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Review

The effect of training distribution, duration, and volume on VO_{2max} and performance in trained cyclists: A systematic review, multilevel meta-analysis, and multivariate meta-regression

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ABSTRACT

Objective: This study aimed to systematically investigate whether polarized or non-polarized training leads to greater physiological and performance adaptations in cyclists.
Design: A systematic review and meta-analysis were conducted, focusing on interventions categorized as polarized, non-polarized, or unclear. Inclusion criteria required participants to be at least recreationally trained cyclists (VO_{2max} ≥ 59 ml/kg/min) and interventions lasting > 4 weeks.
Methods: A multi-level random-effects meta-analysis using restricted maximum likelihood estimation was performed. A multivariate meta-regression assessed associations between training volume, VO_{2max}, and time-trial performance.
Results: Forty-one studies, comprising 81 training groups and 797 participants, were included. Training significantly improved VO_{2max} across all groups ($g = 0.42$, 95 % confidence interval = 0.31–0.53, $P \leq 0.001$) and time-trial performance ($g = 0.39$, 95 % confidence interval = 0.25–0.53, $P \leq 0.001$), with no significant differences between training modalities ($P > 0.05$). Longer intervention durations positively influenced VO_{2max} ($g = 0.03$, 95 % confidence interval = 0.02–0.05, $P < 0.001$) and time-trial performance ($g = 0.04$, 95 % confidence interval = 0.03–0.06, $P < 0.001$). No associations were found between weekly or total training volume and changes in VO_{2max} or time-trial performance.
Conclusions: Polarized and non-polarized training modalities yield comparable improvements in VO_{2max} and time-trial performance in trained cyclists. Beyond achieving a necessary training volume, further increases do not appear to enhance performance. These findings encourage athletes and coaches to prioritize effective training distribution rather than fixating on total volume or a specific model
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Practical implications

When considering training intensity distribution selection in trained cyclists, it is likely that any combination of structured training will improve VO_{2max}, with POL offering a potential benefit over other modalities. However, while uncertain, POL may be less suitable for improving TT performance. The results of this review also emphasize that caution must be taken in relation to total training volume as increased training volume may not cause notable increases in VO_{2max} and TT performance, especially in well-trained athletes. As such, coaches and athletes should consider a balance between volume and intensity to optimize performance.

1. Introduction

High level cyclists are known to perform extremely high training volumes to increase performance.[1] As such, there is a need to optimally manipulate training variables to maximize performance adaptations while maintaining high volumes of training. One method used by athletes to manipulate training is to alter the distribution of training intensity across preestablished training zones with a common approach being polarized (POL) training distribution.[2–4] The POL training approach has classically been described whereby an athlete spends ~80 % of their training time in the lower-intensity (moderate) zone and ~20 % at the very high-intensity (severe) zone, with a limited amount of time spent in the middle (heavy) intensity zone.[5] However, the effectiveness of POL and many other forms of training intensity distribution manipulation to improve performance has

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been challenged in recent years.[2] Indeed an influential review paper by Seiler demonstrated that emphasizing high intensity interval training (HIIT) in this population may not lead to performance improvements, questioning the efficacy of intensity focused training distributions.[5] While systematic and narrative reviews have attempted to ascertain which modality of training is optimal for maximizing performance in endurance athletes more broadly, they offer limited insight for cyclists.[2–4] Previous reviews have often combined studies using various sports such as running, swimming, skiing, cycling or a combination thereof, with conflicting outcomes that may not be relevant to cycling and its specific physiological demands.[2–4] A systematic review by Rosenblat et al.[3] compared POL to threshold training intensity distribution on endurance performance and reported that POL was moderately (ES = −0.66) more beneficial than threshold on time trial (TT) performance. However, this analysis was limited to four studies, with one study using a cyclist exclusive cohort.[3] In addition, a systematic review and meta-analysis by Rosenblat et al.[6] reported that both high intensity interval training and sprint interval training (SIT) were beneficial at improving time trial (TT) performance. More recently, Galán-Rioja et al.[2] performed a narrative review on training intensity distribution, volume, and periodization models in elite cyclists and stated that no clear evidence is currently available to suggest a POL training model is optimal in trained road cyclists for improving performance. However, these results must be taken with caution as Galán-Rioja et al. did not perform a meta-analysis due to cited logistical complexities comparing different modalities of training within athlete groups.[2] Finally, it is also important to note that studies included in previous reviews have often included untrained, sedentary, or recreationally trained individuals, which limits the relevance for elite and competitive athletes due to differences in the capacity for improvement between these cohorts.[7,8] Given the growing yet speculative debate concerning POL and NP training intensity distribution, the present review's purpose was to systematically investigate and perform a meta-analysis on the effects of POL and NP interventions on physiological and performance adaptations in trained cyclists.[9,10]

2. Methods

This systematic review and meta-analysis was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines.[11] The protocol for this review was registered on the Open Science Framework (https://osf.io/469gp/?view_only=cdc35f8c985340e8879511118fdee161).

2.1. Search strategy

A systematic search of three databases (PubMed, Web of Science, Ovid) was conducted on the 23rd of October 2023 to identify all relevant studies assessing the effect of various training distributions on aerobic fitness and performance. Full-text articles published in peer-reviewed literature in English between inception and 23rd October 2023 were included. The search strategy was created with assistance from an academic librarian, and is presented in Supplementary digital content, Table 1. Database search results were exported to Endnote© (version 22.1, Thomson-Reuters, Toronto, CA, USA) for removal of duplicates, and then uploaded to Covidence© Systematic Review Software (Veritas Health Innovation, Melbourne, VIC, Australia). The titles and abstracts were independently screened by two authors (BC and MA). Full texts of potentially eligible articles were then screened by the same two authors to determine their final inclusion–exclusion status. Any disagreement between the two authors was resolved by a third author (HB or SC), and the reference lists of all eligible articles were searched to retrieve any additional studies.

2.2. Inclusion criteria

Inclusion criteria were as follows: (1) peer reviewed and published in the English language, (2) participants were classified as Tier-3 (highly trained/national level) or above level of cyclists as reported by McKay et al.,[12] and (3) any study design that reported pre- and post-training assessments of maximal aerobic fitness (i.e., VO_{2max} or VO_{2peak}) or aerobic performance (i.e., TT performance). The Tier 3 classification by McKay et al.[12] includes a description that athletes achieve within ~20 % of world-leading performance. In the instances that this was required to be consulted, the average VO_{2max} of participants within a particular study was required to be within 20 % (males: ≥59.0 ml/kg/min, females: ≥54.4 ml/kg/min) of world-level values that were described by Haugen et al.[13] Studies were included in the analysis even if they aimed to determine the effectiveness of ergogenic aids (such as altitude masks or dietary manipulation). However, for the purpose of this review, the control group (i.e., without the addition of the ergogenic aid) data from these studies were extracted, ensuring a focus on the effects of training interventions without potential known confounding factors.

2.3. Data extraction

Data were extracted by author BC and entered to an Excel spreadsheet (Microsoft Corporation, Albuquerque, NM, USA). 20 % of these data were independently cross-checked by author MA and no discrepancies were reported. Where data were unavailable in text or table format, the corresponding author of the included study was contacted via email to retrieve the data. Where study data were unavailable or the corresponding author did not respond within two weeks to the original email, data were extracted from relevant graphs using Web Plot Digitizer (v4.4, Ankit Rohatgi, Pacifica, CA, USA). The extracted information included publication details, author information, publication date and location, study participant characteristics, sample size, age, sex, height, body mass, competition level and trial intervention frequency, intensity, time, and relevant training outcomes (VO_{2max}, TT).

2.4. Study classification

To determine the effect of training distribution on relevant training outcomes, studies were classified based on the type of intervention they employed, which included polarized (POL), non-polarized (NP), or those with an unclear classification (NC). For the purpose of this review, to qualify as a polarized (POL) study, interventions needed to meet two criteria: First, they had to report a component of training that consisted of low-intensity, long-duration (LIT) or habitual training. Second, the intervention had to utilize high intensity intervals of less than 5 min at a reported highest possible sustainable intensity or above the Maximal Lactate Steady State. If the prescribed intervals were longer than 5 min, the studies were categorized as NP due to the potential for submaximal levels of intensity. Moreover, longer intervals (>5 min) generally yield a mixed aerobic stimulus, often resulting in submaximal intensity work that aligns more closely with NP or threshold-type distributions. Conversely, studies that did not incorporate or failed to report training intensity distribution with sufficient detail were categorized as NC.

