

1 **A narrative review exploring advances in interval training for endurance athletes**

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6

7 ***Abstract***

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

14 **Key words:** Endurance performance, intermittent exercise, performance enhancement, oxygen
15 uptake

16

17 ***Introduction***

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

27

28 ***Acute studies on interval training programming***

1 Time sustained at a high fraction of maximal oxygen consumption ($\dot{V}O_{2max}$; e.g., $\geq 90\%$) has emerged
2 as a key metric for evaluating the effectiveness of interval training protocols (Midgley et al. 2006;
3 Thevenet et al. 2007; Buchheit and Laursen 2013). Exercising at intensities close to $\dot{V}O_{2max}$ strains the
4 O_2 delivery and utilization system, thereby serving as a potent physiological stimulus for increasing
5 $\dot{V}O_{2max}$ and endurance performance (Wenger and Bell 1986; Buchheit and Laursen 2013). Following
6 this rationale, several studies on endurance athletes over the last 15 years have focused on
7 optimizing the physiological stimulus during interval training (e.g. Thevenet et al. 2007; Almquist et
8 al. 2020; Bossi et al. 2020; Rønnestad et al. 2022a; Held et al. 2023). To maximize the time spent close
9 to $\dot{V}O_{2max}$, a power output between 90 to 100% of maximal aerobic speed/power (MAS/MAP; i.e., the
10 lowest speed/power that elicits $\dot{V}O_{2max}$) is recommended (Billat and Koralsztein 1996; Hill et al. 1997;
11 Hill and Rowell 1997; Laursen and Jenkins 2002; Midgley and Mc Naughton 2006). Importantly,
12 continuous work at MAS/MAP can only be sustained for ~4-7 minutes in trained and well-trained
13 athletes (Laursen et al. 2004; Rønnestad and Hansen 2016). Consequently, researchers have
14 investigated the acute effects of various combinations of workloads and -durations, number of work
15 intervals, as well as different work-rest patterns, to optimize the time spent $\geq 90\% \dot{V}O_{2max}$.

16

17 Usually, a continuous evenly-paced workload is used during long work intervals (interval sessions
18 typically in the range of 4-6 x ~3-8 min). This practice might be viewed as contrasting to the training
19 principle of specificity since most endurance sports display considerable intensity variations during
20 racing. Additionally, alterations in workload during work intervals seems to be a good strategy for
21 inducing longer time with high $\dot{V}O_2$ compared to evenly-paced work intervals. For example, two
22 studies involving well-trained male cross-country skiers, with an average $\dot{V}O_{2max}$ of $\sim 70 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$,
23 adopted a distinctive approach in their roller-ski intervals. They initiated each interval (5-6 x 5 min)
24 with a 1.5-2 min fast start at an intensity corresponding to MAS, followed by a lower velocity at the
25 end of each work interval (referred to as declining exercise intensity, DEC intervals). This DEC interval
26 protocol resulted in higher mean $\dot{V}O_2$ compared to duration- and velocity-matched evenly-paced
27 intervals, with no difference, or even lower, rating of perceived exertion (RPE) (Rønnestad et al.
28 2020b, 2022a). However, only the study with the longest fast start (i.e. 2 min) induced a significant
29 longer time above $90\% \dot{V}O_{2max}$ than the evenly paced intervals (Rønnestad et al. 2022a), while the
30 shorter fast start (1.5 min) was not different from the control setting (Rønnestad et al. 2020b). This
31 suggests that the duration of the fast start is crucial for increasing the time spent above $90\% \dot{V}O_{2max}$.
32 This observation finds further support in a study involving recreational cyclists (7 males, 1 female;
33 $\dot{V}O_{2max}$ of $56 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$). A relatively short total work interval duration (4x3 min) with a short fast
34 start duration (1 min) showed no differences in time above $90\% \dot{V}O_{2max}$ compared to evenly-paced

1 intervals (Miller et al. 2023). Notably, the participants in the latter study had a markedly lower
2 training status than the cross-country skiers in Rønnestad et al. (2020b and 2022a).

