

# A narrative review exploring advances in interval training for endurance athletes

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## Abstract

Interval training is considered an essential training component in endurance athletes. Recently, there has been a focus on optimization of interval training characteristics to sustain a high fraction of maximal oxygen consumption ( $\geq 90\%$   $\dot{V}O_{2\max}$ ) to improve physiological adaptations and performance. Herein, we present a synopsis of the latest research exploring both acute and chronic studies in endurance athletes. Further, a decision flowchart was created for athletes and coaches to select the most appropriate interval training regime for specific individualized goals.

**Key words:** endurance performance, intermittent exercise, performance enhancement, oxygen uptake

## Introduction

Endurance athletes employ a variety of training methods, including continuous low-intensity training and interval training, to enhance their performance. This necessitates that training regimens target one or more of the factors determining endurance performance: (1) maximal aerobic energy production rate, (2) anaerobic capacity, and (3) gross efficiency—how efficiently energy is converted to movement (Joyner and Coyle 2008). Interval training, being an integral component of endurance athletes' training program, is imperative for achieving such improvements. In this paper, we present a condensed overview of acute and chronic studies related to optimization of the interval training session for endurance athletes. Furthermore, we outline a decision flowchart containing specific interval training characteristics tailored to specific training objectives.

## Acute studies on interval training programming

Time sustained at a high fraction of maximal oxygen consumption ( $\dot{V}O_{2\max}$ ; e.g.,  $\geq 90\%$ ) has emerged as a key metric for evaluating the effectiveness of interval training protocols (Midgley et al. 2006; Thevenet et al. 2007; Buchheit and Laursen 2013). Exercising at intensities close to  $\dot{V}O_{2\max}$  strains the  $O_2$  delivery and utilization system, thereby serving as a potent physiological stimulus for increasing  $\dot{V}O_{2\max}$  and endurance performance (Wenger and Bell 1986; Buchheit and Laursen 2013). Following this rationale, several studies on endurance athletes over the last 15 years have focused on optimizing the physiological stimulus during interval training (e.g., Thevenet et al. 2007; Almquist et al. 2020; Bossi et al.

2020; Rønnestad et al. 2022a; Held et al. 2023). To maximize the time spent close to  $\dot{V}O_{2\max}$ , a power output between 90% and 100% of maximal aerobic speed/power (MAS/MAP; i.e., the lowest speed/power that elicits  $\dot{V}O_{2\max}$ ) is recommended (Billat and Koralsztejn 1996; Hill and Rowell 1997; Hill et al. 1997; Laursen and Jenkins 2002; Midgley and Mc Naughton 2006). Importantly, continuous work at MAS/MAP can only be sustained for  $\sim 4$ – $7$  min in trained and well-trained athletes (Laursen et al. 2004; Rønnestad and Hansen 2016). Consequently, researchers have investigated the acute effects of various combinations of workloads and durations, number of work intervals, as well as different work–rest patterns, to optimize the time spent  $\geq 90\%$   $\dot{V}O_{2\max}$ .

Usually, a continuous evenly-paced workload is used during long work intervals (interval sessions typically in the range of  $4$ – $6 \times \sim 3$ – $8$  min). This practice might be viewed as contrasting to the training principle of specificity since most endurance sports display considerable intensity variations during racing. Additionally, alterations in workload during work intervals seems to be a good strategy for inducing longer time with high  $\dot{V}O_2$  compared to evenly-paced work intervals. For example, two studies involving well-trained male cross-country skiers, with an average  $\dot{V}O_{2\max}$  of  $\sim 70 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ , adopted a distinctive approach in their roller-ski intervals. They initiated each interval ( $5$ – $6 \times 5$  min) with a  $1.5$ – $2$  min fast start at an intensity corresponding to MAS, followed by a lower velocity at the end of each work interval (referred to as declining exercise intensity (DEC) intervals). This DEC interval protocol resulted in higher mean  $\dot{V}O_2$  compared to duration- and velocity-matched evenly-paced intervals, with no difference, or even lower, in rating of perceived exertion (RPE) (Rønnestad et al. 2022a, 2020b). However, only the study with the longest fast start (i.e.,  $2$  min)