2.5. Certainty of evidence

The certainty of evidence was independently assessed by two authors (BC and HB) using the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) quality rating analysis.[14] Studies examining the effect of cycling training on VO_{2max}, and time trial performance were assessed separately. The certainty of evidence was categorized as high, moderate, low, or very low. Since more than 25 %

of the included studies were non-randomized controlled trials, the certainty of evidence started as low. Certainty was determined by the confidence in the effect estimate and adjusted based on limitations in study design or execution, inconsistency of results, indirectness of evidence and imprecision. Certainty was downgraded if: >25 % of participants included were from studies identified as having a high risk of bias; where $I^2 > 50$ % (i.e., considerable heterogeneity present) (inconsistency of results); there were significant differences in training cohorts, outcomes measured, or interventions used between studies (indirectness); data from <400 participants per outcome were analyzed (imprecision), and Egger's test was significant (publication bias).[15] Conversely, the certainty of evidence was upgraded by a level if each of the following criteria was met: large magnitude of effect (i.e., $g > 0.8$) and the presence of a dose–response.[14]

2.6. Quality assessment and risk of bias

The methodological quality and risk of bias assessment of the included studies were independently evaluated by two authors (BC and MA) using the Scottish Intercollegiate Guidelines Network (SIGN) for Randomized Controlled Trials risk of bias checklist.[16] SIGN was used as it is a well-established risk of bias tool and was well-suited to review the specific field of papers. Definitions of each appraisal item were agreed upon by the reviewers prior to commencing assessment. Any discrepancies were resolved by a discussion among authors.

2.7. Data analysis

Data handling was performed as per the Cochrane Handbook guidelines.[17] Where extracted data was expressed using the standard error of the mean (SEM), conversion to standard deviation (SD) was performed using the following formula: (SD = SE * sqrt(n)); where n represents the sample size of the group. A Pooled/Delta SD was also calculated.[18]

Quantitative synthesis of data was performed with the 'metafor,' 'clubSandwhich,' and 'rms' packages in R, with plots produced using the 'ggplot2' package (version 4.3.1; R Core Team, https://www.r-project.org/). For each group within the accepted studies, the mean and SD of pre to post changes of outcome measures (VO_{2max} and TT performance) were retrieved. If the SD of the change was not reported, the value was estimated according to recommendations in the Cochrane handbook, using the pre- and post-SD values via the following formula, whereby a conservative correlation of 0.5 was assumed to minimize the likelihood of overstating the intervention effect[17]:

$$\text{SDchange} = \sqrt{\left(\text{SD}^2\text{baseline} + \text{SD}^2\text{post}\right)} - (2 \times \text{Correlation} \times \text{SDbaseline} \times \text{SDpost}).$$

Standardized mean differences (SMDs) were then calculated by dividing the mean difference by the estimate of the change, where the mean difference was calculated as the mean pre–post change in the stretching group minus the mean pre–post change in the control group. Hedges *g* correction was then applied to the SMD to adjust for small sample bias.[19] To account for dependency between effect sizes, a multilevel random-effects model was conducted using a restricted maximum likelihood estimation with robust variance estimation (RVE). Unlike traditional meta-analyses, which require independence of effect sizes, the use of a multilevel meta-analysis accounted for dependency by fitting the study as a random factor in the model, while the RVE allows better estimation of the uncertainty surrounding the effect size estimates.[20] The multilevel model was used to estimate an overall effect size for all included studies, and for the three training distribution types (POL, NP, NC). Effect sizes were interpreted as trivial ($g < 0.2$), small ($g = 0.2$–0.49), medium ($g = 0.5$–0.79), and large ($g = >0.8$).[21] The Q and I^2 statistics were used to analyze statistical heterogeneity within each meta-analysis and indicated the consistency of effect sizes between the included studies.[21] Statistical heterogeneity was considered low ($I^2 < 25$ %), moderate ($I^2 =$ 25–49 %) or high ($I^2 > 50$ %).[21] Publication bias was visualized by funnel plots and examined using Egger's test. Any individual training groups included in the analysis with absolute standardized residuals >2 were considered as outliers, and a sensitivity analysis was conducted in which meta-analyses were repeated with outliers removed to determine their influence.

Additional analysis was conducted to determine whether intervention duration influenced the results of the primary analysis, whereby intervention duration in weeks was included as a continuous predictor variable. Finally, an exploratory multivariate meta regression of all studies was conducted to explore the relationship between weekly and total training volume (hours) and changes in VO_{2max} and TT performance. For this analysis, study ID was included as a random effect to account for dependency.

3. Results

3.1. Search results

Fig. 1 provides a detailed flow diagram of the literature search and screening process. The search identified 4048 potentially relevant articles. After deduplication 2921 articles remained. Title and abstract screening resulted in 211 full-text papers for assessment. Of these, 41 articles met the criteria and were included in the study.

3.2. Study characteristics

Study characteristics are presented in Table 1. In brief, 81 individual training groups and 797 participants met the inclusion criteria and were included in this systematic review and meta-analysis. Of the studies, 23 were randomized controlled trials, with the remaining 21 being non-randomized. The average baseline VO_{2max} was 60.4 ± 4.8 ml/kg/min (range: 54.0–69.1) and the average duration of the interventions was 8.3 ± 4.9 weeks (range: 4–24). 26 studies containing 43 groups reported training volume with sufficient detail to be included in the multivariate meta regression and had an average weekly training volume of 4.9 ± 7.3 (range: 2.6–14.3) h, and an average total training volume of 75.2 ± 71.2 (range: 10.4–301.6) h. Of the 41 included studies, 36 (686 participants) examined VO_{2max} as an outcome measure, while 28 (with 431 participants) examined time trial performance. Lastly, of the 81 individual training groups, 26 were categorized as POL, 28 as NP, and 27 as NC.

3.3. Risk of bias results

No study qualified for high-quality classification in the SIGN assessments. Thirty-seven (84 %) studies were classified as being of acceptable, and seven (16 %) were classified as low quality. The most common issues identified from the risk-of-bias assessment were a lack of participant or assessor blinding and poor participant dropout reporting. Individual results of the risk of bias separated by category can be found in Supplemental digital content, Table 3.

3.4. Effect of training distribution on VO_{2max}

A total of 68 groups from 38 studies included VO_{2max} as an outcome measure and were included in the multilevel meta-analysis. Of these, 23 groups were categorized as POL, 24 as NP, and 21 as NC. There was a significant effect of training on VO_{2max} for all groups combined ($g = 0.42$, 95 % CI = 0.34, 0.54; P ≤ 0.001; *small effect*; Q(df = 67) = 59.9, P =