3

4 A related approach to the fast start involves to initiate the interval session with longer work interval
5 durations, then gradually decreasing the duration of the work intervals while maintaining power
6 output in the subsequent intervals. This approach has been shown to increase the time above
7 90% $\dot{V}O_{2max}$ compared to both a long interval (3 min work – 2 min recovery) and a multiple short
8 interval (30 sec work – 20 sec recovery) cycling protocol in middle-aged amateur cyclists with an
9 average $\dot{V}O_{2max}$ of $\sim 57 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ (Vaccari et al. 2020). Average time above 90% $\dot{V}O_{2max}$ was 312, 179
10 and 183 sec for the interval session with decreasing work interval durations, long intervals and
11 multiple short intervals, respectively. Notably, two out of twelve participants achieved longer time
12 above 90% $\dot{V}O_{2max}$ during long intervals and multiple short intervals compared to the interval session
13 with decreasing work interval duration. This underscores the importance of recognizing individual
14 differences in response to distinct exercise sessions.

15

16 Another alternative for eliciting additional time at a high $\dot{V}O_2$ is to have regular and multiple workload
17 variations during the work intervals (VAR intervals). Bossi et al. (2020) investigated this approach in
18 well-trained male cyclists (average $\dot{V}O_{2max}$ of $69 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) when a 6x5 min interval protocol with
19 three 30-second periods at 100% of MAP, interspersed with cycling at a lower power output, was
20 compared with duration- and power output-matched evenly-paced work intervals. Despite no session
21 differences related to mean heart rate, [blood lactate] and RPE, there were higher mean % of $\dot{V}O_{2max}$
22 and time $\geq 90\% \dot{V}O_{2max}$ during varied compared to evenly-paced work intervals (410 versus 286 sec,
23 respectively; $p=0.02$). A follow-up study on well-trained cross-country skiers which used almost the
24 same protocol, but on roller-skis and with a slightly higher exercise intensity than Bossi et al.,
25 revealed similar findings: VAR intervals induce higher mean % of $\dot{V}O_{2max}$ and longer time $\geq 90\% \dot{V}O_{2max}$
26 than evenly-paced work intervals (15.0 versus 13.2 min, respectively; $p=0.03$) (Rønnestad et al.
27 2022a). However, in contrast, Urianstad et al. (2023) showed that 6x8 min VAR intervals with
28 alternating power outputs between 60-sec at 110% and 60-sec at 90% of 40-min maximal power
29 output (60/60 intervals), did not provide any higher mean % of $\dot{V}O_{2max}$ or longer time $\geq 90\% \dot{V}O_{2max}$
30 (15.3 versus 14.7 min, respectively; $p=0.89$) than evenly-paced 6x8 min work intervals conducted at
31 100% of 40-min maximal power output in a group of well-trained cyclists (11 females, average $\dot{V}O_{2max}$
32 of $63 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$; 8 males, average $\dot{V}O_{2max}$ of $81 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$). Possibly, the divergent results
33 between these two VAR studies on well-trained cyclists were due to the lower amplitude of power

1 output variations in the last study. Compared to the evenly-paced intervals, work intervals were
2 initiated with an average of 27 W in Urianstad et al. (2023) study compared to 63 W higher power
3 output in the Bossi et al. (2020) study.