induced a significant longer time above 90%  $\dot{V}O_{2\max}$  than the evenly-paced intervals (Rønnestad et al. 2022a), while the shorter fast start (1.5 min) was not different from the control setting (Rønnestad et al. 2020b). This suggests that the duration of the fast start is crucial for increasing the time spent above 90%  $\dot{V}O_{2\max}$ . This observation finds further support in a study involving recreational cyclists (7 males, 1 female;  $\dot{V}O_{2\max}$  of 56 mL·min<sup>-1</sup>·kg<sup>-1</sup>). A relatively short total work interval duration (4 × 3 min) with a short fast start duration (1 min) showed no differences in time above 90%  $\dot{V}O_{2\max}$  compared to evenly-paced intervals (Miller et al. 2023). Notably, the participants in the latter study had a markedly lower training status than the cross-country skiers in Rønnestad et al. (2022a, 2020b).

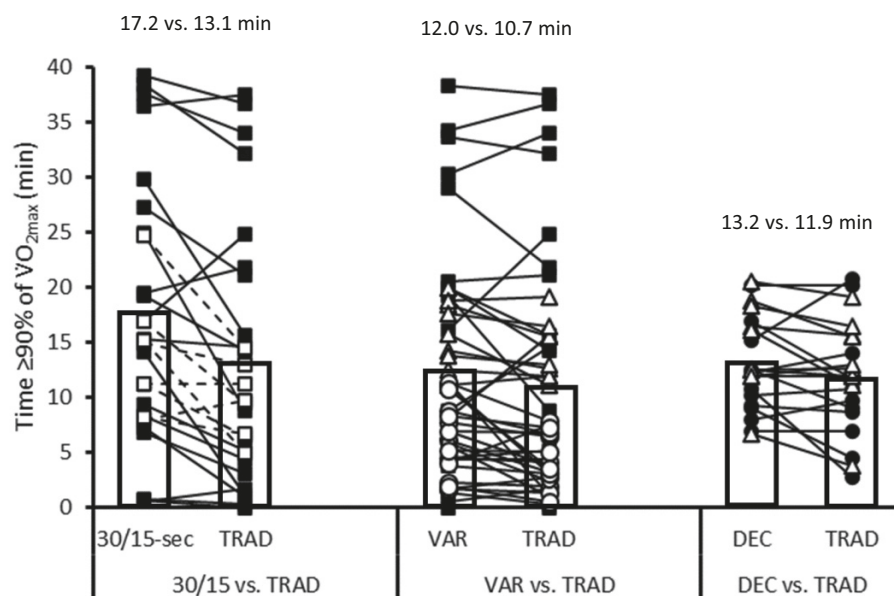
A related approach to the fast start involves to initiate the interval session with longer work interval durations, then gradually decreasing the duration of the work intervals while maintaining power output in the subsequent intervals. This approach has been shown to increase the time above 90%  $\dot{V}O_{2\max}$  compared to both a long interval (3 min work—2 min recovery) and a multiple short interval (30 s work—20 s recovery) cycling protocol in middle-aged amateur cyclists with an average  $\dot{V}O_{2\max}$  of ~57 mL·min<sup>-1</sup>·kg<sup>-1</sup> (Vaccari et al. 2020). Average time above 90%  $\dot{V}O_{2\max}$  was 312, 179, and 183 s for the interval session with decreasing work interval durations, long intervals, and multiple short intervals, respectively. Notably, 2 out of 12 participants achieved longer time above 90%  $\dot{V}O_{2\max}$  during long intervals and multiple short intervals compared to the interval session with decreasing work interval duration. This underscores the importance of recognizing individual differences in response to distinct exercise sessions.

