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# Respiratory frequency is strongly associated with perceived exertion during time trials of different duration

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**ABSTRACT**

In order to provide further insight into the link between respiratory frequency ($f_R$) and the rating of perceived exertion (RPE), the present study investigated the effect of exercise duration on perceptual and physiological responses during self-paced exercise. Nine well-trained competitive male cyclists (23 ± 3 years) performed a preliminary incremental ramp test and three randomised self-paced time trials (TTs) differing in exercise duration (10, 20 and 30 min). Both RPE and $f_R$ increased almost linearly over time, with a less-pronounced rate of increase when absolute exercise duration increased. However, when values were expressed against relative exercise duration, no between-trial differences were found in either RPE or $f_R$. Conversely, between-trial differences were observed for minute ventilation ($\dot{V}_E$), $\dot{V}O_2$ and heart rate (HR), when values were expressed against relative exercise duration. Unlike the relationship between RPE and both $\dot{V}_E$ and HR, the relationship between RPE and $f_R$ was not affected by exercise duration. In conclusion, $f_R$, but not $\dot{V}_E$, HR or $\dot{V}O_2$, shows a strong relationship to RPE and a similar time course, irrespective of exercise duration. These findings indicate that $f_R$ is the best correlate of RPE during self-paced exercise, at least among the parameters and for the range of durations herein investigated.

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**KEYWORDS**
Exercise duration; cycling; pacing strategy; ventilation; central command

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## Introduction

It is commonly recognised that perceived exertion plays a crucial role in regulating workload during self-paced exercise, even though different models have been developed to explain how the brain regulates pacing during exercise (De Koning et al., 2011; Marcora, 2010; Tucker, 2009). Both in time trial (TT) and time to exhaustion (TTE) protocols, the rating of perceived exertion (RPE) increases almost linearly over time, reaches nearly maximal values at the end of exercise and shows a less-pronounced rate of increase when absolute exercise duration increases (Eston, 2012). This progressive increase in RPE during exercise is a major feature of fatigue (Enoka & Stuart, 1992; Noakes, 2004). Interestingly, it has been observed that RPE shows scalar properties, i.e. in trials differing in exercise duration, similar RPE values are reported when RPE is expressed against relative exercise duration (Eston, 2012; Faulkner, Parfitt, & Eston, 2008; Joseph et al., 2008). This holds true when some experimental interventions affecting TTE are administered, i.e. glycogen depletion (Noakes, 2004), prior exercise-induced fatigue (Eston, Faulkner, Gibson, Noakes, & Parfitt, 2007) or muscle damage (Davies, Rowlands, & Eston, 2009), and exposure to different ambient temperatures (Crewe, Tucker, & Noakes, 2008). However, it has been reported that RPE may not scale with time when protocols with considerably different exercise durations are compared, or when some deception strategies are used (Swart et al., 2009).

It has been recently reported that respiratory frequency ($f_R$), but no other physiological parameter, has a strong link with RPE during self-paced maximal-effort exercise, irrespective of the intermittent or continuous nature of the protocol (Nicolò, Bazzucchi, Haxhi, Felici, & Sacchetti, 2014). In addition, in that study, a very good relationship between the two parameters was found in all the conditions tested (Nicolò, Bazzucchi, Haxhi, et al., 2014). A strong link between RPE and $f_R$ is even supported by experimental interventions that attempted to dissociate ventilatory response from perceived exertion (Robertson, 1982). Similar to RPE, $f_R$ shows a progressive almost linear increase over time and reaches nearly maximal values at the end of exercise in a variety of exercise paradigms (Kift & Williams, 2007; Nicolò, Bazzucchi, Haxhi, et al., 2014; Nicolò, Bazzucchi, Lenti, et al., 2014). Moreover, $f_R$ and RPE respond in a similar way to some experimental interventions that affect performance, such as prior exercise-induced muscle fatigue (Marcora, Bosio, & De Morree, 2008) or damage (Davies et al., 2009), and increases in body temperature (Hayashi, Honda, Ogawa, Kondo, & Nishiyasu, 2006).