4 Another alternative to traditional evenly-paced long work intervals is multiple short intervals, which
5 we have known for over 60 years can induce a rather long duration at a high % of $\dot{V}O_{2max}$ (Christensen
6 et al. 1960). Multiple short interval training sessions usually involves a series of 15–45 seconds work
7 periods with an exercise intensity of around 95–115% of MAS/MAP interspersed with active or
8 passive recovery periods lasting 50-100% of the work periods. The replenishment of O_2 to myoglobin
9 during the recovery periods between the work periods (Åstrand et al. 1960), alongside the
10 opportunity for partial resynthesis of phosphocreatine during frequent short recovery periods
11 (Gaitanos et al. 1993), may significantly contribute to explain why multiple short intervals are
12 beneficial for sustaining prolonged periods at a high fraction of $\dot{V}O_{2max}$. In Almquist et al. (2020), well-
13 trained male cyclists (average $\dot{V}O_{2max}$ of 74 mL/min/kg) completed 3 sets of 13x30-sec work intervals
14 separated by 15-sec active recovery periods (30/15 intervals) where they achieved in average 14%
15 higher power output, a higher $\dot{V}O_2$ and longer time $\geq 90\% \dot{V}O_{2max}$ (844 versus 589 sec, respectively)
16 compared to evenly-paced 4x5-min work intervals, without perceiving greater exertion. The study of
17 Almquist et al. (2020) compared effort-matched interval protocols where only the short-interval work
18 periods (30-sec) were included in the total accumulated work interval duration, ending up with
19 comparing 3x9.75 min 30/15 intervals with 4x5 min work intervals. However, similar findings were
20 also observed when the 15-sec recovery periods of the 30/15 intervals were included in the total
21 work interval duration and the mean power output was similar during 6x8 min work intervals (i.e.,
22 corresponding to 40-min maximal power) in well-trained male and female cyclists (Urianstad et al.,
23 2023). In that study, the 30/15 intervals resulted in higher mean % of $\dot{V}O_{2max}$ and longer time
24 $\geq 90\% \dot{V}O_{2max}$ compared to evenly-paced, but work- and duration-matched work intervals (18.7 versus
25 14.7 min, respectively; $p < 0.01$). Interestingly, the findings of the latter study also suggest that for
26 cyclists exhibiting lower fractional utilization of $\dot{V}O_{2max}$ at 4 mmol·L⁻¹ [blood lactate], 30/15 intervals
27 are particularly favorable for achieving a high % of $\dot{V}O_{2max}$ during interval training. That stems from
28 the observed negative interaction between the 30/15 and the evenly-paced interval session in
29 response to a higher percentage of $\dot{V}O_{2max}$ at 4 mmol/L [blood lactate] ($p < 0.05$). Participants with the
30 highest percentages of $\dot{V}O_{2max}$ at 4 mmol/L [blood lactate] (~84-86%) displayed largely similar $\dot{V}O_2$
31 during 30/15 and evenly-paced interval sessions, while, conversely, participants with lower fractional
32 utilization of $\dot{V}O_{2max}$ at 4 mmol/L [blood lactate] (<80%) exhibited higher $\dot{V}O_2$ during 30/15 intervals
33 compared to evenly-paced intervals.

34

1 **Transferability of acute studies to training adaptations**

2 Despite the popularity of quantifying mean % of $\dot{V}O_{2max}$ and time $\geq 90\% \dot{V}O_{2max}$, we must highlight the
3 lack of empirical evidence for its effectiveness. A substantial part of its evidence originated from the
4 well-cited review of Wenger & Bell (1986) where they stated that “the magnitude of change in $\dot{V}O_{2max}$
5 increases as exercise intensity increases from 50 to 100% of $\dot{V}O_{2max}$ ”. Notably, this claim must be
6 based solely on converting % of maximal heart rate or % of heart rate reserve to % of $\dot{V}O_{2max}$ as, to
7 our knowledge, no study to that date had directly measured $\dot{V}O_2$ during interval training sessions.
8 Even today, very few studies have measured $\dot{V}O_2$ during interval sessions in a training intervention to
9 investigate its relationship with training adaptations. Turnes et al. (2016) observed that during a four-
10 week training intervention in male recreational cyclists (average $\dot{V}O_{2max}$ of $\sim 48 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$), the
11 interval session with the longest time at $\dot{V}O_{2max}$ also induced the largest gains in $\dot{V}O_{2max}$ (6.3 versus
12 3.3% increase, $p=0.03$), although no direct correlation was found between the variables. In another
13 study, where well-trained male cross-country skiers (average $\dot{V}O_{2max}$ of $70 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) performed
14 five interval sessions in a one-week interval block (Rønnestad et al. 2022b), there was a tendency to a
15 positive correlation between the achieved time $\geq 90\% \dot{V}O_{2max}$ and improvement in $\dot{V}O_{2max}$ ($r=0.54$,
16 $p=0.07$). Importantly, these two studies were of relatively short duration and $\dot{V}O_2$ was only measured
17 during 2-3 sessions. However, $\dot{V}O_2$ was recently measured during all interval sessions (2-3 weekly
18 sessions of 5x8 min intervals) in a 9-week intervention period in 21 well-trained cyclists (3 females
19 and 19 males; average $\dot{V}O_{2max}$ of $67 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$). That study demonstrated that training adaptations,
20 such as change in mean power output achieved during the last minute of an incremental test
21 ($\rho \dot{V}O_{2max}$), power output at $4 \text{ mmol}\cdot\text{L}^{-1}$ [blood lactate], and $\dot{V}O_{2max}$, were positively related to the % of
22 $\dot{V}O_{2max}$ during the sessions ($r^2_{adjusted}=0.25-0.54$, $p<0.04$) (Odden et al. 2023). However, the precise
23 causal mechanistic insight behind these positive associations remains to be fully elucidated, and the
24 importance of % of $\dot{V}O_{2max}$ during sessions on peripheral adaptations like capillarization and
25 mitochondrial function needs to be investigated. This study confirms that time spent at high $\dot{V}O_2$
26 during interval sessions is indeed important for driving training adaptations. Therefore, in Figure 1,
27 we present individualized data from our lab comparing three main alternative interval sessions (VAR,
28 DEC, and 30/15 intervals) with the traditional evenly-paced approach concerning time spent
29 $\geq 90\% \dot{V}O_{2max}$.