Another alternative for eliciting additional time at a high  $\dot{V}O_2$  is to have regular and multiple workload variations during the work intervals (VAR intervals). Bossi et al. (2020) investigated this approach in well-trained male cyclists (average  $\dot{V}O_{2\max}$  of 69 mL·min<sup>-1</sup>·kg<sup>-1</sup>) when a 6 × 5 min interval protocol with three 30 s periods at 100% of MAP, interspersed with cycling at a lower power output, was compared with duration- and power output-matched evenly-paced work intervals. Despite no session differences related to mean heart rate (blood lactate) and RPE, there were higher mean percentage of  $\dot{V}O_{2\max}$  and time ≥ 90%  $\dot{V}O_{2\max}$  during varied compared to evenly-paced work intervals (410 s vs. 286 s, respectively;  $p = 0.02$ ). A follow-up study on well-trained cross-country skiers which used almost the same protocol, but on roller-skis and with a slightly higher exercise intensity than Bossi et al. revealed similar findings: VAR intervals induce higher mean % of  $\dot{V}O_{2\max}$ , and longer time ≥ 90%  $\dot{V}O_{2\max}$  than evenly-paced work intervals (15.0 min vs. 13.2 min, respectively;  $p = 0.03$ ) (Rønnestad et al. 2022a). However, in contrast, Urianstad et al. (2023) showed that 6 × 8 min VAR intervals with alternating power outputs between 60 s at 110% and 60 s at 90% of 40 min maximal power output (60/60 intervals), did not provide any higher mean percentage of  $\dot{V}O_{2\max}$  or longer time ≥ 90%  $\dot{V}O_{2\max}$  (15.3 min vs. 14.7 min, respectively;  $p = 0.89$ ) than evenly-paced 6 × 8 min work intervals conducted at 100% of 40 min maximal power output in a group of well-trained cy-

clists (11 females, average  $\dot{V}O_{2\max}$  of 63 mL·min<sup>-1</sup>·kg<sup>-1</sup>; 8 males, average  $\dot{V}O_{2\max}$  of 81 mL·min<sup>-1</sup>·kg<sup>-1</sup>). Possibly, the divergent results between these two VAR studies on well-trained cyclists were due to the lower amplitude of power output variations in the last study. Compared to the evenly-paced intervals, work intervals were initiated with an average of 27 W in Urianstad et al. (2023) study compared to 63 W higher power output in the Bossi et al. (2020) study.

