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 (≥ 90% VO_{2max}) 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, in order 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 ($\dot{V}O_{2max}$; e.g., ≥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 $\dot{V}O_{2max}$ strains the O_2 delivery and utilization system, thereby serving as a potent physiological stimulus for increasing $\dot{V}O_{2max}$ 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 $\dot{V}O_{2max}$, a power output between 90 to 100% of maximal aerobic speed/power (MAS/MAP; i.e., the lowest speed/power that elicits $\dot{V}O_{2max}$) is recommended (Billat and Koralsztein 1996; Hill et al. 1997; Hill and Rowell 1997; Laursen and Jenkins 2002; Midgley and Mc Naughton 2006). Importantly, continuous work at MAS/MAP can only be sustained for ~4-7 minutes 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 ≥90%$\dot{V}O_{2max}$.

Usually, a continuous evenly-paced workload is used during long work intervals (interval sessions typically in the range of 4-6 x ~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 $\dot{V}O_{2max}$ of ~70 mL·min^{-1}·kg^{-1}, adopted a distinctive approach in their roller-ski intervals. They initiated each interval (5-6 x 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, rating of perceived exertion (RPE) (Rønnestad et al. 2020b, 2022a). However, only the study with the longest fast start (i.e. 2 min) induced a significant longer time above 90%$\dot{V}O_{2max}$ 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%$\dot{V}O_{2max}$. This observation finds further support in a study involving recreational cyclists (7 males, 1 female; $\dot{V}O_{2max}$ of 56 mL·min^{-1}·kg^{-1}). A relatively short total work interval duration (4x3 min) with a short fast start duration (1 min) showed no differences in time above 90%$\dot{V}O_{2max}$ 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. (2020b and 2022a).

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%$\dot{V}O_{2max}$ compared to both a long interval (3 min work – 2 min recovery) and a multiple short interval (30 sec work – 20 sec recovery) cycling protocol in middle-aged amateur cyclists with an average $\dot{V}O_{2max}$ of ~57 $mL \cdot min^{-1} \cdot kg^{-1}$ (Vaccari et al. 2020). Average time above 90%$\dot{V}O_{2max}$ was 312, 179 and 183 sec for the interval session with decreasing work interval durations, long intervals and multiple short intervals, respectively. Notably, two out of twelve participants achieved longer time above 90%$\dot{V}O_{2max}$ 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 $\dot{V}O_{2max}$ of 69 $mL \cdot min^{-1} \cdot kg^{-1}$) when a 6x5 min interval protocol with three 30-second 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 % of $\dot{V}O_{2max}$ and time ≥90%$\dot{V}O_{2max}$ during varied compared to evenly-paced work intervals (410 versus 286 sec, 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 $\dot{V}O_{2max}$ and longer time ≥90%$\dot{V}O_{2max}$ than evenly-paced work intervals (15.0 versus 13.2 min, respectively; p=0.03) (Rønnestad et al. 2022a). However, in contrast, Urianstad et al. (2023) showed that 6x8 min VAR intervals with alternating power outputs between 60-sec at 110% and 60-sec at 90% of 40-min maximal power output (60/60 intervals), did not provide any higher mean % of $\dot{V}O_{2max}$ or longer time ≥90%$\dot{V}O_{2max}$ (15.3 versus 14.7 min, respectively; p=0.89) than evenly-paced 6x8 min work intervals conducted at 100% of 40-min maximal power output in a group of well-trained cyclists (11 females, average $\dot{V}O_{2max}$ of 63 $mL \cdot min^{-1} \cdot kg^{-1}$; 8 males, average $\dot{V}O_{2max}$ of 81 $mL \cdot min^{-1} \cdot kg^{-1}$). 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 % of $\dot{V}O_{2max}$ (Christensen et al. 1960). Multiple short interval training sessions usually involves a series of 15–45 seconds 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_2 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 $\dot{V}O_{2max}$. In Almquist et al. (2020), well-trained male cyclists (average $\dot{V}O_{2max}$ of 74 mL/min/kg) completed 3 sets of 13x30-sec work intervals separated by 15-sec active recovery periods (30/15 intervals) where they achieved in average 14% higher power output, a higher $\dot{V}O_2$ and longer time ≥90%$\dot{V}O_{2max}$ (844 versus 589 sec, respectively) compared to evenly-paced 4x5-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-sec) were included in the total accumulated work interval duration, ending up with comparing 3x9.75 min 30/15 intervals with 4x5 min work intervals. However, similar findings were also observed when the 15-sec recovery periods of the 30/15 intervals were included in the total work interval duration and the mean power output was similar during 6x8 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 % of $\dot{V}O_{2max}$ and longer time ≥90%$\dot{V}O_{2max}$ compared to evenly-paced, but work- and duration-matched work intervals (18.7 versus 14.7 min, respectively; $p<0.01$). Interestingly, the findings of the latter study also suggest that for cyclists exhibiting lower fractional utilization of $\dot{V}O_{2max}$ at 4 mmol·L^{-1} [blood lactate], 30/15 intervals are particularly favorable for achieving a high % of $\dot{V}O_{2max}$ 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 $\dot{V}O_{2max}$ at 4 mmol/L [blood lactate] ($p<0.05$). Participants with the highest percentages of $\dot{V}O_{2max}$ 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 $\dot{V}O_{2max}$ at 4 mmol/L [blood lactate] (<80%) exhibited higher $\dot{V}O_2$ during 30/15 intervals compared to evenly-paced intervals.