Investigating the effect of exercise duration on perceptual and physiological responses may provide further insight into the link between $f_R$ and RPE. To this end, in the present study three TTs differing in exercise duration (10 min, 20 min and 30 min) were compared. A TT paradigm was used since RPE is recognised as playing a crucial role in regulating workload during self-paced exercise (De Koning et al., 2011; Marcora,

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2010; Tucker, 2009). Besides, we avoided adopting a TTE protocol because it would have confounded the effect of exercise duration on physiological responses, since duration is a function of exercise intensity in a TTE paradigm. We hypothesised that during self-paced exercise of different durations, $f_R$, but no other cardiorespiratory or gas exchange parameter, would have a similar time course as well as a strong relationship to RPE.

## Methods

### Participants

Nine male participants (mean ± SD: age 23 ± 3 years, stature 1.77 ± 0.03 m, body mass 69 ± 6 kg) volunteered to participate in this study. All participants gave their written informed consent according to the declaration of Helsinki. The experimental protocols were approved by the Ethics Committee of the University of Rome Sapienza (243/14). All the participants were well-trained competitive cyclists (De Pauw et al., 2013) with a minimum of 4 years' cycling experience and 250 km training per week. They were asked to refrain from strenuous exercise, consumption of alcohol and caffeine for at least 24 h before each test.

### Experimental overview

All testing was completed in the laboratory with a room temperature of 19–21°C and at the same time of day (± 2 h). Participants reported to the laboratory on four separate occasions over a three-week period, with visits separated by at least 48 hours. In the first visit, participants performed a preliminary ramp incremental exercise test, followed by a familiarisation trial. In the following visits, they performed in a random order three self-paced cycling TTs differing in exercise duration, i.e. 10 min, 20 min and 30 min. All the protocols were performed on an electromagnetically braked cycle ergometer (Lode Excalibur Sport, Groningen, the Netherlands), whose setting was adjusted and recorded for each participant during the first visit to be reproduced in the following visits. Performance, physiological and perceptual responses were measured during all tests.

### Preliminary test and familiarisation trial

Before the incremental test was performed, the Borg 6–20 RPE scale was presented to participants, and appropriate instructions about the scale were given according to established recommendations (Borg, 1998). During the incremental test, participants were asked to rate their perceived exertion every minute during exercise and immediately after exhaustion. Perceived exertion data obtained from this test served for familiarisation purposes and were not used for further analysis.

The ramp incremental test to exhaustion was preceded by a 5-min warm-up at 100 W, 3 min of rest and 3 min pedalling at 20 W. The test consisted of a continuous ramped increase in the work rate of 30 $W{*}min^{-1}$, starting from 20 W. Preferred pedalling cadence (95 ± 2 rpm) was selected by each participant and was kept constant throughout the test, which terminated when cadence fell by more than 10 rpm, despite strong verbal encouragement. During the test, pulmonary gas exchange was measured breath-by-breath as described below. The maximal power output of the test (Pmax) was defined as the highest power output achieved at exhaustion, registered to the nearest 1 W, and the $\dot{V}O_2$max as the highest value of a 30-s average. Breath-by-breath data were averaged over 10 s and the gas exchange threshold (GET) was determined from a cluster of measures including 1) the first disproportionate increase in carbon dioxide output ($\dot{V}CO_2$) from a visual inspection of individual plots of $\dot{V}CO_2$ versus $\dot{V}O_2$, 2) an increase in $\dot{V}_E/\dot{V}O_2$ with no increase in $\dot{V}_E/\dot{V}CO_2$ and 3) an increase in end-tidal $O_2$ tension with no fall in end-tidal $CO_2$ tension (Whipp, 2007). The power output value corresponding to the GET was estimated with account taken of the mean response time of the $\dot{V}O_2$ response, which was assumed to approximate 40 s (Whipp, 2007). After recovering from the incremental exercise test, participants were familiarised with the linear mode of the ergometer used in the TTs. In particular, participants were asked to vary cadence so as to understand the positive exponential relationship between power output and cadence proper of the linear mode (torque is linearly related to cadence, while power output is exponentially related to cadence). In other words, participants experienced that small changes in cadence resulted in relatively important changes in power output.