Another alternative to traditional evenly-paced long work intervals is multiple short intervals, which we have known for over 60 years can induce a rather long duration at a high percentage of  $\dot{V}O_{2\max}$  (Christensen et al. 1960). Multiple short interval training sessions usually involves a series of 15–45 s work periods with an exercise intensity of around 95%–115% of MAS/MAP interspersed with active or passive recovery periods lasting 50%–100% of the work periods. The replenishment of O<sub>2</sub> to myoglobin during the recovery periods between the work periods (Åstrand et al. 1960), alongside the opportunity for partial resynthesis of phosphocreatine during frequent short recovery periods (Gaitanos et al. 1993), may significantly contribute to explain why multiple short intervals are beneficial for sustaining prolonged periods at a high fraction of  $\dot{V}O_{2\max}$ . In Almquist et al. (2020), well-trained male cyclists (average  $\dot{V}O_{2\max}$  of 74 mL/min/kg) completed three sets of 13 × 30 s work intervals separated by 15 s active recovery periods (30/15 intervals) where they achieved on average 14% higher power output, a higher  $\dot{V}O_2$  and longer time ≥ 90%  $\dot{V}O_{2\max}$  (844 s vs. 589 s, respectively) compared to evenly-paced 4 × 5 min work intervals, without perceiving greater exertion. The study of Almquist et al. (2020) compared effort-matched interval protocols where only the short-interval work periods (30 s) were included in the total accumulated work interval duration, ending up with comparing 3 × 9.75 min 30/15 intervals with 4 × 5 min work intervals. However, similar findings were also observed when the 15 s recovery periods of the 30/15 intervals were included in the total work interval duration and the mean power output was similar during 6 × 8 min work intervals (i.e., corresponding to 40 min maximal power) in well-trained male and female cyclists (Urianstad et al. 2023). In that study, the 30/15 intervals resulted in higher mean percentage of  $\dot{V}O_{2\max}$  and longer time ≥ 90%  $\dot{V}O_{2\max}$  compared to evenly-paced, but work- and duration-matched work intervals (18.7 min vs. 14.7 min, respectively;  $p < 0.01$ ). Interestingly, the findings of the latter study also suggest that for cyclists exhibiting lower fractional utilization of  $\dot{V}O_{2\max}$  at 4 mmol·L<sup>-1</sup> (blood lactate), 30/15 intervals are particularly favorable for achieving a high percentage of  $\dot{V}O_{2\max}$  during interval training. That stems from the observed negative interaction between the 30/15 and the evenly-paced interval session in response to a higher percentage of  $\dot{V}O_{2\max}$  at 4 mmol/L (blood lactate) ( $p < 0.05$ ). Participants with the highest percentages of  $\dot{V}O_{2\max}$  at 4 mmol/L (blood lactate) (~84%–86%) displayed largely similar  $\dot{V}O_2$  during 30/15 and evenly-paced interval sessions, while, conversely, participants with lower fractional utilization of  $\dot{V}O_{2\max}$  at 4 mmol/L (blood lactate) (<80%) exhibited higher  $\dot{V}O_2$  during 30/15 intervals compared to evenly-paced intervals.

**Fig. 1.** Time spent  $\geq 90\%$  of maximal oxygen consumption (time  $>90\% \dot{V}O_{2\max}$ ) during interval sessions comparing (i) series of multiple short intervals (30/15 s) with traditional evenly-paced work intervals (TRAD; group differences,  $p = 0.0007$ ), (ii) varied-intensity work intervals (VAR) with TRAD (group differences,  $p = 0.034$ ), and (iii) work intervals with a fast start, i.e., declining exercise intensity (DEC), with TRAD (group differences,  $p = 0.065$ ). All interval session comparisons were matched on mean power/velocity and duration of interval series (multiple short intervals)/work intervals and consisted of  $6 \times 8$  min cycling (black squares; [Urianstad et al. 2023](#)),  $5 \times 5$  min double pooling on roller skis (white triangles, [Rønnestad et al. 2021](#)),  $6 \times 5$  min cycling (white circles, [Bossi et al. 2020](#)), and  $5 \times 5$  min skating on roller skis (black circles, [Rønnestad et al. 2020b](#)). The only exception is the study of [Almquist et al. \(2020\)](#) where only the short-interval work duration (30 s) was included in the total work interval duration (and not the 15 s reliefs), ending in a total work interval duration of 19.5 min (3 series  $\times$  13  $\times$  30 s work/15 s relief) that was compared with a total of 20 min work interval duration ( $4 \times 5$  min, TRAD). The instruction was to aim for the highest possible mean power output during all work intervals, which ended up with a higher work interval power during the 30/15 s intervals than during TRAD intervals (white squares and dotted lines, [Almquist et al. 2020](#)). Mean values are shown by the columns.