Transferability of acute studies to training adaptations

Despite the popularity of quantifying mean % of $\dot{V}O_{2max}$ and time ≥90%$\dot{V}O_{2max}$, 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 & Bell (1986) where they stated that "the magnitude of change in $\dot{V}O_{2max}$ increases as exercise intensity increases from 50 to 100% of $\dot{V}O_{2max}$". Notably, this claim must be based solely on converting % of maximal heart rate or % of heart rate reserve to % of $\dot{V}O_{2max}$ 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 four-week training intervention in male recreational cyclists (average $\dot{V}O_{2max}$ of ~48 $mL \cdot min^{-1} \cdot kg^{-1}$), the interval session with the longest time at $\dot{V}O_{2max}$ also induced the largest gains in $\dot{V}O_{2max}$ (6.3 versus 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 $\dot{V}O_{2max}$ of 70 $mL \cdot min^{-1} \cdot kg^{-1}$) performed five interval sessions in a one-week interval block (Rønnestad et al. 2022b), there was a tendency to a positive correlation between the achieved time ≥90%$\dot{V}O_{2max}$ and improvement in $\dot{V}O_{2max}$ (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 5x8 min intervals) in a 9-week intervention period in 21 well-trained cyclists (3 females and 19 males; average $\dot{V}O_{2max}$ of 67 $mL \cdot min^{-1} \cdot kg^{-1}$). That study demonstrated that training adaptations, such as change in mean power output achieved during the last minute of an incremental test (p$\dot{V}O_{2max}$), power output at 4 $mmol \cdot L^{-1}$ [blood lactate], and $\dot{V}O_{2max}$, were positively related to the % of $\dot{V}O_{2max}$ during the sessions ($r^2_{adjusted}$=0.25-0.54, 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 % of $\dot{V}O_{2max}$ 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 Figure 1, we present individualized data from our lab comparing three main alternative interval sessions (VAR, DEC, and 30/15 intervals) with the traditional evenly-paced approach concerning time spent ≥90%$\dot{V}O_{2max}$.

Figure 1 here

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 13x30-sec work intervals separated by 15-sec active recovery periods) for 10 weeks exhibited significantly greater improvements in $\dot{V}O_{2max}$ and cycling performance compared to those following a regimen of 4x5 min evenly-paced intervals (Rønnestad et al. 2015). Specifically, $\dot{V}O_{2max}$ increased on average by 8.7% and 2.6% with 30/15 and 4x5 min intervals, respectively ($p \leq 0.05$). Similarly, the corresponding values for changes in $p\dot{V}O_{2max}$ 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 $\dot{V}O_{2max}$ of 73 $mL \cdot min^{-1} \cdot kg^{-1}$), and displayed that three weekly 30/15 interval sessions for three weeks also in that population resulted in greater performance enhancement than 4x5 min evenly-paced intervals (Rønnestad et al. 2020a), including larger improvement in 20-min maximal power output (4.7% versus -1.4%, $p<0.01$), $p\dot{V}O_{2max}$ (3.7% versus -0.3%, $p<0.05$) and power output at 4 $mmol \cdot L^{-1}$ [lactate] (2.0% versus -2.8%, $p<0.05$). Another study demonstrated that a 1-week microcycle with five 30/15 interval sessions (5x(12x30/15)) induced larger increments in $\dot{V}O_{2max}$ and power output at 4 $mmol \cdot L^{-1}$ [blood lactate] than five 6x5 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 Figure 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 display 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.