### Time trials

In visits 2–4, participants performed three TTs differing in exercise duration, i.e. 10 min (TT10), 20 min (TT20) and 30 min (TT30). In each trial, participants were asked to self-regulate the workload so as to achieve the maximal mean power output possible. The TTs were performed with the ergometer set in the linear mode, also called the rpm-dependent mode. For TT20 and TT30, the α linear factor of the ergometer (indicating the slope of the relationship between torque and cadence) was selected according to a previous study where a TT30 was performed by well-trained competitive cyclists (Nicolò, Bazzucchi, Haxhi, et al., 2014). Briefly, the α linear factor was set for each participant considering the 50% Δ (the power output halfway between the GET and Pmax, expressed in W) and the preferred cadence, according to the formula: $\alpha = 50\%\ \Delta/\text{preferred cadence}^2$. Since a TT10 lies within the severe-intensity domain (Jones, Vanhatalo, Burnley, Morton, & Poole, 2010) and a relatively high power output was expected, a slightly different formula was used to obtain the α linear factor for this trial: $\alpha = (50\%\ \Delta/\text{preferred cadence}^2) + 0.001$. In other words, the slope of the relationship between torque and cadence was increased by 0.001, compared with the slope used for the other two TTs.

Before the TTs, a standardised warm-up consisting of 3 min at 100 W, 6 min at 50% of Pmax, 1 min at 60% of Pmax and 1 min at 100 W was performed. Three minutes of rest and 3 min pedalling at 20 W preceded the TTs.

With the exception of elapsed time and time to be completed, no feedback on performance or physiological measurements and no encouragement were given to participants during the TTs, to minimise external factor influence (Currell & Jeukendrup, 2008). Power output and all the physiological parameters were measured continuously during exercise, while RPE was collected every minute.

### Measurements

Pulmonary gas exchange, ventilatory parameters ($f_R$, minute ventilation ($\dot{V}_E$) and tidal volume) and heart rate (HR) were measured breath-by-breath using open-circuit indirect calorimetry (Quark b2, Cosmed, Rome, Italy). Appropriate calibration procedures were performed following the manufacturer's instructions.

### Data analysis

When expressing physiological parameters against relative exercise duration, values were averaged over 1, 2 and 3 min for TT10, TT20 and TT30, respectively. Data averaged in this way were also used to relate $f_R$, minute ventilation and HR with RPE. Since RPE was measured at discrete points in time (every minute during exercise), values collected every 1, 2 and 3 min for TT10, TT20 and TT30, respectively, were considered to express RPE values as a % of total duration of exercise, to calculate mean values and to obtain the relationship between RPE and the three above-cited physiological parameters.

For all the physiological parameters reported in Table 1 and all the TTs, the peak value was defined as the highest value obtained from a 30 s average. The same analysis was used to obtain physiological parameters' maximum values from the incremental test.

**Table 1.** Mean and peak values of performance, physiological parameters and RPE for the three time trials.

| | TT10 | TT20 | TT30 |
|---|---|---|---|
| Power output$_{mean}$ (W) | 345 ± 31 [ab] | 312 ± 34 [b] | 297 ± 31 |
| Cadence$_{mean}$ (rpm) | 98 ± 2 [ab] | 94 ± 2 [b] | 92 ± 2 |
| $\dot{V}O_{2mean}$ (mL·min$^{-1}$) | 4004 ± 316 [ab] | 3839 ± 372 | 3707 ± 372 |
| $\dot{V}O_{2mean}$ (%$VO_2$max) | 91 ± 4 [ab] | 87 ± 4 | 84 ± 4 |
| $\dot{V}O_{2peak}$ (mL·min$^{-1}$) | 4348 ± 326 [b] | 4168 ± 341 | 3993 ± 356 |
| $\dot{V}O_{2peak}$ (%$VO_2$max) | 98 ± 4 [b] | 94 ± 7 | 90 ± 7 |
| $\dot{V}CO_{2mean}$ (mL·min$^{-1}$) | 4003 ± 338 [ab] | 3727 ± 368 [b] | 3523 ± 339 |
| RER$_{mean}$ | 0.99 ± 0.02 [ab] | 0.97 ± 0.02 [b] | 0.95 ± 0.02 |
| HR$_{mean}$ (beats·min$^{-1}$) | 176 ± 7 | 173 ± 7 | 172 ± 6 |
| HR$_{peak}$ (beats·min$^{-1}$) | 187 ± 7 | 185 ± 8 | 184 ± 9 |
| $\dot{V}_{Emean}$ (L·min$^{-1}$) | 137 ± 18 [b] | 127 ± 21 [b] | 118 ± 17 |
| $\dot{V}_{Epeak}$ (L·min$^{-1}$) | 173 ± 23 | 162 ± 26 | 154 ± 28 |
| $f_{Rmean}$ (breaths·min$^{-1}$) | 45 ± 6 | 45 ± 6 | 44 ± 5 |
| $f_{Rpeak}$ (breaths·min$^{-1}$) | 57 ± 7 | 57 ± 6 | 59 ± 8 |
| $V_{Tmean}$ (L) | 3 ± 0.4 [ab] | 2.8 ± 0.4 [b] | 2.7 ± 0.3 |
| $V_{Tpeak}$ (L) | 3.3 ± 0.3 [ab] | 3.1 ± 0.4 | 3 ± 0.4 |
| RPE$_{mean}$ | 16.3 ± 0.6 | 16 ± 0.6 | 15.9 ± 0.6 |
| RPE$_{peak}$ | 19.6 ± 0.7 | 19.7 ± 1.0 | 19.4 ± 1.1 |

