggests that the effect of belief in associating altitude level and magnitude of improvements is minimal.

A second important methodological point that can prove challenging to implement in the field during an RSH protocol is the concept of experimenter blinding, which aims to eliminate the Pygmalion effect. In order to mitigate this effect, the present study was conducted following the recommendation of Montero and Lundby, whereby neither the test session encourager nor the participants were informed of the training conditions (Montero and Lundby, 2017). Considering the beliefs among researchers about the benefit of hypoxia for repeated sprint training, it is possible that the Pygmalion effect may have influenced some of the findings in the existing literature. We identified five studies adhering to the double-blind protocol with a placebo group. Of these, three demonstrated a benefit of hypoxia [4,11,13]. However, as previously mentioned, no information was provided on the percentage of deception among the participants. Altogether, these results suggest that the placebo effect or the Pygmalion effect would not play a major role in the response to repeated-sprints training in hypoxia.

4.3. Conclusion

In conclusion, the present study shows that, despite indications of reduced O_2 availability (decreased SpO_2 and increased HR), real or perceived hypoxia did not result in enhanced performance in recreationally trained subjects compared to the placebo group. Moreover, the belief of training in hypoxia per se did not influence the response to training compared to the normoxic group. Therefore, RSH training does not (consistently) provide further performance enhancement, and it appears relevant to gain a deeper understanding of the specific conditions associated with repeated-sprint training that would be most beneficial for most of the athletes.

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Declaration of competing interest

Guilhem Belda is founding president and shareholder of Semaxone which has no direct link with the manuscript.

CRediT authorship contribution statement

Alexandre P. Gutknecht: Conceptualization, Investigation, Writing – original draft. Martin Gonzalez-Figueres: Investigation, Writing – review and editing. Guilhem Belda: Software, Writing – review and editing. Grégoire Vergotte: Formal analysis, Writing - Review & Editing. Stéphane Perrey: Resources, Writing - Review & Editing. François B. Favier: Conceptualization, Investigation, Writing – original draft.

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Data availability

Data will be made available on reasonable request.

Figures legends

Fig. 1. CONSORT 2025 Flow Diagram. Flow diagram of the progress through the phases of the randomised trial.

Fig. 2. Overview of the experimental schedule. Fam.: familiarization; each icon represents one session. Wingate test: 30-s all out cycling; RSA test: 10 x 6-s cycling sprints interspersed with 24s of recovery; Repeated-sprint training: 3 sets of 8 x 6-s cycling sprints interspersed with 24s of recovery.

Fig. 3. Estimation of hypoxia severity by participants in the RSN-P and RSH groups. Circles and squares represent individual and mean data, respectively.

Fig 4. Individual and average values of the mean power output during the RSA and Wingate tests. Mean power during the RSA (A) and 30-s Wingate (B) tests. Circles and squares represent individual and mean data, respectively. P-values and effect sizes are bold when significant and of large magnitude, respectively. G x T: group x time interaction.

References

Beard, A., Ashby, J., Chambers, R., Brocherie, F., Millet, G.P., 2019. Repeated-Sprint Training in Hypoxia in International Rugby Union Players. International Journal of Sports Physiology and Performance 14, 850–854. https://doi.org/10.1123/ijspp.2018-0170

Bérdi, M., Köteles, F., Szabó, A., Bárdos, G., 2011. Placebo Effects in Sport and Exercise: A Meta-Analysis. EJMH 6, 196–212. https://doi.org/10.5708/EJMH.6.2011.2.5

Billaut, F., Bishop, D.J., Schaerz, S., Noakes, T.D., 2011. Influence of knowledge of sprint number on pacing during repeated-sprint exercise. Med Sci Sports Exerc 43, 665–672. https://doi.org/10.1249/MSS.0b013e3181f6ee3b

Birol, A., Aras, D., Akalan, C., Aldhahi, M.I., Gülü, M., 2024. Three sessions of repeated sprint training in normobaric hypoxia improves sprinting performance. Heliyon 10, e27607. https://doi.org/10.1016/j.heliyon.2024.e27607

Brechbuhl, C., Brocherie, F., Millet, G., Schmitt, L., 2018a. Effects of Repeated-Sprint Training in Hypoxia on Tennis-Specific Performance in Well-Trained Players. Sports Med Int Open 02, E123–E132. https://doi.org/10.1055/a-0719-4797