Figure 2 here

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Competing interests

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

Data availability

This article does not report new data.

References

Almquist, N.W., Nygaard, H., Vegge, G., Hammarström, D., Ellefsen, S., and Rønnestad, B.R. 2020. Systemic and muscular responses to effort-matched short intervals and long intervals in elite cyclists. Scand. J. Med. Sci. Sport. **30**(7): 1140–1150. doi:10.1111/sms.13672.

Åstrand, I., Åstrand, P.O., Christensen, E.H., and Hedman, R. 1960. Intermittent muscular work. Acta Physiol. Scand. **48**: 448–53. doi:10.1111/j.1748-1716.1960.tb01879.x.

Billat, L. V, and Koralsztein, J.P. 1996. Significance of the velocity at VO2max and time to exhaustion at this velocity. Sports Med. **22**(2): 90–108. doi:10.2165/00007256-199622020-00004.

Bossi, A.H., Mesquida, C., Passfield, L., Rønnestad, B.R., and Hopker, J.G. 2020. Optimizing interval training through power-output variation within the work intervals. Int. J. Sports Physiol. Perform. **15**(7): 982–989. doi:10.1123/ijspp.2019-0260.

Buchheit, M., and Laursen, P.B. 2013. High-intensity interval training, solutions to the programming puzzle: Part I: Cardiopulmonary emphasis. Sport. Med. **43**(5): 313–338. doi:10.1007/s40279-013-0029-x.

Christensen, E.H., Hedman, R., and Saltin, B. 1960. Intermittent and continuous running. (A further contribution to the physiology of intermittent work.). Acta Physiol. Scand. **50**: 269–86. doi:10.1111/j.1748-1716.1960.tb00181.x.

Comfort, P., and Matthews, M. 2010. Assessment and Needs Analysis. *In* Sports Rehabilitation and Injury Prevention. *Edited by* P. Comfort and E. Abrahamson. Wiley. pp. 39–63. doi:10.1002/9781118685150.ch3.

Gaitanos, G.C., Williams, C., Boobis, L.H., and Brooks, S. 1993. Human muscle metabolism during intermittent maximal exercise. J. Appl. Physiol. **75**(2): 712–719. doi:10.1152/jappl.1993.75.2.712.

Hawley, J.A. 2002. Adaptations of skeletal muscle to prolonged, intense endurance training. Clin. Exp. Pharmacol. Physiol. **29**(3): 218–22. doi:10.1046/j.1440-1681.2002.03623.x.

Hawley, J.A. 2008. Specificity of training adaptation: Time for a rethink? J. Physiol. **586**(1): 1–2. doi:10.1113/jphysiol.2007.147397.

Held, S., Rappelt, L., Giesen, R., Wiedenmann, T., Deutsch, J.P., Wicker, P., and Donath, L. 2023. Increased oxygen uptake in well-trained runners during uphill high intensity running intervals: A randomized crossover testing. Front. Physiol. **14**(February): 1–7. doi:10.3389/fphys.2023.1117314.

Hill, D.W., and Rowell, A.L. 1997. Responses to exercise at the velocity associated with VO2max. Med. Sci. Sports Exerc. **29**(1): 113–6. doi:10.1097/00005768-199701000-00016.

Hill, D.W., Williams, C.S., and Burt, S.E. 1997. Responses to exercise at 92% and 100% of the velocity associated with VO2max. Int. J. Sports Med. **18**(5): 325–329. doi:10.1055/s-2007-972641.

Joyner, M.J., and Coyle, E.F. 2008. Endurance exercise performance: the physiology of champions. J. Physiol. **586**(1): 35–44.