*Note*: Values are mean ± SD. TT10 = 10-min time trial, TT20 = 20-min time trial, TT30 = 30-min time trial, $\dot{V}O_2$ = oxygen uptake, $\dot{V}CO_2$ = carbon dioxide output, RER = respiratory exchange ratio, HR = heart rate, $\dot{V}_E$ = minute ventilation, $f_R$ = respiratory frequency, $V_T$ = tidal volume, RPE = rating of perceived exertion

[a]$P < 0.05$ vs. TT20

[b]$P < 0.05$ vs. TT30

### Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics 20 (SPSS Inc, Chicago, Illinois, USA). A one-way repeated-measures ANOVA was used to analyse mean and peak values of performance, physiological parameters and RPE for the three TTs. In case of a significant effect of trial, the Bonferroni test was used as follow-up analysis. Partial eta squared ($\eta_p^2$) effect sizes for the effect of trial were calculated. An effect of $\eta_p^2 \geq 0.01$ indicates a small, $\eta_p^2 \geq 0.059$ a medium and $\eta_p^2 \geq 0.138$ a large effect (Cohen, 1988). A two-way repeated-measures ANOVA (trial x time) was used to analyse the effect of trial on performance, physiological and perceptual parameters as a function of relative exercise duration. When the sphericity assumption was violated, the Greenhouse–Geisser adjustment was performed. Partial eta squared ($\eta_p^2$) effect sizes for the trial x time interaction and for the main effects of trial and time were calculated. In case of a significant interaction, a one-way repeated-measures ANOVA was used to test the simple main effects of trial at different time points, with subsequent follow-up Bonferroni test performed in case of significant simple main effect. In case of a significant main effect of trial, the Bonferroni test was used as a follow-up analysis. Within-subjects correlation coefficients (r) were computed for the correlations among RPE/$f_R$, RPE/$\dot{V}_E$ and RPE/HR, using a previously described method (Bland & Altman, 1995). Briefly, this method adjusts for repeated observations within participants, by using multiple regression with "participant" treated as a categorical factor using dummy variables. A correlation coefficient and a $P$ value were obtained considering the three TTs together, as well as for each TT separately. A $P$ value $< 0.05$ was considered statistically significant in all analyses. The results are expressed as mean (±SD).

## Results

The $\dot{V}O_2$max and the Pmax measured during the ramp incremental test were 4437 ± 472 mL·min$^{-1}$ (65 ± 8 mL·kg$^{-1}$·min$^{-1}$) and 439 ± 34 W, respectively. $\dot{V}O_2$ and power output corresponding to the GET were 2842 ± 325 mL·min$^{-1}$ and 210 ± 31 W, respectively.

Table 1 reports mean and peak values of performance and physiological parameters for the three TTs. An effect of trial ($P < 0.031$, $\eta_p^2 > 0.354$) was found for all the parameters reported in the table, except for RPE, $f_R$ and HR$_{peak}$. Although HR$_{mean}$ and $\dot{V}_{Epeak}$ showed a main effect of trial ($P = 0.023$, $\eta_p^2 = 0.375$ and $P = 0.030$, $\eta_p^2 = 0.355$, respectively), follow-up tests (Bonferroni) only indicated a statistical trend ($P = 0.080$ for TT10 vs. TT20 and $P = 0.084$ for TT10 vs. TT30, for HR$_{mean}$ and $\dot{V}_{Epeak}$, respectively). In addition, no differences were found between $f_{Rpeak}$ values from the three TTs and $f_R$ maximum value registered during the incremental exercise test (60 ± 6).