Brechbuhl, C., Brocherie, F., Willis, S.J., Blokker, T., Montalvan, B., Girard, O., Millet, G.P., Schmitt, L., 2020. On the Use of the Repeated-Sprint Training in Hypoxia in Tennis. Front. Physiol. 11, 588821. https://doi.org/10.3389/fphys.2020.588821

Brechbuhl, C., Schmitt, L., Millet, G.P., Brocherie, F., 2018b. Shock microcycle of repeated-sprint training in hypoxia and tennis performance: Case study in a rookie professional player. International Journal of Sports Science & Coaching 13, 723–728. https://doi.org/10.1177/1747954118783586

Brocherie, F., Millet, G.P., Girard, O., 2017. Psychophysiological Responses to Repeated-Sprint Training in Normobaric Hypoxia and Normoxia. International Journal of Sports Physiology and Performance 12, 115–123. https://doi.org/10.1123/ijspp.2016-0052

Brocherie, F., Millet, G.P., Hauser, A., Steiner, T., Rysman, J., Wehrlin, J.P., Girard, O., 2015. "Live High–Train Low and High" Hypoxic Training Improves Team-Sport Performance. Medicine & Science in Sports & Exercise 47, 2140–2149. https://doi.org/10.1249/MSS.0000000000000630

Brocherie, F., Racinais, S., Cocking, S., Townsend, N., Couderc, A., Piscione, J., Girard, O., 2023. Repeated-Sprint Training at 5000-m Simulated Altitude in Preparation for the World Rugby Women's Sevens Series: Too High? Med Sci Sports Exerc 55, 1923–1932. https://doi.org/10.1249/MSS.0000000000003226

Camacho-Cardenosa, M., Camacho-Cardenosa, A., Martínez Guardado, I., Marcos-Serrano, M., Timon, R., Olcina, G., 2017. A new dose of maximal-intensity interval training in hypoxia to improve body composition and hemoglobin and hematocrit levels: a pilot study. J Sports Med Phys Fitness 57. https://doi.org/10.23736/S0022-4707.16.06549-X

Clark, V.R., Hopkins, W.G., Hawley, J.A., Burke, L.M., 2000. Placebo effect of carbohydrate feedings during a 40-km cycling time trial: Medicine & Science in Sports & Exercise 1642–1647. https://doi.org/10.1097/00005768-200009000-00019

De La Vega, R., Alberti, S., Ruíz-Barquín, R., Soós, I., Szabo, A., 2017. Induced beliefs about a fictive energy drink influences 200-m sprint performance †. European Journal of Sport Science 17, 1084–1089. https://doi.org/10.1080/17461391.2017.1339735

de Poli, R.A.B., Miyagi, W.E., Zagatto, A.M., 2021. Anaerobic Capacity is Associated with Metabolic Contribution and Mechanical Output Measured During the Wingate Test. J Hum Kinet 79, 65–75. https://doi.org/10.2478/hukin-2021-0063

Faiss, R., Girard, O., Millet, G.P., 2013. Advancing hypoxic training in team sports: from intermittent hypoxic training to repeated sprint training in hypoxia. Br J Sports Med 47, i45–i50. https://doi.org/10.1136/bjsports-2013-092741

Faiss, R., Raberin, A., Brocherie, F., Millet, G.P., 2024. Repeated-sprint training in hypoxia: A review with 10 years of perspective. J Sports Sci 1–15. https://doi.org/10.1080/02640414.2024.2416821

Fisher, S., Greenberg, R.P., 1997. From Placebo to Panacea: Putting Psychiatric Drugs to the Test. Wiley.

Fornasier-Santos, C., Millet, G.P., Woorons, X., 2018. Repeated-sprint training in hypoxia induced by voluntary hypoventilation improves running repeated-sprint ability in rugby players. European Journal of Sport Science 18, 504–512. https://doi.org/10.1080/17461391.2018.1431312

Galvin, H.M., Cooke, K., Sumners, D.P., Mileva, K.N., Bowtell, J.L., 2013. Repeated sprint training in normobaric hypoxia. Br J Sports Med 47, i74–i79. https://doi.org/10.1136/bjsports-2013-092826

Gatterer, H., Klarod, K., Heinrich, D., Schlemmer, P., Dilitz, S., Burtscher, M., 2015. Effects of a 12-day maximal shuttle-run shock microcycle in hypoxia on soccer specific performance and oxidative stress. Appl. Physiol. Nutr. Metab. 40, 842–845. https://doi.org/10.1139/apnm-2014-0479

Gatterer, H., Menz, V., Salazar-Martinez, E., Sumbalova, Z., Garcia-Souza, L.F., Velika, B., Gnaiger, E., Burtscher, M., 2018. Exercise Performance, Muscle Oxygen Extraction and Blood Cell Mitochondrial Respiration after Repeated-Sprint and Sprint Interval Training in Hypoxia: A Pilot Study. J Sports Sci Med 17, 339–347.