30 **Figure 1 here**

32 **Efficiency of interval training programming in longitudinal training studies**

1 In line with the acute studies proclaiming multiple short intervals to elicit a greater physiological
2 stimulus than evenly-paced long intervals (Rønnestad and Hansen 2016; Almquist et al. 2020;
3 Urianstad et al. 2023), longitudinal training studies largely supports this view. In a work interval
4 duration- and effort-matched study on well-trained male cyclists, where participants were instructed
5 to perform all interval sessions with their highest possible power output across work intervals, those
6 engaging in two weekly 30/15 interval sessions (three sets of 13x30-sec work intervals separated by
7 15-sec active recovery periods) for 10 weeks exhibited significantly greater improvements in $\dot{V}O_{2max}$
8 and cycling performance compared to those following a regimen of 4x5 min evenly-paced intervals
9 (Rønnestad et al. 2015). Specifically, $\dot{V}O_{2max}$ increased on average by 8.7% and 2.6% with 30/15 and
10 4x5 min intervals, respectively ($p \leq 0.05$). Similarly, the corresponding values for changes in $p\dot{V}O_{2max}$
11 and 40-min maximal power output were 8.5% versus 1.5% and 12% versus 4% (both $p \leq 0.05$). A
12 follow-up study was performed on elite cyclists (average $\dot{V}O_{2max}$ of $73 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$), and displayed
13 that three weekly 30/15 interval sessions for three weeks also in that population resulted in greater
14 performance enhancement than 4x5 min evenly-paced intervals (Rønnestad et al. 2020a), including
15 larger improvement in 20-min maximal power output (4.7% versus -1.4%, $p < 0.01$), $p\dot{V}O_{2max}$ (3.7%
16 versus -0.3%, $p < 0.05$) and power output at $4 \text{ mmol} \cdot \text{L}^{-1}$ [lactate] (2.0% versus -2.8%, $p < 0.05$). Another
17 study demonstrated that a 1-week microcycle with five 30/15 interval sessions (5x(12x30/15))
18 induced larger increments in $\dot{V}O_{2max}$ and power output at $4 \text{ mmol} \cdot \text{L}^{-1}$ [blood lactate] than five 6x5 min
19 evenly-paced interval sessions in well-trained male cyclists ($p = 0.02$ and 0.04 , respectively)
20 (Rønnestad et al. 2021). To summarize, it seems like multiple short intervals, and in particular the
21 30/15 protocol, is a potent strategy compared to the more traditional long-interval protocol for well-
22 trained endurance athletes.

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

28

29 ***Recommendations for interval training programming***

30 During training programming, it has been recommended to consider; 1) the demands of the sport, 2)
31 the individual characteristics of the athlete (e.g., strengths and weaknesses; training history), and 3)
32 tailoring and prioritizing training to allow each individual athlete to meet these specific demands
33 (Comfort and Matthews 2010).

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

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

16 **Figure 2 here**

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19 **Competing interests**

20 Knut Sindre Mølmen and Bent R. Rønnestad declare that they have no conflicts of interest relevant to
21 the content of this article.