No interaction but significant main effects both of trial ($P < 0.001$, $\eta_p^2 = 0.954$) and of time ($P < 0.003$, $\eta_p^2 = 0.504$) were observed for absolute power output values expressed against relative exercise duration (Figure 1, panel A). Symbols in the figure show the results of the Bonferroni follow-up analysis for the main effect of trial. The main effect of trial

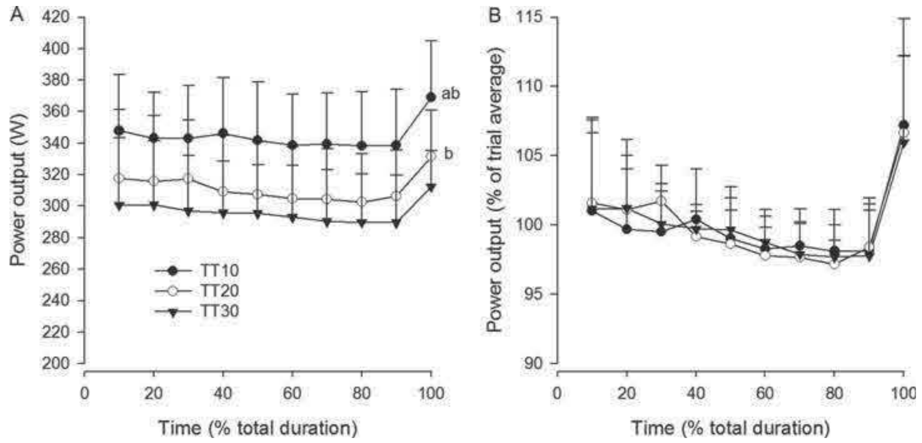


Figure 1. Time course of absolute (A) and normalised (B) power output expressed as a function of relative exercise duration for TT10 (closed circles), TT20 (open circles) and TT30 (closed triangles). Values are mean ± SD. Letters indicate results of follow-up tests for the main effect of trial. (a) $P < 0.05$ vs. TT20; (b) $P < 0.05$ vs. TT3.

disappeared when power output values were normalised for the average power output of each trial (Figure 1, panel B).

Figure 2 reports RPE and $f_R$ responses as a function of absolute (panel A and C) and relative (panel B and D) duration of exercise. While both parameters showed an almost linear increase over time with a less-pronounced rate of increase with absolute exercise duration, neither interaction effect nor main effect of trial was observed when expressing values against relative exercise duration. Conversely, a significant main effect of time ($P < 0.001$, $\eta_p^2 > 0.883$) was found for both RPE and $f_R$. Contrary to RPE and $f_R$, the parameters reported in Figure 3, i.e. $\dot{V}O_2$, HR, $\dot{V}_E$ and tidal volume ($V_T$), all showed a main effect of trial ($P < 0.024$, $\eta_p^2 > 0.374$), time ($P < 0.001$, $\eta_p^2 > 0.801$) as well as an interaction ($P < 0.001$,