Geers, A.L., Kosbab, K., Helfer, S.G., Weiland, P.E., Wellman, J.A., 2007. Further evidence for individual differences in placebo responding: an interactionist perspective. J Psychosom Res 62, 563–570. https://doi.org/10.1016/j.jpsychores.2006.12.005

Glaister, M., Howatson, G., Pattison, J.R., McInnes, G., 2008. The Reliability and Validity of Fatigue Measures During Multiple-Sprint Work: An Issue Revisited. Journal of Strength and Conditioning Research 22, 1597–1601. https://doi.org/10.1519/JSC.0b013e318181ab80

Gonzalez-Custodio, A., Crespo, C., Timón, R., Olcina, G., 2024. Effects of a Combined Method of Normobaric Hypoxia on the Repeated Sprint Ability Performance of a Nine-Time World Champion Triathlete: A Case Report. Behav Sci (Basel) 14, 1084. https://doi.org/10.3390/bs14111084

Goods, P.S.R., Dawson, B., Landers, G.J., Gore, C.J., Peeling, P., 2015. No Additional Benefit of Repeat-Sprint Training in Hypoxia than in Normoxia on Sea-Level Repeat-Sprint Ability.

Gutknecht, A.P., Gonzalez-Figueres, M., Brioche, T., Maurelli, O., Perrey, S., Favier, F.B., 2022. Maximizing anaerobic performance with repeated-sprint training in hypoxia: In search of an optimal altitude based on pulse oxygen saturation monitoring. Front. Physiol. 13, 1010086. https://doi.org/10.3389/fphys.2022.1010086

Hamlin, M.J., Olsen, P.D., Marshall, H.C., Lizamore, C.A., Elliot, C.A., 2017a. Hypoxic Repeat Sprint Training Improves Rugby Player's Repeated Sprint but Not Endurance Performance. Front. Physiol. 8. https://doi.org/10.3389/fphys.2017.00024

Hamlin, M.J., Olsen, P.D., Marshall, H.C., Lizamore, C.A., Elliot, C.A., 2017b. Hypoxic Repeat Sprint Training Improves Rugby Player's Repeated Sprint but Not Endurance Performance. Front Physiol 8, 24. https://doi.org/10.3389/fphys.2017.00024

Hooper, S.L., Mackinnon, L.T., 1995. Monitoring overtraining in athletes. Recommendations. Sports Med 20, 321–327. https://doi.org/10.2165/00007256-199520050-00003

Jensen, M.P., Karoly, P., 1991. Motivation and expectancy factors in symptom perception: a laboratory study of the placebo effect. Psychosom Med 53, 144–152. https://doi.org/10.1097/00006842-199103000-00004

Kasai, N., Kojima, C., Sumi, D., Takahashi, H., Goto, K., Suzuki, Y., 2017. Impact of 5 Days of Sprint Training in Hypoxia on Performance and Muscle Energy Substances. Int J Sports Med 38, 983–991. https://doi.org/10.1055/s-0043-117413

Kasai, N., Mizuno, S., Ishimoto, S., Sakamoto, E., Maruta, M., Kurihara, T., Kurosawa, Y., Goto, K., 2019. Impact of Six Consecutive Days of Sprint Training in Hypoxia on Performance in Competitive Sprint Runners. Journal of Strength and Conditioning Research 33, 36–43. https://doi.org/10.1519/JSC.0000000000001954

Kienle, G.S., Kiene, H., 1997. The powerful placebo effect: fact or fiction? J Clin Epidemiol 50, 1311–1318. https://doi.org/10.1016/s0895-4356(97)00203-5

Knaier, R., Infanger, D., Niemeyer, M., Cajochen, C., Schmidt-Trucksäss, A., 2019. In Athletes, the Diurnal Variations in Maximum Oxygen Uptake Are More Than Twice as Large as the Day-to-Day Variations. Front Physiol 10, 219. https://doi.org/10.3389/fphys.2019.00219

Lanfranchi, C., Willis, S.J., Laramée, L., Conde Alonso, S., Pialoux, V., Kayser, B., Place, N., Millet, G.P., Zanou, N., 2024. Repeated sprint training in hypoxia induces specific skeletal muscle adaptations through S100A protein signaling. The FASEB Journal 38, e23615. https://doi.org/10.1096/fj.202302084RR