Laursen, P.B., and Jenkins, D.G. 2002. The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. Sports Med. **32**(1): 53–73. doi:10.2165/00007256-200232010-00003.

Laursen, P.B., Shing, C.M., and Jenkins, D.G. 2004. Temporal Aspects of the VO2 response at the power output associated with VO2peak in well trained cyclists—implications for interval training prescription. Res. Q. Exerc. Sport **75**(4): 423–428. doi:10.1080/02701367.2004.10609175.

Midgley, A.W., and Mc Naughton, L.R. 2006. Time at or near VO2max during continuous and intermittent running. A review with special reference to considerations for the optimisation of training protocols to elicit the longest time at or near VO2max. J. Sports Med. Phys. Fitness **46**(1): 1–14. Available from http://www.ncbi.nlm.nih.gov/pubmed/16596093.

Midgley, A.W., McNaughton, L.R., and Wilkinson, M. 2006. Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners? Empirical research findings, current opinions, physiological rationale and practical recommendations. Sport. Med. **36**(2): 117–132. doi:10.2165/00007256-200636020-00003.

Miller, P., Perez, N., and Farrell, J.W. 2023. Acute Oxygen Consumption Response to Fast Start High-Intensity Intermittent Exercise. Sports **11**(12): 238. doi:10.3390/sports11120238.

Odden, I., Nymoen, L., Urianstad, T., Hammarström, D., Mølmen, K.S., and Rønnestad, B.R. 2023. The higher fraction of V̇O2max during interval training, the greater gains in performance. J. Sci. Cycl. **12**(2): 62–64. Available from https://jsc-journal.com/index.php/JSC/article/view/810.

Rønnestad, B.R., Bakken, T.A., Thyli, V., Hansen, J., Ellefsen, S., and Hammarstrøm, D. 2022a. Increasing Oxygen Uptake in Cross-Country Skiers by Speed Variation in Work Intervals. Int. J. Sports Physiol. Perform. **17**(3): 384–390. doi:10.1123/ijspp.2021-0226.

Rønnestad, B.R., Bjerkrheim, K.A., Hansen, J., and Mølmen, K.S. 2022b. A 6-day high-intensity interval microcycle improves indicators of endurance performance in elite cross-country skiers. Front. Sport. Act. living **4**: 948127. doi:10.3389/fspor.2022.948127.

Rønnestad, B.R., and Hansen, J. 2016. Optimizing Interval Training at Power Output Associated With Peak Oxygen Uptake in Well-Trained Cyclists. J. Strength Cond. Res. **30**(4): 999–1006. doi:10.1519/JSC.0b013e3182a73e8a.

Rønnestad, B.R., Hansen, J., Nygaard, H., and Lundby, C. 2020a. Superior performance improvements in elite cyclists following short-interval vs effort-matched long-interval training. Scand. J. Med. Sci. Sport. **30**(5): 849–857. doi:10.1111/sms.13627.

Rønnestad, B.R., Hansen, J., Vegge, G., Tønnessen, E., and Slettaløkken, G. 2015. Short intervals induce superior training adaptations compared with long intervals in cyclists - an effort-matched approach. Scand. J. Med. Sci. Sports **25**(2): 143–51. doi:10.1111/sms.12165.

Rønnestad, B.R., Øfsteng, S.J., Zambolin, F., Raastad, T., and Hammarström, D. 2021. Superior physiological adaptations after a microcycle of short intervals versus long intervals in cyclists. Int. J. Sports Physiol. Perform. **16**(10): 1432–1438. doi:10.1123/IJSPP.2020-0647.

Rønnestad, B.R., Rømer, T., and Hansen, J. 2020b. Increasing Oxygen Uptake in Well-Trained Cross-Country Skiers During Work Intervals With a Fast Start. Int. J. Sports Physiol. Perform. **15**(3): 383–389. doi:10.1123/ijspp.2018-0360.

Thevenet, D., Tardieu-Berger, M., Berthoin, S., and Prioux, J. 2007. Influence of recovery mode (passive vs. active) on time spent at maximal oxygen uptake during an intermittent session in young and endurance-trained athletes. Eur. J. Appl. Physiol. **99**(2): 133–142. doi:10.1007/s00421-006-0327-1.