22 **Data availability**

23 This article does not report new data.

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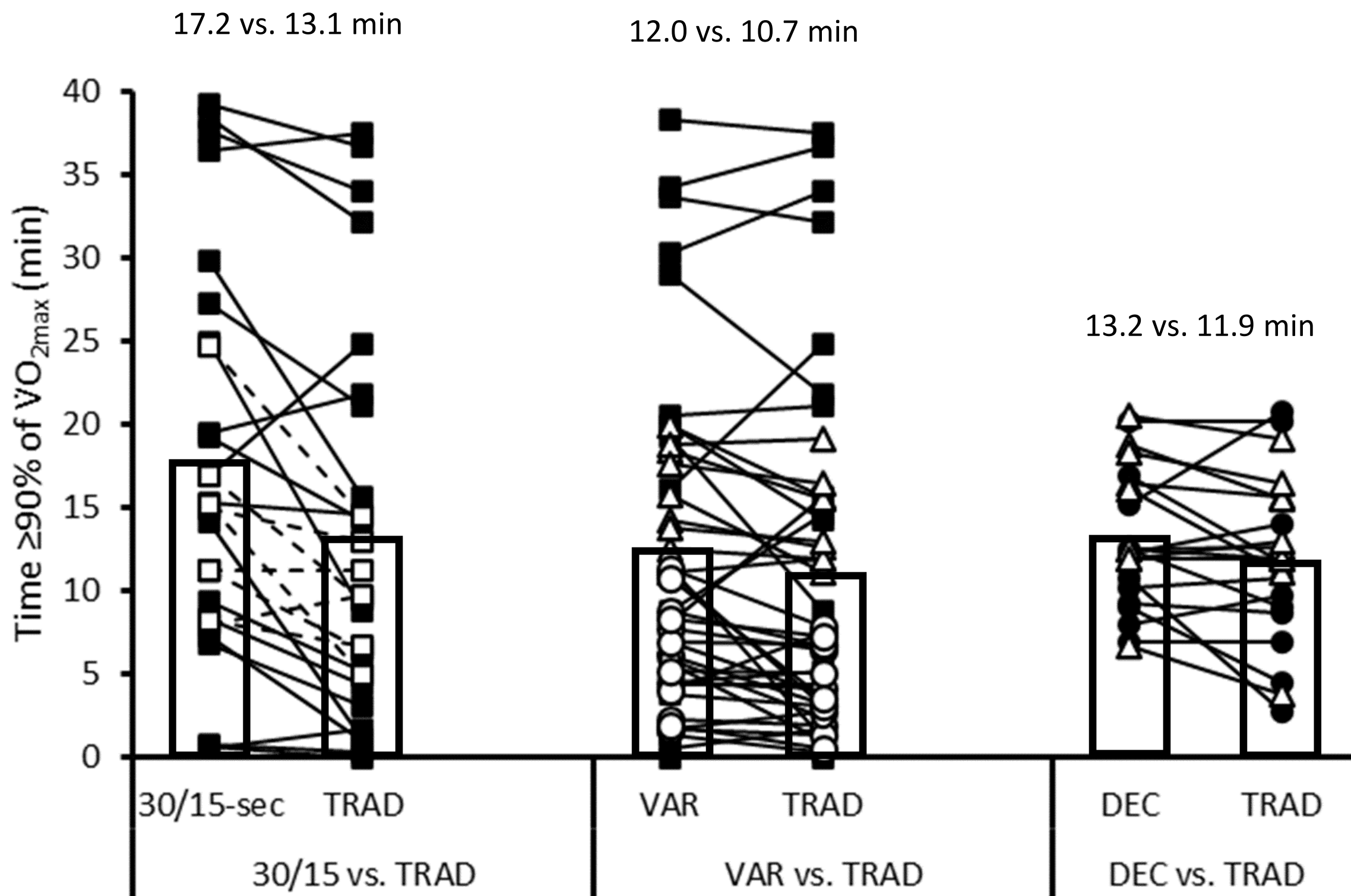
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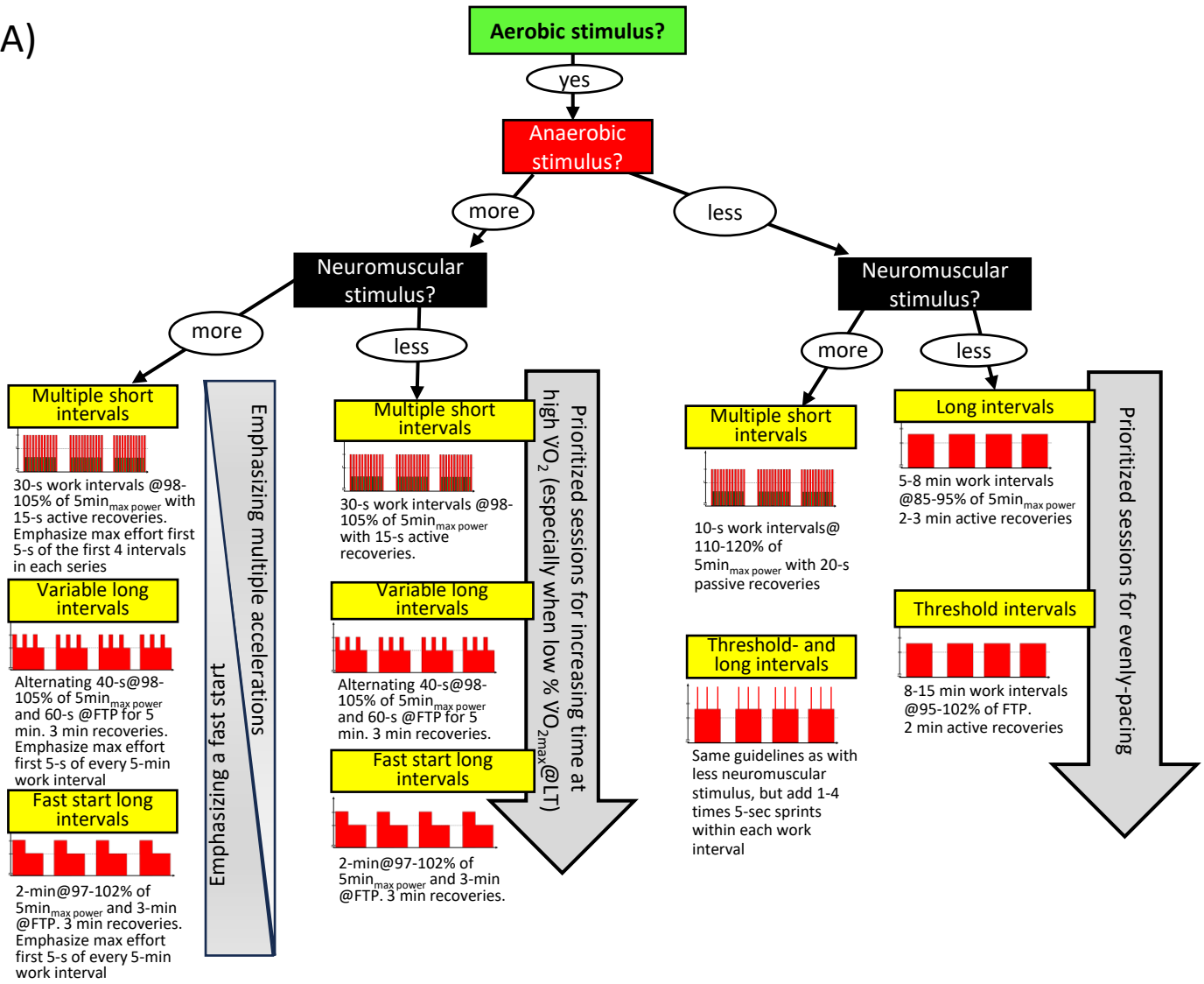
1 **Figure captions**