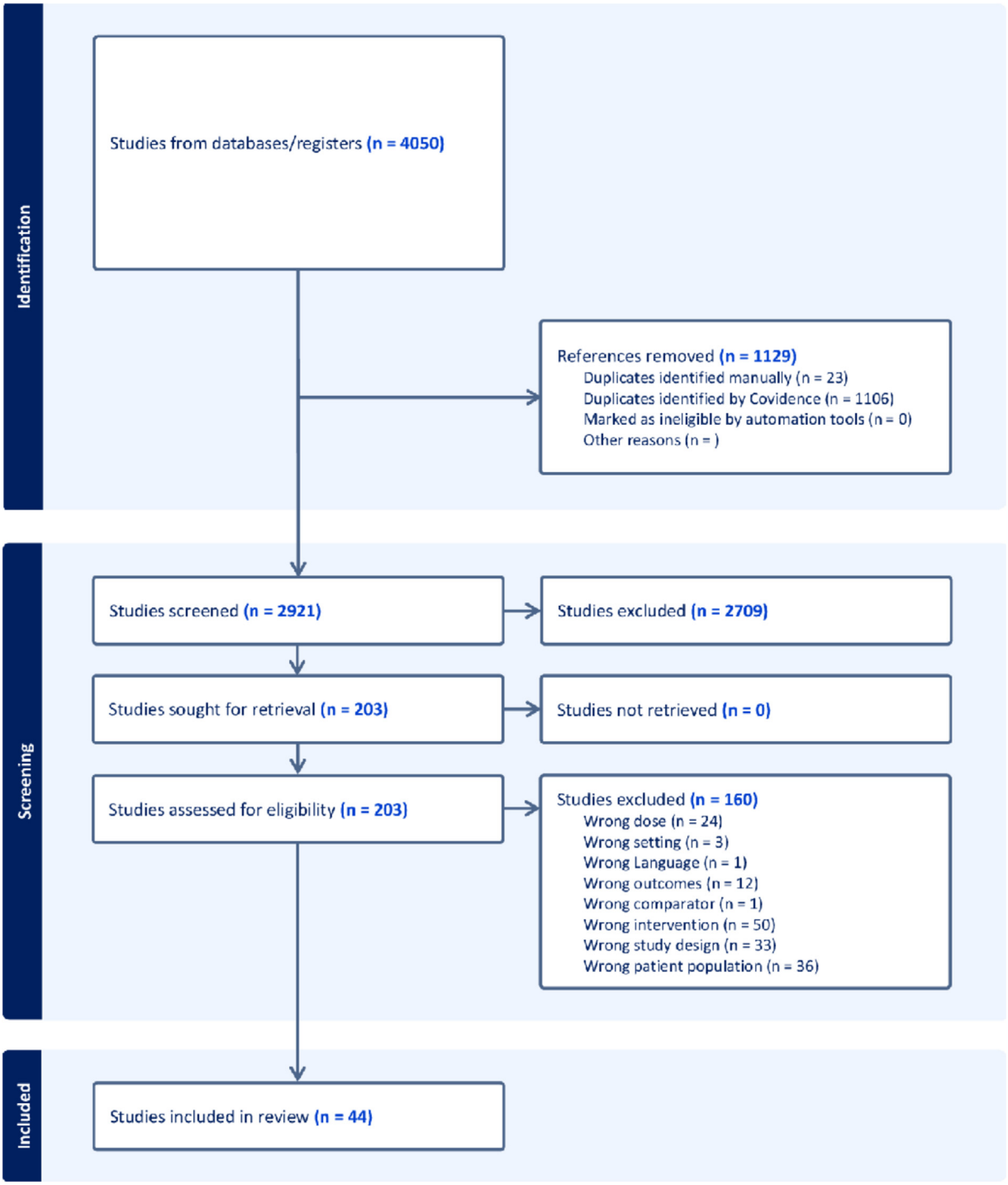


Fig. 1. PRISMA flowchart for screening of articles.

0.717; $I^2 = 3.01$ %), as well as POL ($g = 0.52$, 95 % CI = 0.32, 0.73; $P < 0.001$; *medium effect*; Q(df = 22) = 18.7, P = 0.666; $I^2 = 0.00$ %), NP ($g = 0.38$, 95 % CI = 0.19, 0.57; P = 0.001; *small effect*; Q(df = 23) = 18.3, P = 0.741; $I^2 = 0.00$ %), and NC ($g = 0.34$, 95 % CI = 0.08, 0.61; P = 0.017; *small effect*; Q(df = 20) = 21.1, P = 0.389; $I^2 = 10.25$ %) groups in isolation. Forest plots of VO_{2max} analysis can be found in Supplementary digital content Figs. 1, 3, 4, and 5. Multilevel meta-analysis indicated there were no significant differences between any of the training distribution groups and changes in VO_{2max} (Table 2). There was a positive association observed between intervention duration in weeks and improvements in VO_{2max} ($g = 0.03$, 95 % CI = 0.01, 0.06, P = 0.008; *trivial effect*; QE(df = 67) = 77.0, P = 0.190; $I^2 = 23.79$ %).

Inspection of funnel plots (Fig. 7) and results of Egger's test suggested publication bias was unlikely (intercept = 0.26, P = 0.414). Evaluation of standardized residuals identified two outliers (Hebisz et al.[36] and Laursen et al.[27]). Following the removal of outliers, the magnitude of training on VO_{2max} reduced slightly ($g = 0.39$, 95 % CI = 0.28, 0.51, $P < 0.001$), with negligible between-study heterogeneity (Q(df = 65) = 50.5, P = 0.907; $I^2 = 0.00$ %).

Table 1
Study demographics.

Studies	Participant characteristics (mean ± SD)	Categorization N=	Intervention	Outcomes and results
Almquist et al.[22]	30 highly trained cyclists (age: 35 ± 12 years, mass: 83 ± 2 kg).	NP (n = 14)	Block 3 × 4 week blocks: Week 1: 4 * MIT. Week 2: 3 * LIT. Week 3: 4 * HIIT, Week 4: deload. HIT sessions consisted of 5 min maximal sustainable intervals, MIT = 12 min	VO_{2max}: ↑ 54.0 ± 14 to 58.6 ± 6.73 mL/kg/min. TT: 3.33 ± 0.56 to 3.5 ± 0.6 W/kg
	Age: 40 ± 12 years, mass: 79 ± 8 kg.	NP (n = 16)	Traditional performed 3 * 4 week blocks. HIT, MIT, and LIT sessions distributed throughout the first 3 weeks.	VO_{2max}: ↑ 59.3 ± 8.1 to 61.2 ± 7.3 mL/kg/min. TT: 3.4 ± 0.5 to 3.6 ± 0.5 W/kg
Creer et al.[23]	17 recreationally trained cyclists with ≥2 years of cycling training experience (age: 25 ± 2 years, mass: 69 ± 5 kg).	POL (n = 10)	SIT group performed two controlled sessions per week of 4 * 30 s all-out sprints, each separated by 4 min at 50 W. Two additional intervals were added each week (a total of 10 sprints per session by week 4).	VO_{2max}: ↑ 4.0 ± 0.4 to 4.2 ± 0.4 L·min
	CON (age: 24 ± 0 years, mass: 68 ± 5 kg).	NP (n = 7)	Cyclists performed a total of 28 min of SIT over the intervention. Cyclists were only required to maintain pre-intervention endurance levels	VO_{2max}: 4.1 ± 0.5 to 4.2 ± 0.4 L·min
Hebisz and Hebisz [24]	24 trained cyclists with >3 year experience. SIT + HIIT + CET (age: 21 ± 7 years, mass: 69 ± 6 kg).	POL (n = 12)	SIT + HIIT + ET performed: SIT = 4 × 4 (30 s active rest). HIIT = 5–7 * 4 min. ET = 120–180 min at intensities of SIT = all out. HIIT = 85–95 % MAP. ET 55–60 % MAP for a total of 10–13 h per week	VO_{2max}: ↑ 62.3 ± 6.4 to 66.3 ± 5.3 mL/kg/min
	HIIT + CET (age: 20 ± 8 years, mass: 70 ± 8 kg).	POL (n = 12)	As SIT + HIT + ET however no SIT was performed.	VO_{2max}: ↑ 59.6 ± 8.4 to 61.2 ± 10.1 mL/kg/min
Hebisz et al.[25]	26 national level cyclists (age: 18 ± 1 years, mass: 62 ± 8 kg).	POL (n = 13)	Both POL and BP performed the same interval sessions of SIT = 4 * 4 (30 s rest). HIIT = 5–7 * 4 min. SIT intensity = all out. HIIT intensity = 90 % MAP. The BT group alternated between 17-day mesocycles consisting of LIT and 11-day blocks consisting of training SIT, and HIIT, while the POL group performed SIT, HIIT, and LIT simultaneously.	VO_{2max}: ↑ 60.0 ± 4.8 to 63.6 ± 4.3 mL/kg/min
	POL (age: 18 ± 1 years, mass: 63 ± 8 kg)	POL (n = 13)		VO_{2max}: ↑ 57.5 ± 5.8 to 65.3 ± 8.7 mL/kg/min
Hebisz et al.[26]	25 well trained cyclists (age: 18 ± 4 years, mass: 66 ± 9 kg)	POL (n = 12)	Both groups performed the same intervention: SIT = 2 * (3–4 * 4 * 30 s). (HIIT = 5–7 * 5 min) * 2 weekly. 2 * CET. Intensity: SIT = all out. HIIT = 85–95 % MAP. CET = 55–60 % MAP.	VO_{2max}: ↑ 58.9 ± 5 to 64.5 ± 6.8 mL/kg/min
	CON (age: 20 ± 5 years, mass: 66 ± 11 kg)	POL (n = 13)	The CON group did not partake in SIT.	VO_{2max}: 54.4 ± 8.2 to 56.7 ± 8.7 mL/kg/min
Laursen et al.[27]	41 trained male cyclists, with ≥3 years of training experience (age: 25 ± 6 years, mass: 75 ± 7 kg).	NC (n = 8)	Cyclists trained 2× week. Each interval session contained 8 bouts at MAP, for a work duration of 60 % of the time to exhaustion at MAP, with a 1:2 recovery ratio	VO_{2max}: ↑ 5.00 ± 0.52 to 5.26 ± 0.47 L·min TT: ↑ 42.2 ± 2.4 to 44.4 ± 2.8 kph
		NC (n = 9)	Cyclists trained 2 * PW. The intervention in this group was the same as Short-HIIT1, except that recovery duration was dependent on HR returning to 65 % HRmax	VO_{2max}: ↑ 4.89 ± 0.38 to 5.28 ± 0.35 L·min TT: ↑ 41.4 ± 2.5 to 43.7 ± 2.4 kph
		NC (n = 10)	Cyclists trained 2× per week. SIT performed 12 * 30 s efforts at 175 % PPO, with 4.5 min of recovery between bouts	VO_{2max}: ↑ 4.91 ± 0.37 to 5.06 ± 0.46 L·min TT: ↑ 41.9 ± 2.6 to 43.7 ± 2.1 kph
		NP (n = 11)	Participants were asked to continue with their LIT/MIT training program	VO_{2max}: 65 ± 5.9 to 68.8 ± 4.1 mL/kg/min TT: 41.8 ± 1.4 to 41.4 ± 1.5 kph
Rønnestad et al.[28]	Trained cyclists, with ≥3 years of training experience (age: 30 ± 7 years, mass: 76 ± 6 kg).	NP (n = 10)	BP group conducted a one-week block of 5 HIIT sessions, followed by a 3-week period of one HIIT session PW and a high volume of LIT	VO_{2max}: ↑ 62 ± 2 to 65 ± 2.3 mL/kg/min
	TRAD (age: 32 ± 6 years, mass: 76 ± 7 kg).	NP (n = 9)	TRAD: performed 2 * HIIT PW through intervention alternating between 5 * 6 and 6 * 5 min intervals > LT2, interspersed with relatively high vol of LIT	VO_{2max}: 63 ± 2 to 63 ± 4 mL/kg/min
Rønnestad et al.[29]	Trained cyclists, with ≥3 years of training experience (age: 32 ± 7 years, mass: 76 ± 7 kg).	NP (n = 8)	BP group conducted a one-week block of 5 HIIT sessions, followed by a 3-week period of one HIIT session PW and a high volume of LIT	VO_{2max}: ↑ 62 ± 4.7 to 68 ± 5 mL/kg/min TT: ↑ 3.71 ± 0.38 to 4.00 ± 0.31 W/kg
	Age: 34 ± 6 years, mass: 78 ± 7 kg.	NP (n = 7)	TRAD: performed 2 * HIIT PW through intervention alternating between 5 * 6 and 6 * 5 min intervals > LT2, interspersed with relatively high volume of LIT	VO_{2max}: ↑ 62 ± 4.9 to 66 ± 4 mL/kg/min TT: ↑ 3.98 ± 0.31 to 4.14 ± 0.3 W/kg
Hebisz et al.[30]	24 trained cyclists. SIT + HIIT1 (age: 21 ± 6 years, mass: 70 ± 9 kg).	POL (n = 10)	Cyclists performed HIIT (once a week), SIT (2 * PW) and MIT concomitantly (2 * PW). HIIT sessions involved 5–7 repetitions of 5 min at an intensity of 85–95 % MAP, with 10–15 min of recovery between intervals at 45–50 % MAP. SIT sessions consisted of 3–4 sets of 4 * 30-s all-out repetitions with 90 s recovery ≤ 30 W between repetitions. Recovery between sets lasted 25 min at ≤50 % MAP. MIT sessions lasted 120–180 min, performed at 70–80 % HRmax. Weekly training volume was 11–13 h, apart from every fourth	VO_{2max}: ↑ 57.4 ± 3.4 to 63.5 ± 6.1 mL/kg/min