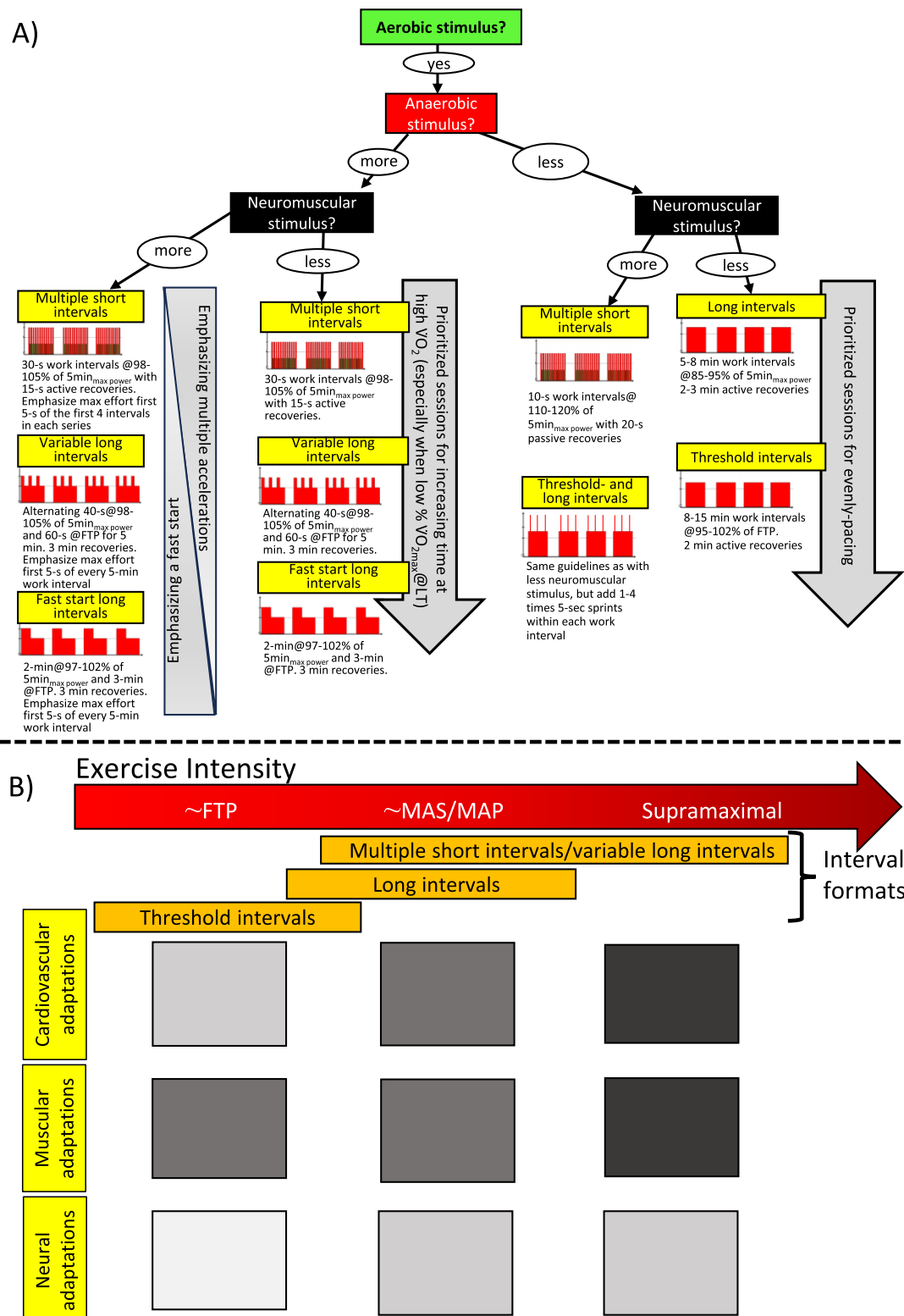


## Transferability of acute studies to training adaptations

Despite the popularity of quantifying mean percentage of  $\dot{V}O_{2\max}$  and time  $\geq 90\% \dot{V}O_{2\max}$ , we must highlight the lack of empirical evidence for its effectiveness. A substantial part of its evidence originated from the well-cited review of [Wenger and Bell \(1986\)](#) where they stated that “the magnitude of change in  $\dot{V}O_{2\max}$  increases as exercise intensity increases from 50% to 100% of  $\dot{V}O_{2\max}$ ”. Notably, this claim must be based solely on converting percentage of maximal heart rate or percentage of heart rate reserve to percentage of  $\dot{V}O_{2\max}$  as, to our knowledge, no study to that date had directly measured  $\dot{V}O_2$  during interval training sessions. Even today, very few studies have measured  $\dot{V}O_2$  during interval sessions in a training intervention to investigate its relationship with training adaptations. [Turnes et al. \(2016\)](#) observed that during a 4-week training intervention in male recreational cyclists (average  $\dot{V}O_{2\max}$  of  $\sim 48 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ ), the interval session with the longest time at  $\dot{V}O_{2\max}$  also induced the largest gains in  $\dot{V}O_{2\max}$  (6.3% vs. 3.3% increase;  $p = 0.03$ ), although no direct correlation was found between the variables. In another study, where well-trained male cross-country skiers (average  $\dot{V}O_{2\max}$  of  $70 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ )

performed five interval sessions in a 1-week interval block ([Rønnestad et al. 2022b](#)), there was a tendency to a positive correlation between the achieved time  $\geq 90\% \dot{V}O_{2\max}$  and improvement in  $\dot{V}O_{2\max}$  ( $r = 0.54$ ,  $p = 0.07$ ). Importantly, these two studies were of relatively short duration and  $\dot{V}O_2$  was only measured during 2–3 sessions. However,  $\dot{V}O_2$  was recently measured during all interval sessions (2–3 weekly sessions of  $5 \times 8$  min intervals) in a 9-week intervention period in 21 well-trained cyclists (3 females and 19 males; average  $\dot{V}O_{2\max}$  of  $67 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ ). That study demonstrated that training adaptations, such as change in mean power output achieved during the last minute of an incremental test ( $p\dot{V}O_{2\max}$ ), power output at 4 mmol·L<sup>-1</sup> (blood lactate), and  $\dot{V}O_{2\max}$ , were positively related to the percentage of  $\dot{V}O_{2\max}$  during the sessions ( $r^2_{\text{adjusted}} = 0.25\text{--}0.54$ ,  $p < 0.04$ ) ([Odden et al. 2023](#)). However, the precise causal mechanistic insight behind these positive associations remains to be fully elucidated, and the importance of percentage of  $\dot{V}O_{2\max}$  during sessions on peripheral adaptations like capillarization and mitochondrial function needs to be investigated. This study confirms that time spent at high  $\dot{V}O_2$  during interval sessions is indeed important for driving training adaptations. Therefore, in [Fig. 1](#), we present individualized data from our lab comparing three main alternative interval sessions (VAR,

**Fig. 2.** (A) Suggestion for decision flowchart based on main stimulus wanted for a specific interval session. Note that there are many other options and modifications than mentioned in this general figure, and that individual adjustments of power are needed. Sessions which are annotated to provide more neuromuscular stimulus are sessions that are designed to repeatedly activate high-threshold motor units. (B) Overview of the main adaptations expected by the different interval formats with their associated exercise intensity. Note that the level of adaptations is individually different and amongst others affected by training status and that there is a gradual overlap between both the main training adaptations, as well as exercise intensity, within each interval format. The darker colour of the squares, the larger adaptational effect of the interval format. FTP, functional threshold power (i.e., the highest average power you can sustain for 1 h); MAS/MAP, maximal aerobic speed/power (i.e., the lowest speed/power that elicits  $\dot{V}O_{2max}$ ); % $\dot{V}O_{2max@LT}$ , % of  $\dot{V}O_{2max}$  at lactate threshold.





DEC, and 30/15 intervals) with the traditional evenly-paced approach concerning time spent  $\geq 90\%$   $\dot{V}O_{2\max}$ .