Turnes, T., de Aguiar, R.A., Cruz, R.S. de O., and Caputo, F. 2016. Interval training in the boundaries of severe domain: effects on aerobic parameters. Eur. J. Appl. Physiol. **116**(1): 161–169. Springer Berlin Heidelberg. doi:10.1007/s00421-015-3263-0.

Urianstad, T., Lorentzen, H.C., Odden, I., Mølmen, K.S., Hamarsland, H., and Rønnestad, B.R. 2023. Optimizing the high-intensity interval session through workload alterations in well-trained female and male cyclists. J. Sci. Cycl. **12**(2): 79–81. Available from https://jsc-journal.com/index.php/JSC/article/view/811.

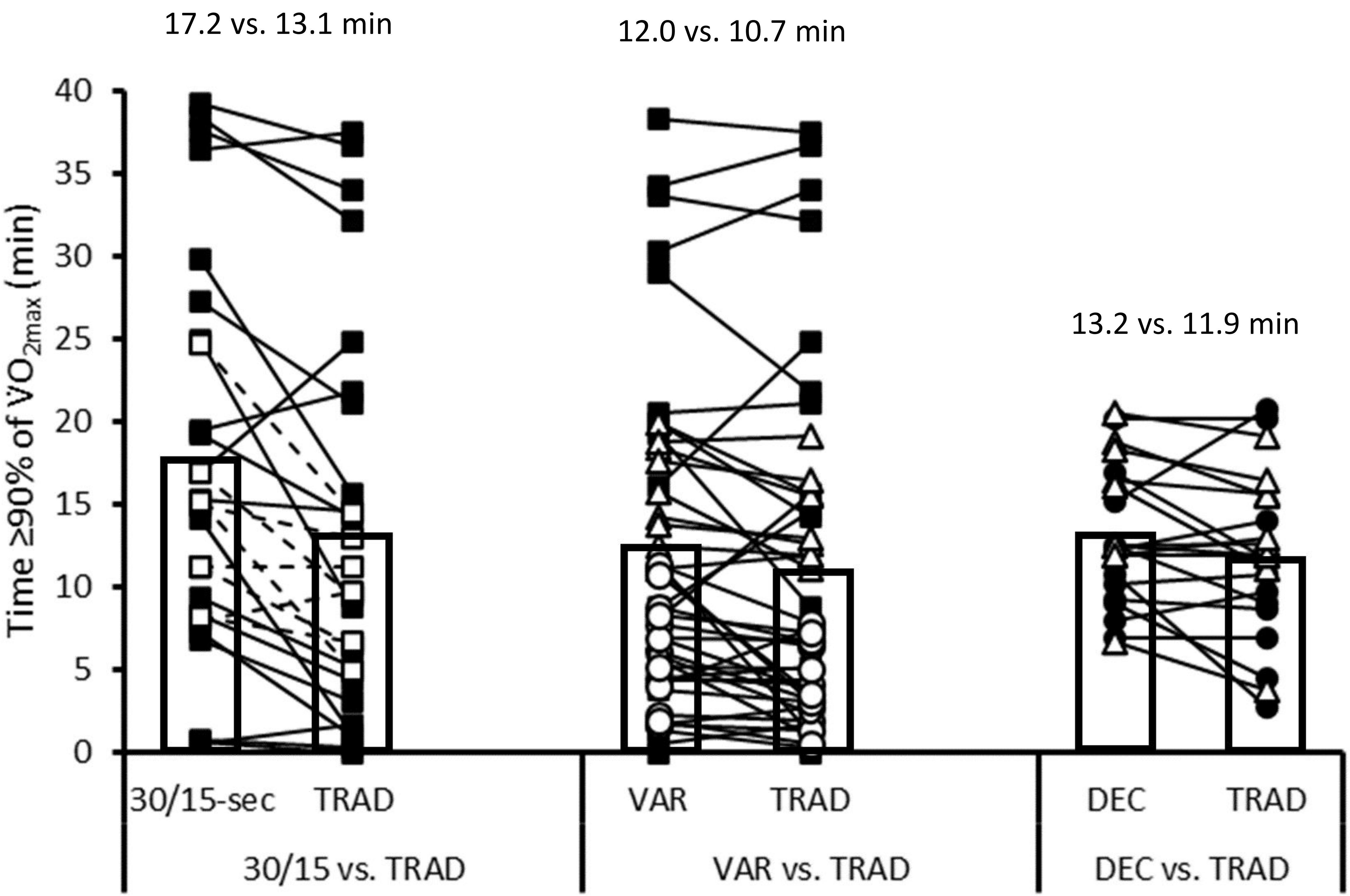
Vaccari, F., Giovanelli, N., and Lazzer, S. 2020. High-intensity decreasing interval training (HIDIT) increases time above 90% V˙ O2peak. Eur. J. Appl. Physiol. **120**(11): 2397–2405. Springer Berlin Heidelberg. doi:10.1007/s00421-020-04463-w.