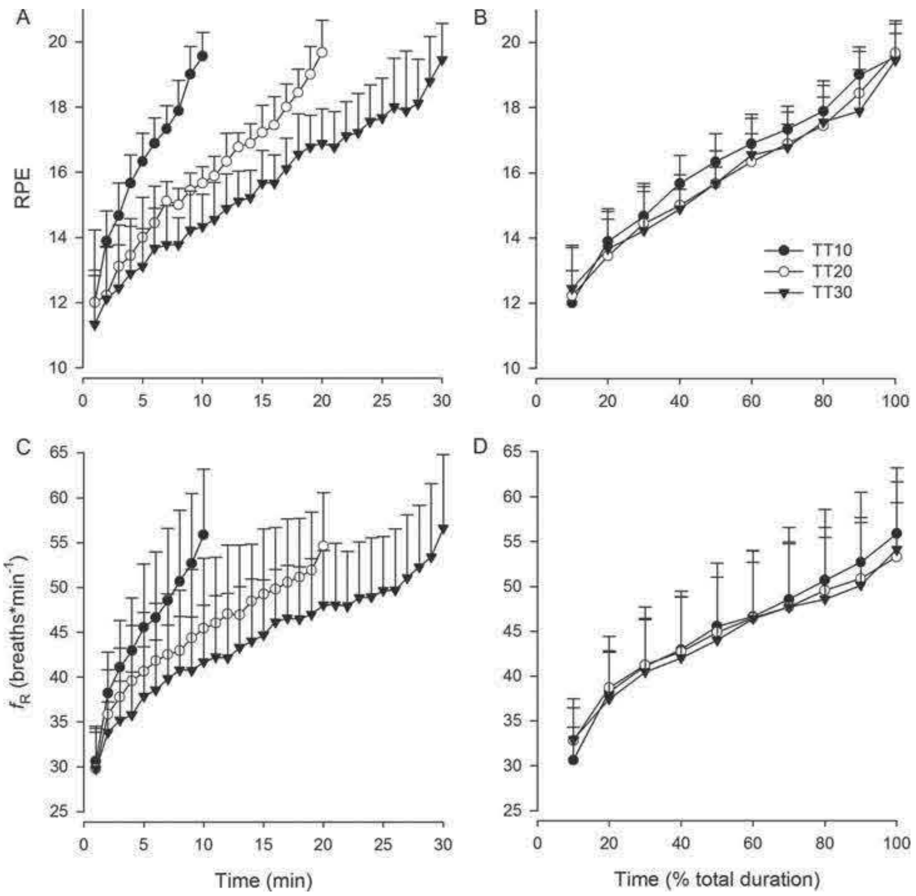


Figure 2. Perceived exertion and respiratory frequency expressed as a function of absolute (A and C) and relative (B and D) duration of exercise for TT10 (closed circles), TT20 (open circles) and TT30 (closed triangles). Values are mean ± SD.