(continued on next page)

Table 1 (*continued*)

Studies	Participant characteristics (mean ± SD)	Categorization N=	Intervention	Outcomes and results
			week in which volume decreased by ~50 %	
	SIT + HIIT2 (age: 21 ± 4 years, mass: 67 ± 8 kg).	POL (n = 7)	Cyclists had a low-volume, high-intensity training background (7–9 h week). The 8-week intervention followed the same structure and volume as SIT + HIIT1.	VO_{2max}: ↑ 58.6 ± 5.9 to 63.6 ± 3.9 mL/kg/min
	Age: 20 ± 4 years, mass: 68 ± 9 kg.	NP (n = 7)	Training consisted of high-volume cycling at moderate intensities (14–16 h week). Cyclists performed both varied-intensity training and MIT. Varied-intensity training sessions were held 2 * PW and followed a sequence of several minutes at 65–70 %, followed by 80–85 % and then 70–80 % HRmax repeated multiple times for 120–180 min. MICT sessions were identical to SIT + HIIT1 and SIT + HIIT2 but were 3 * PW. Training volume was identical to pre-intervention, with a ~50 % reduction every fourth week.	No significant changes in CON
Sylta et al.[31]	69 male well-trained cyclists (age: 38 ± 8 years). 6 subjects were excluded from the analysis due to failure to comply with at least 70 % of prescribed interval sessions and/or absence from post-intervention testing.	NP (n = 23)	Three 4-week mesocycles. Increasing group performed 8 interval sessions in mesocycle 1 (weeks 1–4, 4 * 16 min intervals), 8 interval sessions in mesocycle 2 (weeks 5–8, 4 * 8 min intervals) and 8 interval sessions in mesocycle 3 (weeks 9–12, 4 * 4 min intervals). Intervals were prescribed at maximal sustainable intensity. Recovery between work bouts was 2 min in all interval sessions.	VO_{2max}: ↑ 62 ± 5.8 to 66.5 ± 6.1 mL/kg/min TT: ↑ 281 ± 34 to 300 ± 30 W
		NP (n = 20)	Decreasing group followed the same three 4-week mesocycle structure as increasing. Decreasing performed the interval sessions in the opposite mesocycle order as increasing (weeks 1–4, 4 * 4 min intervals; weeks 5–8, 4 * 8 min; weeks 9–12, 4 * 16 min).	VO_{2max}: ↑ 60.6 ± 5.6 to 64 ± 5.4 mL/kg/min TT: ↑ 279 ± 29 to 297 ± 26.4 W
		NP (n = 20)	Mix group followed the same mesocycle structure as the two previous training groups. Mix performed the 24 interval sessions in alternating order (session 1: 4 * 16 min; session 2: 4 * 8 min; session 3: 4 * 4 min; session 4: 4 * 16 min). The intensity at which intervals were performed and duration of recovery bouts were similar to increasing and decreasing.	VO_{2max}: 62 ± 5.6 to 64 ± 5.4 mL/kg/min TT: ↑ 287 ± 27 to 297 ± 27.5 W
Christensen et al.[32]	8 trained cyclists (age: 33 ± 8 years, mass: 81 ± 8 kg)	POL (n = 8)	Training consisted of 4 interval sessions PW involving SIT and HIIT.	No significant differences in VO_{2max}
Arezzolo et al.[33]	9 trained cyclists (age: 32 ± 10 years, mass: 73 ± 7 kg).	POL (n = 9)	Cyclists performed 8 * 1 min exercise bouts with 5 min active rest between each bout 2 * PW at ~120 % VO_{2max} with 6.4 ± 3.4 hour habitual exercise per week.	VO_{2max}: 58.3 ± 6.3 to 58.8 ± 7.2 mL/kg/min
Dressendorfer et al.[34]	9 trained cyclists (age: 24 ± 2 years, mass: 76 ± 7 kg).	NC (n = 9)	3 phases: 6 week capacity building by increasing volume, 18 day power building by increasing work intensity, & 10 day reduced training frequency.	VO_{2max}: 4.46 ± 0.4 to 4.88 ± 0.31 L·min TT: ↓ 35:15 ± 2:36 to 32:38 ± 2.2 (min:s)
Eigendorf et al.[35]	7 trained cyclists (age: 26 ± 2 years, mass: 77 ± 1 kg).	NP (n = 9)	Two 3 week-periods of SIT (90 intervals of 6 s cycling at 250 % maximum power)	VO_{2max}: 3.71 ± 0.79 to 3.81 ± 0.52 L·min
Hebisz et al.[36]	12 trained cyclists (age: 24 ± 3 years, mass: 66 ± 8 kg).	POL (n = 12)	Combined CET with a sprint and HIIT protocol, which, respectively, were based on 30 s maximal repetitions and 4 min high intensity repetitions for 8 weeks	VO_{2max}: ↑ 57.9 ± 6.8 to 66.6 ± 5.3 mL/kg/min
	13 trained cyclists (age: 25 ± 5 years, mass: 63 ± 6 kg).	NP (n = 13)	Trained using CET (moderate) intensity and variable-intensity (high–moderate–low) free of maximal efforts	VO_{2max}: 61.3 ± 7.5 to 62.4 ± 6.9 mL/kg/min
Hopker et al.[37]	29 trained cyclists (age: 35 ± 8 years; mass: 72 ± 8 kg).	NC	Cyclists supplemented habitual training with 2 HIIT sessions PW (involving both 4 min 'on' and 4 min 'off' intervals at a power output equivalent to the 4 $mmol \cdot L^{-1}$ lactate point, and maximal sprint repetitions) for 12 weeks	VO_{2max}: 60 ± 6.9 to 58.2 ± 7.2 mL/kg/min
		NP	All training performed under the HR equating to their 4 mmol·L lactate point − 5 beats per minute.	VO_{2max}: 58.6 ± 8.8 to 57.4 ± 5.5 mL/kg/min
Hebisz et al.[38]	20 trained cyclists (age: 19 ± 5 years, mass: 69 ± 9 kg).	POL (n = 20)	Twenty well-trained cyclists completed an 8-week intervention of SIT (8–16 30 s maximal sprints), HIIT (4–6 bouts at 85–95 % MAP), and CET (2–3 hour cycling at 70–80 % power at the ventilatory threshold).	VO_{2max}: ↑ 67.7 ± 6.3 to 73.4 ± 7.6 mL/kg/min
Hanstock et al.[39]	25 trained cyclists (age: 30 ± 9 years).	NC	Long intervals: 4 * 8 min intervals with 2 min recovery periods	VO_{2max}: 4.89 ± 0.4 to 5.05 ± 0.4 L·min
		NC	Short intervals 1: 4 × (12 × 40 / 20 s) intervals with 2 min recovery periods	VO_{2max}: 4.66 ± 0.4 to 4.82 ± 0.4 L·min
		NC	Short intervals 2: 4 * (8 * 40 / 20 s) intervals with 2 min recovery periods.	VO_{2max}: 4.66 ± 0.4 to 4.67 ± 0.4 L·min