Wenger, H.A., and Bell, G.J. 1986. The Interactions of Intensity, Frequency and Duration of Exercise Training in Altering Cardiorespiratory Fitness. Sport. Med. **3**(5): 346–356. doi:10.2165/00007256-198603050-00004.

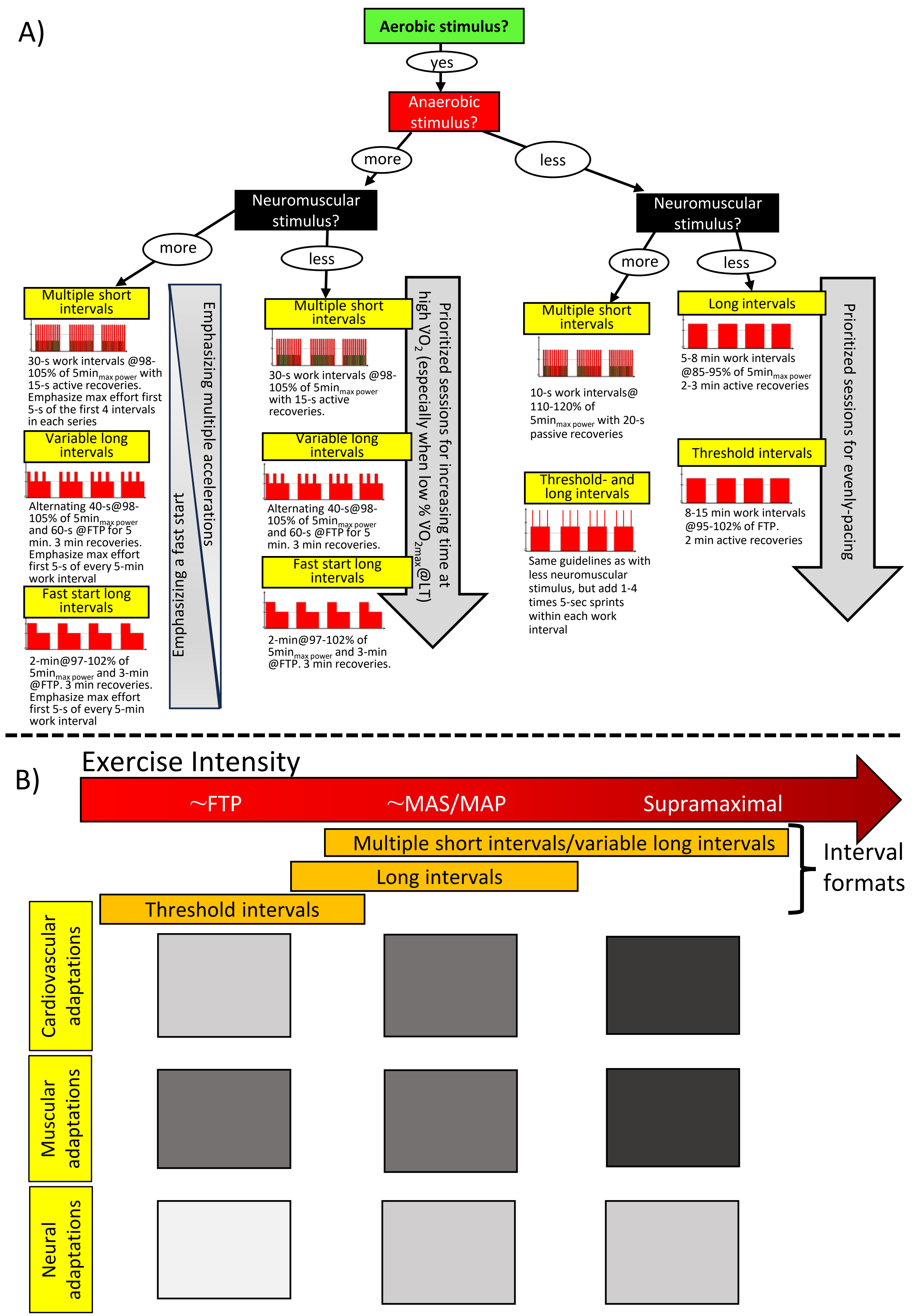
Figure captions

Figure 1: Time spent ≥90% of maximal oxygen consumption (time >90%$\dot{V}O_{2max}$) during interval sessions comparing i) series of multiple short intervals (30/15-sec) with traditional evenly-paced work intervals (TRAD; group differences, p=0.0007), ii) varied-intensity work intervals (VAR) with traditional evenly-paced work intervals (TRAD; group differences, p=0.034), iii) work intervals with a fast start, i.e., declining exercise intensity (DEC), with traditional evenly-paced work intervals (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 6x8 min cycling (black squares; Urianstad et al., 2023), 5x5 min double pooling on roller skis (white triangles, Rønnestad et al., 2021), 6x5 min cycling (white circles, Bossi et al., 2020), and 5x5 min skating on roller skis (black circles, Rønnestad et al., 2020). The only exception is the study of Almquist et al. (2020) where only the short-interval work duration (30-sec) was included in the total work interval duration (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 was compared with a total of 20 min work interval duration (4x5 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-sec intervals than during TRAD intervals (white squares and dotted lines, Almquist et al. 2020). Mean values are shown by the columns.

Figure 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 1h); MAS/MAP, maximal aerobic 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.



17.2 vs. 13.1 min
12.0 vs. 10.7 min
13.2 vs. 11.9 min
Time ≥90% of VO2max (min)
0
5
10
15
20
25
30
35
40
30/15-sec
TRAD
VAR