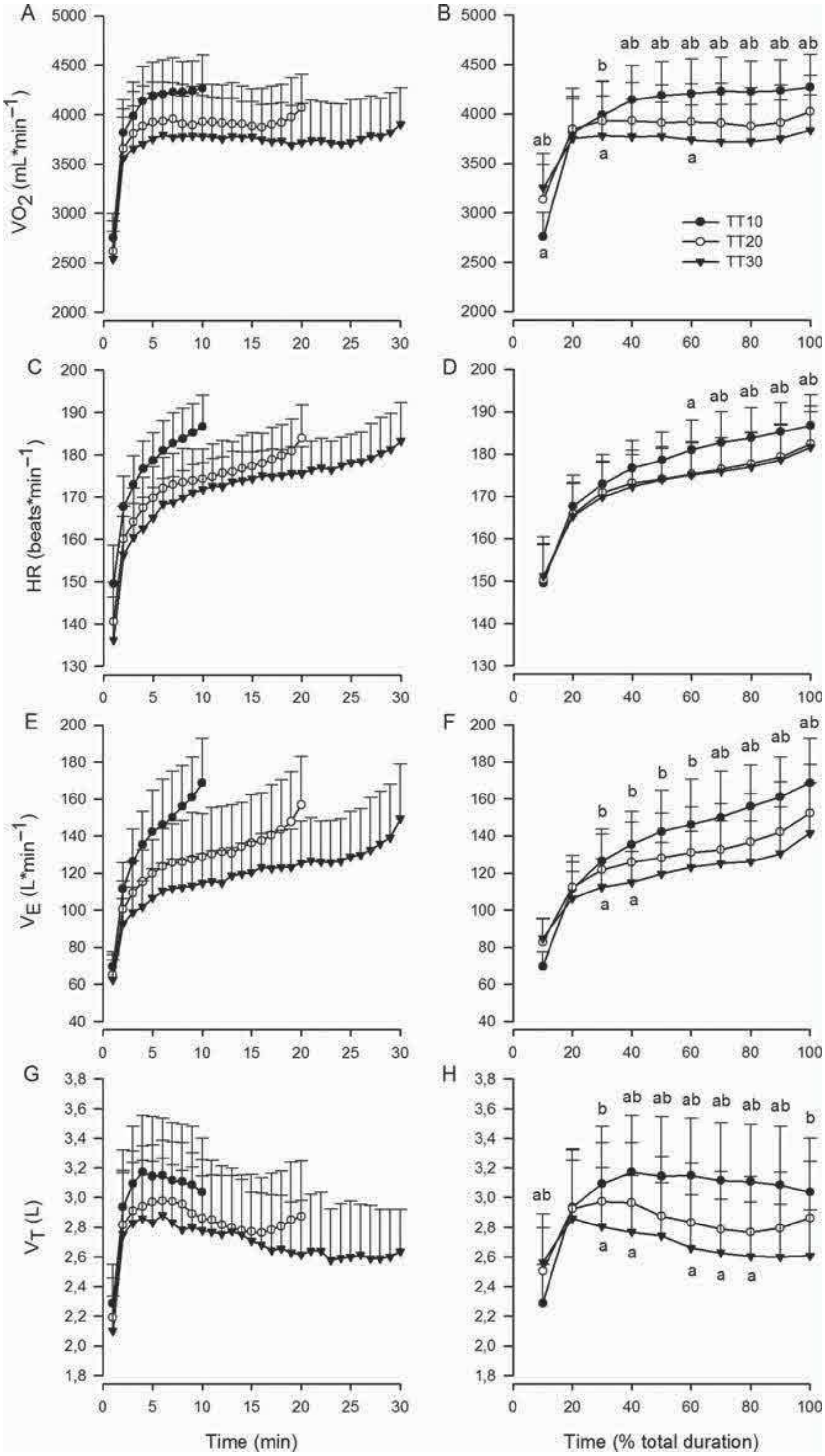


**Figure 3.** $\dot{V}O_2$, HR, $\dot{V}_E$ and $V_T$ expressed as a function of absolute (A, C, E and G) and relative (B, D, F and H) duration of exercise for TT10 (closed circles), TT20 (open circles) and TT30 (closed triangles). Values are mean ± SD. When expressed against relative duration of exercise, a significant interaction was observed for all parameters. Letters indicate results of follow-up tests. (a) $P < 0.05$ vs. TT20; (b) $P < 0.05$ vs. TT30.

$\eta_p^2 > 0.298$), when expressed against relative exercise duration (panels B, D, F and H). Symbols in the figure show the results of the Bonferroni follow-up analysis.

RPE was significantly related ($P < 0.001$) with $f_R$ (r = 0.89), $\dot{V}_E$ (r = 0.80) and HR (r = 0.81) when the three TTs were considered together. Significant correlations (all $P$ levels < 0.001) were also observed between RPE and the three physiological parameters in all the TTs considered separately, i.e. $f_R$ (TT10 = 0.94; TT20 = 0.88 and TT30 = 0.90), $\dot{V}_E$ (TT10 = 0.91; TT20 = 0.83 and TT30 = 0.84) and HR (TT10 = 0.89; TT20 = 0.83 and TT30 = 0.80). These relationships are represented in Figure 4, which shows that only $f_R$ is

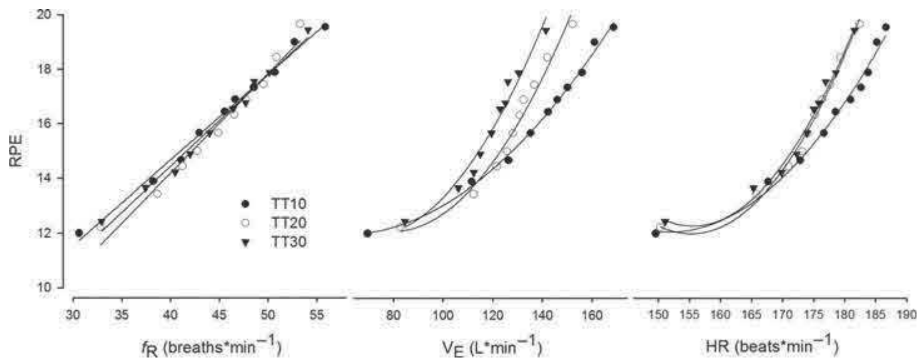


**Figure 4.** Relationships between RPE/$f_R$, RPE/$\dot{V}_E$ and RPE/HR for TT10 (closed circles), TT20 (open circles) and TT30 (closed triangles). Each symbol represents the mean value of all participants at each time point.

linearly related with RPE across the entire duration of exercise, since the relationships between RPE/$\dot{V}_E$ and RPE/HR are better described by a non-linear function (parabolic). The figure also shows that RPE/$\dot{V}_E$ and RPE/HR relationships – but not RPE/$f_R$ relationship – are affected by exercise duration.