Table 1 (*continued*)

Studies	Participant characteristics (mean ± SD)	Categorization N=	Intervention	Outcomes and results
Leoculture et al.[40]	Well trained cyclists: (age: 19 ± 1 years, mass: 70 ± 1 kg).	POL (n = 7)	Two HIIT sessions and one CET session were performed each week for 4 weeks	VO_{2max}: ↑ 69.1 ± 2.6 to 73.2 ± 3.8 mL/kg/min TT: ↑ 261 ± 10 to 276 ± 8 W
Nimmerichter et al.[41]	Well trained cyclists: Int60 (age: 30 ± 6 years, mass: 70 ± 6 kg).	POL (n = 6)	Group 1 performed uphill interval training with a cadence of 60 rpm. Intervals for all groups consisted of 6 * 5 min intervals at an intensity corresponding to RCP power, interspersed with 5 min at 30–50 % of RCP power over 6 weeks	VO_{2max}: 61.5 ± 5 to 60.8 ± 3.3 mL/kg/min TT: 295 ± 15 to 300 ± 25 W
	Int100 (age: 31 ± 6 years, mass: 71 ± 5 kg).	POL (n = 6)	Group 2 performed level-ground interval training with a cadence of 100 rpm	$VO_{2max:}$ 58.8 ± 6 to 60.1 ± 7.7 mL/kg/min TT: 299 ± 48 to 306 ± 49 W
	Con (age: 33 ± 5 years, mass: 75 ± 4 kg).	NP (n = 5)	Group 3 continued their CET throughout the 4 weeks	VO_{2max}: 55.4 ± 4.3 to 57.2 ± 5.2 mL/kg/min TT: 292 ± 18 to 283 ± 30 W
Javaloyes et al.[42]	Well trained cyclists (age: 30 ± 10 years, mass: 72 ± 10 kg).	NP (n = 8)	Training blocks consist of 3 blocks of HIIT (4 HIIT sessions PW) followed by a block of LIT (4 LIT sessions and 1 HIIT session).	VO_{2max}: 59 ± 6.2 to 62.6 ± 6.6 mL/kg/min TT: 262 ± 30 to 264 ± 33 W
	Age: 28 ± 13 years, mass: 73 ± 4 kg.	NC (n = 7)	Training was prescribed according to their HR-variability morning values following a decision-making schema	VO_{2max}: 58.9 ± 5.6 to 61 ± 6 mL/kg/min TT: ↑ 261 ± 28 to 280 ± 39 W
Lamberts et al.[43]	Trained cyclists (age: 30 ± 6 years, mass: 73 ± 8 kg).	NC (n = 14)	Training included HIIT sessions, rest days and recovery rides. One HIIT training session consisted of eight intervals at approximately 80 % of PPO. Each interval of 4 min was followed by a 90 s self-paced recovery.	VO_{2max}: 60.3 ± 7.2 to 61.7 ± 6.5 mL/kg/min TT: ↑ 255 ± 26 to 270 ± 24 W
Lindsay et al.[44]	Competitive cyclists (age: 25 ± 3 years, mass: 79 ± 4 kg).	POL (n = 8)	Training involved HIIT on six occasions during a 28-day period and consisted of 6–8 repetitions each 5 min in duration at a power output equivalent to 80 % of each subject's PPO. Between each 5 min work bout, the subjects pedaled for 1 min at a low intensity.	TT: ↑ 300 ± 42 to 326 ± 43 W
Kilding et al.[45]	Trained cyclists (age: 24.8 ± 9.1 years, mass: 75 ± 11 kg).	POL (n = 16)	Training involved 6 weeks POL and periodized endurance training on an ergometer consisting HIIT sessions 3 D/Pw and additional LIT 2 D/Pw.	TT: ↑ 275 ± 40 to 287 ± 40 W
Kristoffersen et al.[46]	Trained cyclists (age: 47 ± 6 years, mass: 78 ± 7 kg).	POL (n = 11)	12 week low cadence interval training 5 * 6 min at a HR of 73–82 % of HR max measured at the VO_{2max} test prior the intervention period, with 3 min active rest at freely chosen cadence and low intensity (60–72 % of HR max).	VO_{2max}: 57.2 ± 4.8 to 58.5 ± 4.8 mL/kg/min TT: 278 ± 23 to 276 ± 35 W
		NC (n = 10)	Freely chosen cadence group added 90 min of cycling at freely chosen cadence at moderate intensity (73–82 % of HRmax)	VO_{2max}: ↑ 58.9 ± 2.4 to 62.2 ± 3.2 mL/kg/min TT: ↑ 284 ± 42 to 287 ± 50 W
Norris et al.[47]	Competitive cyclists (age: 23 ± 3 years, mass: 70 ± 9 kg).	NP (n = 16)	Cyclists undertook 8 weeks of progressive endurance training, consisting of 5 * PW.	VO_{2max}: ↑ 56.8 ± 6.8 to 60.8 ± 6.9 mL/kg/min TT: ↓ 77.6 ± 6.6 to 71.1 ± 5 (min:s)
Roels et al.[48]	Normoxic group: (age: 33 ± 2 years, mass: 71 ± 5 kg)	NP (n = 11)	Subjects performed two interval sessions per week. Each session consisted of a 15 min warm-up, followed by an interval training session and a cool-down of 10 min for 8 weeks	VO_{2max}: 4.47 ± 0.36 to 4.69 ± 0.29 mL/kg/min
Rønnestad et al.[49]	Competitive cyclists (age: 32 ± 8 years, mass: 77 ± 5 kg).	POL (n = 7)	Cyclists performed either 5 * 6 min or 6 * 5 min work periods interspersed with recovery periods that lasted 50 % of the work period for 16 weeks	VO_{2max}: 69 ± 6 to 71 ± 8 mL/kg/min
Rønnestad et al.[50]	Age: 30 ± 7 years, mass: 77 ± 5 kg. 20 well-trained cyclists (age: 33 ± 10 years, mass: 76 ± 6 kg).	NP (n = 6) POL (n = 9)	Traditional group focused on LIT throughout Cyclists performed SIT 3 * PW. Each session consisted of 3 sets of 30 second work intervals separated by 15 second recovery periods performed continuously for 9.5 min. Recovery between each set was 3 min.	VO_{2max}: 68 ± 5 to 69 ± 6 mL/kg/min VO_{2max}: ↑ 5.0 ± 4.7 to 5.4 ± 4.7 L·min TT: ↑ 270 ± 33 to 290 ± 17 W
		POL (n = 7)	Cyclists performed 3 * PW HIIT sessions of 4 * 5 min intervals at their maximal sustainable intensity for each interval, interspersed with 2.5 min recovery bouts at 50 % of power output used during work intervals.	VO_{2max}: to 5.0 ± 6.7 to 5.1 ± 5.3 L·min TT: 290 ± 48 to 285 ± 44 W
Taylor et al.[51]	Trained cyclists (age: 32 ± 7 years, mass: 75 ± 8 kg).	NC (n = 10)	Cyclists performed 4 weeks of 4 to 7 SIT efforts with 4.5 min recovery twice per week.	VO_{2max}: 61.8 ± 4.7 to 61.1 ± 4.9 mL/kg/min TT: 280 ± 26,288 ± 29 W
Ventura et al.[52]	Endurance trained cyclists (age: 25 ± 2 years, mass: 72 ± 2 kg).	NC (n = 5)	Six week training period, 3 * PW for 30 min, interval structure not reported.	VO_{2max}: 62.3 ± 1.5 to 61.9 ± 2.0 mL/kg/min
Hebisz et al.[53]	Competitive cyclist (age: 23 ± 5 years, mass: 64 ± 9 kg). Age: 24 ± 4 years, mass: 67 ± 6 kg.	NP (n = 14) NP (n = 14)	Both groups consisted of programs that included HIIT, SIT and LIT over a 6-month period	VO_{2max}: 59.2 ± 6.7 mL/kg/min (reported as non-significant change) VO_{2max}: 56.3 ± 4.3 mL/kg/min (reported as non-significant change)
Williams et al.[54]	Trained cyclists (age: 28 ± 7 years, mass: 70 ± 7 kg).	NC (n = 6)	Control group performed 3 * 1 hour sessions at 70 % PPO PW for 4 weeks.	VO_{2max}: 62.7 ± 8 to 61.4 ± 9.6 mL/kg/min