## Efficiency of interval training programming in longitudinal training studies

In line with the acute studies proclaiming multiple short intervals to elicit a greater physiological stimulus than evenly-paced long intervals (Rønnestad and Hansen 2016; Almquist et al. 2020; Urianstad et al. 2023), longitudinal training studies largely supports this view. In a work interval duration- and effort-matched study on well-trained male cyclists, where participants were instructed to perform all interval sessions with their highest possible power output across work intervals, those engaging in two weekly 30/15 interval sessions (three sets of  $13 \times 30$  s work intervals separated by 15 s active recovery periods) for 10 weeks exhibited significantly greater improvements in  $\dot{V}O_{2\max}$  and cycling performance compared to those following a regimen of  $4 \times 5$  min evenly-paced intervals (Rønnestad et al. 2015). Specifically,  $\dot{V}O_{2\max}$  increased on average by 8.7% and 2.6% with 30/15 and  $4 \times 5$  min intervals, respectively ( $p \leq 0.05$ ). Similarly, the corresponding values for changes in  $\dot{V}O_{2\max}$  and 40 min maximal power output were 8.5% versus 1.5% and 12% versus 4% (both  $p \leq 0.05$ ). A follow-up study was performed on elite cyclists (average  $\dot{V}O_{2\max}$  of  $73 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ ), and displayed that three weekly 30/15 interval sessions for three weeks also in that population resulted in greater performance enhancement than  $4 \times 5$  min evenly-paced intervals (Rønnestad et al. 2020a), including larger improvement in 20 min maximal power output (4.7% vs.  $-1.4\%$ ,  $p < 0.01$ ),  $\dot{V}O_{2\max}$  (3.7% vs.  $-0.3\%$ ,  $p < 0.05$ ), and power output at  $4 \text{ mmol} \cdot \text{L}^{-1}$  (lactate) (2.0% vs.  $-2.8\%$ ,  $p < 0.05$ ). Another study demonstrated that a 1-week microcycle with five 30/15 interval sessions ( $5 \times (12 \times 30/15)$ ) induced larger increments in  $\dot{V}O_{2\max}$  and power output at  $4 \text{ mmol} \cdot \text{L}^{-1}$  (blood lactate) than five  $6 \times 5$  min evenly-paced interval sessions in well-trained male cyclists ( $p = 0.02$  and  $0.04$ , respectively) (Rønnestad et al. 2021). To summarize, it seems like multiple short intervals, and in particular the 30/15 protocol, is a potent strategy compared to the more traditional long-interval protocol for well-trained endurance athletes.

To our knowledge, the long-term training adaptations of long intervals performed with power output variation within work intervals (i.e., VAR intervals), as in the acute studies of Bossi et al. (2020) and Urianstad et al. (2023), have not been scientifically compared against the responses to evenly-paced long intervals. However, there is a short-term study on well-trained cross-country skiers, which indicates that VAR intervals can induce substantial training adaptations (Rønnestad et al. 2022b).

## Recommendations for interval training programming

During training programming, it has been recommended to consider (1) the demands of the sport, (2) the individual

characteristics of the athlete (e.g., strengths and weaknesses; training history), and (3) tailoring and prioritizing training to allow each individual athlete to meet these specific demands (Comfort and Matthews 2010).

In Fig. 2A, we suggest a decision flowchart presenting alternatives for appropriate interval session characteristics to optimize specific goals. A particular emphasis is put on the training principle of specificity, meaning that training responses are highly specific to the type, frequency, and duration of exercise performed (Hawley 2002, 2008). This means that the closer the exercise training is to the requirements and the demands of the desired outcome (e.g., a specific competition), the better the outcome will be (Hawley 2008). Note that the different interval designs can give slightly different stimulus by simply adjusting the exercise intensity. Figure 2B displays an overview of the main adaptations expected by the different interval session protocols. Note that training responses are both specific to the stress applied, but also partly overlapping between different protocols and exercise intensities.

In summary, current evidence demonstrate that manipulation of the workload within the work intervals affects the demands and stimuli of the session, which affects the acute and chronic physiological and molecular response. Therefore, the characteristics of interval training should be carefully planned according to the main goal of the training session as well as which stimuli or ability the athlete wants to emphasize during the session and the specific training period.

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### Data availability

This article does not report new data.

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## Competing interests

The authors declare that they have no conflicts of interest relevant to the content of this article.

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