Midgley, A.W., Marchant, D.C., Levy, A.R., 2018. A call to action towards an evidence-based approach to using verbal encouragement during maximal exercise testing. Clin Physiol Funct Imaging 38, 547–553. https://doi.org/10.1111/cpf.12454

Millet, G., Girard, O., Beard, A., Brocherie, F., 2019. Repeated sprint training in hypoxia – an innovative method. Dtsch Z Sportmed 2019, 115–122. https://doi.org/10.5960/dzsm.2019.374

Montero, D., Lundby, C., 2017. No Improved Performance With Repeated-Sprint Training in Hypoxia Versus Normoxia: A Double-Blind and Crossover Study. International Journal of Sports Physiology and Performance 12, 161–167. https://doi.org/10.1123/ijspp.2015-0691

Moussa, I., Leroy, A., Sauliere, G., Schipman, J., Toussaint, J.-F., Sedeaud, A., 2019. Robust Exponential Decreasing Index (REDI): adaptive and robust method for computing

cumulated workload. BMJ Open Sport Exerc Med 5, e000573. https://doi.org/10.1136/bmjsem-2019-000573

Piperi, A., Warnier, G., VAN Doorslaer DE Ten Ryen, S., Benoit, N., Antoine, N., Copine, S., Francaux, M., Deldicque, L., 2024. Repeated Sprint Training in Hypoxia Improves Repeated Sprint Ability to Exhaustion Similarly in Active Males and Females. Med Sci Sports Exerc 56, 1988–1999. https://doi.org/10.1249/MSS.0000000000003485

Pires, F.O., Dos Anjos, C.A.S., Covolan, R.J.M., Fontes, E.B., Noakes, T.D., St Clair Gibson, A., Magalhães, F.H., Ugrinowitsch, C., 2018. Caffeine and Placebo Improved Maximal Exercise Performance Despite Unchanged Motor Cortex Activation and Greater Prefrontal Cortex Deoxygenation. Front. Physiol. 9, 1144. https://doi.org/10.3389/fphys.2018.01144

Raberin, A., Elmer, J., Willis, S.J., Richard, T., Vernillo, G., Iaia, F.M., Girard, O., Malatesta, D., Millet, G.P., 2022. The Oxidative–Glycolytic Balance Influenced by Sprint Duration Is Key during Repeated Sprint in Hypoxia. Medicine & Science in Sports & Exercise 55, 245–254. https://doi.org/10.1249/MSS.0000000000003042

Scherr, J., Wolfarth, B., Christle, J.W., Pressler, A., Wagenpfeil, S., Halle, M., 2013. Associations between Borg's rating of perceived exertion and physiological measures of exercise intensity. Eur J Appl Physiol 113, 147–155. https://doi.org/10.1007/s00421-012-2421-x

Trincat, L., Woorons, X., Millet, G.P., 2017. Repeated-Sprint Training in Hypoxia Induced by Voluntary Hypoventilation in Swimming. International Journal of Sports Physiology and Performance 12, 329–335. https://doi.org/10.1123/ijspp.2015-0674

Turner, G., Fudge, B.W., Pringle, J.S.M., Maxwell, N.S., Richardson, A.J., 2019. Altitude training in endurance running: perceptions of elite athletes and support staff. J Sports Sci 37, 163–172. https://doi.org/10.1080/02640414.2018.1488383

Woorons, X., Dupuy, O., Mucci, P., Millet, G.P., Pichon, A., 2019. Cerebral and Muscle Oxygenation during Repeated Shuttle Run Sprints with Hypoventilation. Int J Sports Med 40, 376–384. https://doi.org/10.1055/a-0836-9011

Woorons, X., Faucher, C., Dufour, S.P., Brocherie, F., Robach, P., Connes, P., Brugniaux, J.V., Verges, S., Gaston, A.F., Millet, G., Dupuy, O., Pichon, A., 2024. Hypoventilation training including maximal end-expiratory breath holding improves the ability to repeat high-intensity efforts in elite judo athletes. Front Physiol 15, 1441696. https://doi.org/10.3389/fphys.2024.1441696

Woorons, X., Mollard, P., Pichon, A., Duvallet, A., Richalet, J.-P., Lamberto, C., 2008. Effects of a 4-week training with voluntary hypoventilation carried out at low pulmonary volumes. Respir Physiol Neurobiol 160, 123–130. https://doi.org/10.1016/j.resp.2007.09.010