(*continued on next page*)

Table 1 (*continued*)

Studies	Participant characteristics (mean ± SD)	Categorization N=	Intervention	Outcomes and results
				TT: 274 ± 37 to 281 ± 34 W
Weston et al.[55]	Well trained cyclists (age: 22 ± 3 years, mass: 78 ± 6 kg).	NC (n = 6)	Subjects completed 6 HIIT ergometer sessions over a 28-day period on an stationary bike. A session consisted of 6–8 repetitions of 5 min duration for 80 % of the subjects' pre-determined PPO. Recovery intervals were 1 min, during which time the subject pedaled at ~100 W	TT: ↓ 57.1 ± 4.4 to 55.9 ± 4.2 (min:s)
Westgarth-Taylor et al.[56]	Endurance trained cyclists (age: 25 ± 4 years, mass: 80 ± 13 kg).	NP (n = 8)	Over 6 weeks, cyclists replaced 15 % of their 300 km PW endurance training with 12 HIIT sessions, each consisting of 6–9 5 min efforts at 80 % of W peak, separated by a 1 min recovery.	TT: ↑ 40 ± 3.6 to 43 ± 4.2 kph
Nearly et al.[57]	Endurance trained cyclists (age: 25 ± 6 years, mass: 67 ± 8 kg).	NP (n = 25)	Participants trained 5 D/Pw, 60 min, at 75–85 % VO_{2max} for 8 weeks	VO_{2max}: 3.69 ± 0.3 to 3.91 ± 0.58 mL/kg/min
Tseh et al.[58]	14 cyclists (age: 23 ± 4 years, mass: 68 ± 10 kg).	NC (n = 5) (Rollers)	Cyclists rode low intensity for 4.5 min, and then during the last 30 s of the 5 min interval at high intensity. This 5 min interval was repeated 8 * 40 min 3 * PW for 8 weeks	VO_{2max}: 67.6 ± 9.4 to 68.3 ± 10 mL/kg/min TT: ↓ 16:51 ± 2:06 to 16:30 ± 1:53 (min:s)
		NC (n = 5) (Ergo)	Cyclists rode at low intensity for 4.5 min, and then during the last 30 s of the 5 min interval at high intensity. This 5 min interval was repeated 8 * 40 min 3 * PW for 8 weeks	VO_{2max}: 65.6 ± 11.3 to 64.8 ± 12.4 mL/kg/min TT: ↓ 17:01 ± 113 to 16:48 ± 2 (min:s)
		NC (n = 4) (Con)	Control was encouraged to train normally throughout the 8 weeks as if each participant was not involved with the research study.	VO_{2max}: 72.8 ± 11.7 to 71.6 ± 12.1 mL/kg/min TT: 16:48 ± 189 to 16:50 ± 3:12 (min:s)
Swart et al.[59]	21 well-trained cyclists, with ≥3 years of competitive experience (age: 31 ± 6 years, mass: 74 ± 8 kg).	POL (n = 6)	Cyclists performed 2× per week HIIT sessions. Each session consisted of 8 * 4 min intervals at 80 % of power output at MAP, interspersed by 90 s recovery periods at self-selected intensity.	VO_{2max}: 59.9 ± 7 to 60.2 ± 0 mL/kg/min TT: ↓ 65:14 ± 2:31 to 63:43 ± 1:59 (min:s)
		POL (n = 6)	Cyclists performed the same intervals as short HIIT1 but performed their intervals at the HR coinciding with 80 % of MAP. Due to HR lag, cyclists were asked to achieve the target HR within the first 3 min in interval 1, 2 min in interval 2, and 1 min in intervals 3–8.	VO_{2max}: 60.3 ± 4 to 63.5 ± 2 mL/kg/min TT: ↓ 66:15 ± 2:06 to 64:48 ± 2:07 (min:s)
		NC (n = 5)	CON performed a 40 km TT twice a week at <70 % MAP. Cyclists were also required to complete the same training as the HIIT groups outside of the laboratory environment (LIT to MIT)	No significant differences in VO_{2max} between baseline and post-intervention in either group.
Hommel et al.[60]	20 recreationally trained cyclists. SIT (age: 27.9 ± 1 years, mass: 73 ± 4 kg).	NC SIT (n = 10)	Cyclists trained 3 * PW. During weeks 1–2, interval sessions consisted of 4 * 30 second all-out efforts, interspersed with a fixed recovery period (~30 W) of 4.5 min. The number of Wingate tests in each interval session progressively increased during the intervention (5 all-out efforts in weeks 3–4; and 6 in weeks 5–6).	VO_{2max}: ↑ 62.6 ± 8.8 to 65.2 ± 7.9 mL/kg/min
	CON (age: 26 ± 2 years, mass: 75 ± 11 kg).	NC CON (n = 10)	Cyclists trained 3 D/Pw throughout the intervention. Each session consisted of 60 min of cycling at a blood lactate of 1.5–2.5 mmol·L^{-1}, performed throughout the study period.	VO_{2max}: ↑ 61.0 ± 4.8 to 66.7 ± 4.8 mL/kg/min. Differences in VO_{2max} between SIT and CON were not statistically significant post-intervention
Christensen et al.[61]	Well trained cyclists (LOW: n = 8; age: 28 ± 7 years)	NP (n = 8)	Both groups performed the same HIT. For one group, total volume was lowered by ~33 % by omitting MIT. Both groups performed the same HIT weekly comprised by recovery from races (day 1), 5 * ~4 min at the highest possible mean intensity on with ~3 min recovery (day 2), 12 * ~30 s SIT with ~5 min recovery (day 3), 5 * ~4 min at the highest possible intensity with ~3 min recovery (day 4), LIT (day 5), and racing for ~3 h (day 6 and/or 7).	VO_{2max}: 5.1 ± 0.5 to 5.2 ± 0.6 L·min TT: ↑ 302 ± 33 to 310 ± 35 W
	NOR: n = 10; age: 27 ± 6 years.	POL (n = 10)		VO_{2max}: 5.2 ± 0.5 to 5.3 ± 0.3 L·min. TT: 309 ± 23 to 314 ± 19 W
Cardinale et al.[62]	Trained cyclists (age: 35.3 ± 6.4 years, mass: 75 ± 9 kg).	POL (n = 11)	Cyclists performed 6 week POL and periodized endurance training on an ergometer consisting of supervised HIIT sessions 3 D/Pw and additional LIT 2 D/pw.	VO_{2max}: 4.7 ± 0.7 to 4.6 ± 0.7 L·min TT: 301 ± 54.5 to 305 ± 59.6 W

CET = continuous endurance training, CON = control group, D/pw = days per week, ET = endurance training, HIIT = high-intensity interval training, HIT = high intensity training, HR = heart rate, KPH = kilometers per hour, LIT = low-intensity training, MAP = maximum aerobic power, MIT = moderate-intensity training, NC = not clear, NP = not polarized, POL = polarized, PPO = peak power output, PW = per week, RCP = respiratory compensation point, S = seconds, SIT = sprint interval training, TT = time trial, VO_{2max} = maximal oxygen uptake, VO_{2peak} = peak oxygen uptake, W = watts, W/kg = watts per kilogram, ↑↓ = Statistical significance. TT protocols were reported as follows: Laursen et al.,[27] Leoculture et al.,[40] Javaloyes et al.,[42] Lamberts et al.,[43] Lindsay et al.,[44] Norris and Petersen,[47] Weston et al.,[55] Westgarth-Taylor,[56] Swart et al.,[59] 40 km, Dressendorfer et al.,[34] Kilding et al.,[45] 20 km, Taylor et al.,[51] 15 km, Tseh et al.,[58] 10 km, Almquist et al.,[22] Rønnestad et al.,[29] Sylta et al.,[31] Rønnestad et al.,[50] 40 min, Kristoffersen et al.,[46] Williams et al.,[54] 30 min, Nimmerichter et al.,[41] Cardinale et al.,[62] 20 min, and Christensen et al.,[61] 400 kcal.