2 **Figure 1:** Time spent $\geq 90\%$ of maximal oxygen consumption (time $>90\% \dot{V}O_{2max}$) during interval sessions comparing i) series
3 of multiple short intervals (30/15-sec) with traditional evenly-paced work intervals (TRAD; group differences, $p=0.0007$), ii)
4 varied-intensity work intervals (VAR) with traditional evenly-paced work intervals (TRAD; group differences, $p=0.034$), iii)
5 work intervals with a fast start, i.e., declining exercise intensity (DEC), with traditional evenly-paced work intervals (TRAD;
6 group differences, $p=0.065$). All interval session comparisons were matched on mean power/velocity and duration of
7 interval series (multiple short intervals)/work intervals and consisted of 6x8 min cycling (black squares; Urianstad et al.,
8 2023), 5x5 min double pooling on roller skis (white triangles, Rønnestad et al., 2021), 6x5 min cycling (white circles, Bossi et
9 al., 2020), and 5x5 min skating on roller skis (black circles, Rønnestad et al., 2020). The only exception is the study of
10 Almquist et al. (2020) where only the short-interval work duration (30-sec) was included in the total work interval duration
11 (and not the 15-sec reliefs), ending in a total work interval duration of 19.5 min (3 series x 13x30-sec work/15-sec relief) that
12 was compared with a total of 20 min work interval duration (4x5 min, TRAD). The instruction was to aim for the highest
13 possible mean power output during all work intervals, which ended up with a higher work interval power during the 30/15-
14 sec intervals than during TRAD intervals (white squares and dotted lines, Almquist et al. 2020). Mean values are shown by
15 the columns.

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



A)



B)

Exercise Intensity