TRAD
DEC
TRAD
30/15 vs. TRAD
VAR vs. TRAD
DEC vs. TRAD



A)
Aerobic stimulus?
yes
Anaerobic stimulus?
more
less
Neuromuscular stimulus?
more
less
Multiple short intervals
30-s work intervals @98-105% of 5min$_{max\ power}$ with 15-s active recoveries. Emphasize max effort first 5-s of the first 4 intervals in each series
Variable long intervals
Alternating 40-s@98-105% of 5min$_{max\ power}$ and 60-s @FTP for 5 min. 3 min recoveries. Emphasize max effort first 5-s of every 5-min work interval
Fast start long intervals
2-min@97-102% of 5min$_{max\ power}$ and 3-min @FTP. 3 min recoveries. Emphasize max effort first 5-s of every 5-min work interval
Emphasizing multiple accelerations
Emphasizing a fast start
Multiple short intervals
30-s work intervals @98-105% of 5min$_{max\ power}$ with 15-s active recoveries.
Variable long intervals
Alternating 40-s@98-105% of 5min$_{max\ power}$ and 60-s @FTP for 5 min. 3 min recoveries.
Fast start long intervals
2-min@97-102% of 5min$_{max\ power}$ and 3-min @FTP. 3 min recoveries.
Prioritized sessions for increasing time at high VO_2 (especially when low % VO_{2max} @LT)
Neuromuscular stimulus?
more
less
Multiple short intervals
10-s work intervals@ 110-120% of 5min$_{max\ power}$ with 20-s passive recoveries
Threshold- and long intervals
Same guidelines as with less neuromuscular stimulus, but add 1-4 times 5-sec sprints within each work interval
Long intervals
5-8 min work intervals @85-95% of 5min$_{max\ power}$ 2-3 min active recoveries
Threshold intervals
8-15 min work intervals @95-102% of FTP. 2 min active recoveries
Prioritized sessions for evenly-pacing
B)
Exercise Intensity
~FTP
~MAS/MAP
Supramaximal
Multiple short intervals/variable long intervals
Long intervals
Threshold intervals
Interval formats
Cardiovascular adaptations
Muscular adaptations
Neural adaptations