Table 2
Subgroup analysis of VO_{2max} and TT performance.

Subgroup	n	Individual estimates		Between condition comparison	
		g (95 % CI)	P=	Difference *g* (95 % CI)	P=
VO_{2max}					
Polarized (reference group)	23	0.53 (0.34, 0.71)	<0.001	Reference	
Non-polarized	24	0.39 (0.22, 0.56)	<0.001	−0.14 (−0.41, 0.12)	0.273
Not clear	21	0.34 (0.10, 0.57)	0.005	−0.18 (−0.51, 0.14)	0.248
Time trial performance					
Polarized (reference group)	14	0.31 (0.03, 0.58)	0.031	Reference	
Non-polarized	16	0.40 (0.18, 0.62)	0.002	0.09 (−0.15, 0.34)	0.425
Not clear	15	0.47 (0.18, 0.75)	0.004	0.16 (−0.10, 0.42)	0.206

VO_{2max} = maximal oxygen uptake.

3.5. Effect of training distribution on TT performance

A total of 45 groups from 25 studies included time trial performance as an outcome measure and were included in the multilevel meta-analysis. Of these, 14 were categorized as POL, 16 as NP, and 15 as NC. There was a significant effect of training on time trial performance for all groups ($g = 0.39$, 95 % CI = 0.29, 0.49; $P < 0.001$; *small effect*; $Q(df = 44) = 19.4$, $P = 0.999$; $I^2 = 0.00$ %), as well as POL ($g = 0.31$, 95 % CI = 0.17, 0.44; $P < 0.001$; *small effect*; $Q(df = 13) = 3.5$, $P = 0.996$; $I^2 = 0.00$ %), NP ($g = 0.40$, 95 % CI = 0.15, 0.66; $P = 0.009$; *small effect*; $Q(df = 15) = 10.5$, $P = 0.785$; $I^2 = 0.00$ %) and NC ($g = 0.47$, 95 % CI = 0.22, 0.72; $P = 0.003$; *small effect*; $Q(df = 14) = 4.6$, $P = 0.990$; $I^2 = 0.00$ %) groups. However, there were no significant differences between any of the training distribution groups and changes in time trial performance (Table 3). Forest plots of time trial analysis can be found in Supplementary digital content Figs. 6, 8, 9, and 10. There was a positive association observed between intervention duration in weeks and improvements in TT performance ($g = 0.04$, 95 % CI = 0.03, 0.06, $P < 0.001$; *trivial effect*; $QE(df = 43) = 22.4$, $P = 0.996$; $I^2 = 0.00$ %).

Inspection of funnel plots (Supplementary digital content, Fig. 7) and results of Egger's test suggested low risk of publication bias (intercept = −0.14, P = 0.540). Evaluation of standardized residuals identified one outlier.[63] Following the removal of this outlier, the magnitude of training on time trial performance reduced slightly ($g = 0.36$, 95 % CI = 0.27, 0.45, $P < 0.001$), with negligible between-study heterogeneity ($Q(df = 43) = 15.0$, $P = 1.000$; $I^2 = 0.00$ %).

3.6. Effect of training volume on VO_{2max}

Of the 34 studies that reported VO_{2max} as an outcome measure, 20 (containing 36 groups) reported habitual training volume and were included in the exploratory multivariate meta-regression. Results indicated that there was no association between weekly ($g = -0.03$, 95 % CI = −0.07, 0.01; $P = 0.167$; *small effect*; $QE(df = 34) = 32.1$, $P = 0.562$; $I^2 = 1.43$ %) or total ($g = -0.00$, 95 % CI = −0.005, 0.003; $P = 0.526$; *small effect*; $QE(df = 34) = 32.6$, $P = 0.538$; $I^2 = 0.00$ %) training volume and changes in VO_{2max} (Fig. 2).

3.7. Effect of training volume on TT performance

Of the 25 studies that reported time trial performance as an outcome measure, 10 (containing 17 groups) reported habitual training volume and were included in the exploratory multivariate meta-regression. There was no association between weekly ($g = -0.00$, 95 % CI = −0.04, 0.04; $P = 0.867$; *small effect*; $QE(df = 15) = 3.8$, $P = 0.998$; $I^2 = 0.00$ %) or total ($g = 0.00$, 95 % CI = −0.004, 0.007; $P = 0.459$; *small effect*; $QE(df = 15) = 3.5$, $P = 0.999$; $I^2 = 0.00$ %) training volume and changes in TT performance (Fig. 3).

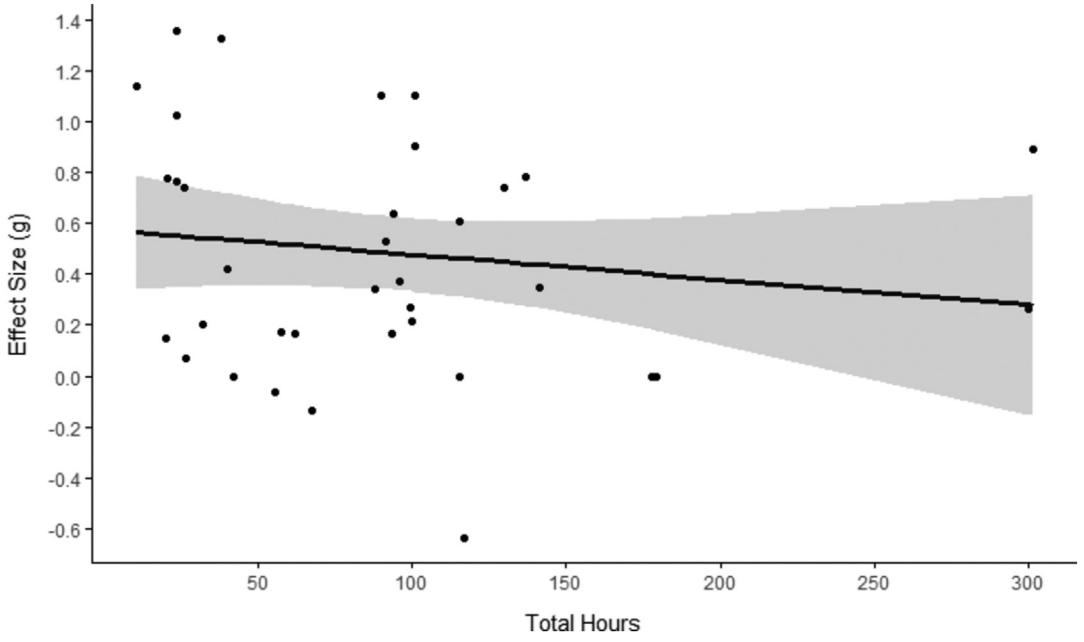


Fig. 2. The association between total intervention training volume in hours and changes in VO_{2max}.

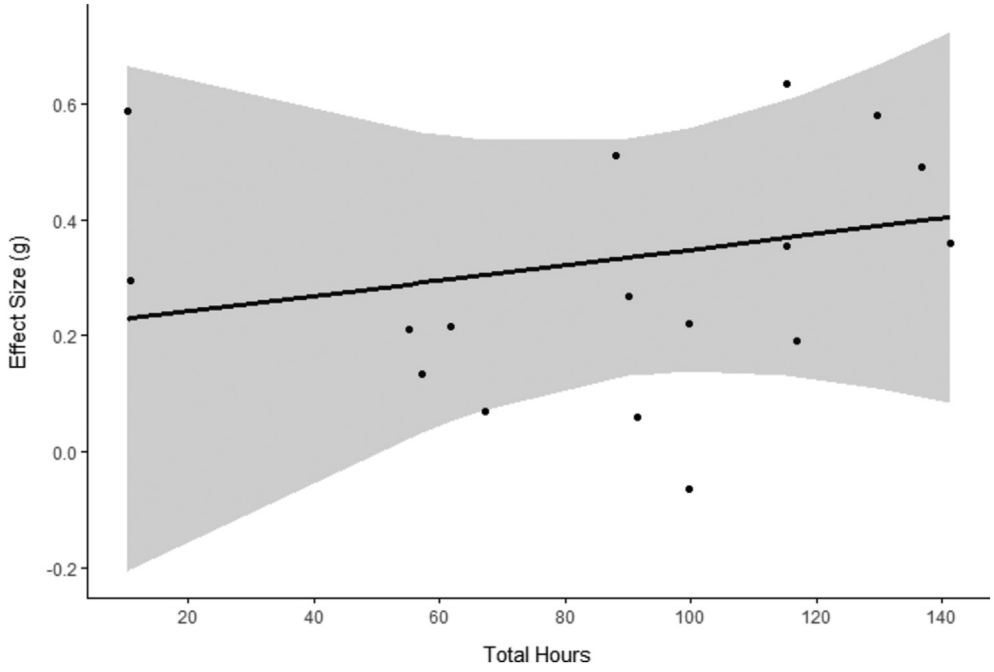


Fig. 3. The association between total intervention training volume in hours and changes in TT performance.

3.8. Certainty of evidence

GRADE certainty of evidence assessment tables are provided in Supplemental digital content, Table 2. The certainty of evidence for both the VO_{2max} and TT performance analyses started as low, due to the more than 25 % of included studies being non-randomized trials. There was no dose–response relationship observed, nor did either analysis present with a large effect. Consequently, the certainty of evidence for both the VO_{2max} and TT analyses was considered low.

4. Discussion

This systematic review and meta-analysis provides the most comprehensive evaluation of training intensity distribution manipulation and training volume on VO_{2max} and TT performance in trained cyclists to date. The primary aim of this systematic review and meta-analysis was to compare the effects of POL and NP training interventions and determine their effects on VO_{2max} and TT performance in highly trained and competitive cyclists. A total of 44 studies containing 81 groups were identified for meta-analysis. There were no significant differences between POL and NP training groups and changes in VO_{2max} or TT performance. While training duration was positively associated with improvements in both VO_{2max} and TT performance, there were no associations observed with weekly and total training volume on these outcomes.

4.1. Effect of training intensity distribution on VO_{2max} and TT performance

The results of this meta-analysis indicate that POL is likely to enhance VO_{2max} in trained cyclists but does not show superiority over other training intensity distribution methods. Our findings are consistent with the review of Galán-Rioja et al. that reported there is currently no evidence to support the superiority of any specific training method in this population.[2] However, this conflicts with the previous meta-analysis by Rosenblat et al. that reported POL may lead to a greater improvement in TT performance than threshold training.[3] The observed discrepancy may be attributed, in part, to the heterogeneric nature and the limited number of studies ($n = 4$) that were available for inclusion in the meta-analysis conducted by Rosenblat et al.,[3] while our meta-analysis of VO_{2max} included 38 different studies, which is likely to provide a more comprehensive assessment of training intensity distribution on performance. Another potential explanation to these conflicting findings could be due to POL training being characterized in a dichotomous fashion, despite some training interventions being "more polarized" than others. As such, while some studies were classified as POL and others non-POL, they may not be heterogeneous enough in training distribution to truly cause a different effect. A possible solution to this dichotomous categorization would be for future studies to classify using a polarization index, which generates an arbitrary unit of polarization and thus allowing for a regression analysis.[64] One interesting finding that deserves mention pertains to the effect of training intensity distribution in time trial performance. While there was a positive effect of all training methods to improve TT performance, POL training had a slightly smaller effect than other modalities (despite not being significantly different). The broad range of TT test durations examined in the studies (e.g., short 5 km tests vs. longer 40 km trials) may have influenced the results. It is possible that certain training intensity distributions, such as POL, might be better suited for longer TT events, emphasizing aerobic development, while others may favor shorter, high-intensity events. Unfortunately, the variability in protocols limited our ability to quantitatively analyze these effects, suggesting a need for more standardized research in the future. While the exact reason for this is unclear, it may be that, as POL training is generally characterized by high volumes of low intensity training, it provides sufficient stimulus for physiological adaptation (i.e., VO_{2max}), but not sufficient high intensity training to maximize TT performance. This supposition is supported by Podlogar et al., who reported that changes in VO_{2max} may not necessarily correlate to improvements in TT performance in endurance athletes.[65] Podlogar et al.[65] findings may be partially supported when examining the effect of training intensity distribution on VO_{2max} in the present review, whereby POL caused a medium effect, and NP and NC a small effect, but this did not translate to larger improvements in TT for the POL group. However, it is again important to note that these differences were not statistically significant, and these observations are merely speculative.

4.2. Effect of training duration and volume on VO_{2max} and TT performance

Intervention duration was positively associated with improvements in both VO_{2max} and TT performance, which is a logical finding. It stands to reason that longer interventions provide more opportunity for adaptations to occur, which is likely to contribute to larger training outcomes. However, surprisingly, results of the meta-regression indicated no association between training volume and changes in VO_{2max} or TT performance. While this finding goes against conventional wisdom, there are some possible explanations. Firstly, higher training volumes are typically more common in highly trained athletes, for whom adaptations to any stimulus are often minimal or limited.[1,66,67] As such, it may be that those studies that had higher training volumes (inclusive of habitual training volume) were simply closer to their genetic ceiling, and therefore had less potential for adaptation to occur. Secondly, training with higher volumes necessitates lower training intensities. As such, this may suggest that in trained athletes, higher training intensity may be more important once a certain threshold of training volume has been met. To the authors' knowledge, one study (which was also included in this review) has explored this in detail which provides support for this finding. Christensen et al. examined the effect of reduced volume training compare to a "normal" training volume in trained cyclists on TT performance, and found no differences between conditions,[61] further indicating that once a "volume" threshold has been met, additional increases may not necessarily contribute to further improvements in performance. Regardless of the reasons, this finding suggests that adaptations in VO_{2max} and TT performance may not be influenced by high volumes alone. Therefore, caution should be exercised when prescribing high volumes of low intensity training to trained cohorts.

4.3. Limitations

Firstly, it was commonplace for studies included in this review to prescribed training intervention intensity off pre-intervention markers such as VO_{2max}, HR or PWR, which may not accurately account for physiological changes in training zone demarcation over a program. This has the potential to influence the true amount of time spent in the prescribed training zones, which will influence training intensity distribution. Secondly, many studies included athletes that maintained their habitual training, but as this was not reported in detail, they were not included in the meta regression. As such, the exploratory analysis examining the association between training volume and improvements in VO_{2max} and TT performance only included a small number of studies and should be interpreted with caution. Thirdly, there were large amounts of heterogeneity among the reporting of TT protocols among included studies, with several studies reporting wide variations in duration performed (ranging from <5 min to 40 km). For the effect size estimates used in the present study were calculated using pooled SD, which was derived from pre- and post-SD measures with an assumed correlation of 0.5. While this was done to reduce the likelihood of overestimating intervention effects, it does not account for the exact correlation between pre- and post-values or the precise variability in change scores, which may result in either overestimating or underestimating the true effect. While we took care in classifying training interventions as POL, NP, or NC, not all studies clearly reported habitual or uncontrolled components of training which may have introduced classification errors. As noted in the Galán-Rioja et al. review, logistical challenges in analysis exist due to the large heterogeneity among studies.[2] Finally, while fatigue resistance has received notable attention in recent literature, it was beyond the scope of this review.

4.4. Recommendations for future research

As previously discussed in detail, there were limitations in the reporting of included studies pertaining to habitual training volume that could have impacted training intensity distribution categorization. Future research should provide detailed descriptions of participants' habitual training logs to ensure the effects of a given intervention are understood in the context it is applied. Moreover, studies examining the effect of POL training should report a polarization index to provide a more detailed evaluation of how polarized a training intervention is, rather than categorizing it dichotomously. Finally, no studies included athletes classified as tier 5 (e.g., Olympic or world medalist) by McKay et al.[12] As such, we concur with findings of Rosenblat et al. that reported the utilization of online training platforms like TrainingPeaks or Strava, which record numerous training parameters, could provide access to rich data from elite athletes without the necessity of intervention or training disruption.[3] However, it must be noted that world-class level athletes are often reluctant to share valuable training data and future resources should work to improve the athlete–researcher dynamic in this process. In addition, several test-protocol utilization habitual training data have been validated and reported to be reliable in predicting factors such as critical PWR, functional threshold PWR, and physiological training zones which would be beneficial in retrospective and observational studies.[68]

5. Conclusion

This review reports that the optimization of training in well trained cyclists cannot be solely explained by the training intensity distribution model and an individualized approach that considers the physiological and competitive requirements of the athlete is justified. It is also noteworthy that, while the adaptations to training were small these may be relevant in well trained cohorts. Finally, caution should be considered regarding total training volume, with higher volumes yielding no greater improvements in performance. Interestingly, given the similarities in outcomes between training intensity distributions, further investigation is needed into the other training factors that may influence these outcomes.

CRediT authorship contribution statement

All authors contributed to the study conception and design. Material preparation and data collection were performed by Ben Cove and Mitchell Anderson. Data analysis was conducted by Ben Cove and Hunter Bennett. The first draft of the manuscript was written by Ben Cove and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Confirmation of ethical compliance

No ethical application or approval was required for this systematic review.

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Declaration of interest statement

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2024.12.005.

Data availability

The data used for this meta-analysis can be accessed here: https://osf.io/jz9na.

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