## Discussion

The main original finding is that, among the cardiorespiratory and gas exchange parameters measured in the present study, $f_R$ is the only one to consistently show a strong relationship and a similar time course to RPE across all three TTs (10 min, 20 min and 30 min). This indicates that $f_R$ is the best correlate of RPE during self-paced exercise, at least among the parameters and for the range of exercise duration herein investigated. Since the increase in RPE during exercise is recognised as being a major feature of fatigue (Enoka & Stuart, 1992; Noakes, 2004), as well as playing a pivotal role in regulating pacing during exercise (De Koning et al., 2011; Eston, 2012; Marcora, 2010; Tucker, 2009), the present findings suggest that $f_R$ is an important physiological parameter to be monitored during self-paced exercise.

Similar to RPE, we found a progressive almost linear increase of $f_R$ in all the trials, maximal $f_R$ values reached at the end of exercise and a decline in the rate of increase in $f_R$ with the increase in absolute exercise duration. These data corroborate findings from previous studies that reported similar $f_R$ responses during various exercise paradigms, i.e. continuous TTE (Davies et al., 2009; Kift & Williams, 2007), continuous TT (Wuthrich, Eberle, & Spengler, 2014), intermittent TTE (Nicolò, Bazzucchi, Lenti, et al., 2014) and intermittent TT (Nicolò, Bazzucchi, Haxhi, et al., 2014). However, very few studies, limited to the investigation of TTE protocols, reported $f_R$ values expressed against relative exercise duration (Davies et al., 2009; Pires et al., 2011). Among these, Davies et al. (2009) pointed out that the effect of exercise-induced muscle damage on $f_R$ and $V_E$ responses disappeared when the values were expressed against the % of TTE.

This is the first study that systematically investigated, using a TT paradigm, the effect of exercise duration on the relationship between RPE and the physiological parameters supposed to predominantly mediate perceived exertion. We found that $f_R$ was better related to RPE than any other physiological parameter. While exercise duration did not affect the relationship between RPE and $f_R$, it did affect the relationships between RPE and both $\dot{V}_E$ and HR. Our data also show that only $f_R$ has a strong linear relationship with RPE across the entire duration of exercise. The relationships between RPE and both $\dot{V}_E$ and HR were better described by a non-linear function, particularly when considering the entire duration of exercise.

While the majority of evidence linking HR with RPE is derived from correlational data, several experimental interventions managed to dissociate the two parameters (Robertson, 1982). Conversely, previous studies attempting to dissociate the respiratory response from RPE found in fact a strong link (Robertson, 1982). Notably, the link between $\dot{V}_E$ and RPE is primarily determined by $f_R$, but not $V_T$ (Robertson et al., 1986). In the present investigation this is particularly evident with the manipulation of exercise duration. Indeed, since $V_T$, but not $f_R$, significantly decreased with exercise duration, $\dot{V}_E$ decreased accordingly, and the relationship between $\dot{V}_E$ and RPE was in turn affected. In this view, it is interesting to report that in a previous investigation $\dot{V}_E$ and RPE response did not dissociate when continuous and different intermittent self-paced protocols – with the same exercise duration – were compared (Nicolò, Bazzucchi, Haxhi, et al., 2014).

Importantly, the strong relationship found between $f_R$ and RPE is consistent with our current understanding of the role of central command in the regulation of ventilation and perceived exertion during exercise. Central command is defined as the activity of premotor and motor areas of the brain related to voluntary muscle contraction (De Morree, Klein, & Marcora, 2012). The corollary discharge of central command to the locomotor muscles projects both to medullary respiratory centres contributing to drive ventilation during exercise (Paterson, 2014) and to sensory areas of the brain generating perceived exertion (Berchicci, Menotti, Macaluso, & DiRusso, 2013; De Morree, Klein, & Marcora, 2014; De Morree et al., 2012; Enoka & Stuart, 1992; Marcora, 2009). Specifically, this corollary discharge is the sensory signal of the leg effort component of overall perceived exertion (Stendardi, Grazzini, Gigliotti, Lotti, & Scano, 2005). Since it has been reported that $f_R$, but not $V_T$, responds to central command to the locomotor muscles

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(Bell & Duffin, 2006; Thornton et al., 2001), a first neurophysiological link between $f_R$ and perceived exertion is evident. Furthermore, the corollary discharge of central command to the respiratory muscles projects to sensory areas of the brain, generating respiratory effort (De Morree & Marcora, 2015; Laviolette & Laveneziana, 2014; O'Donnell et al., 2007), another major component of overall perceived exertion (Marcora, 2009; Stendardi et al., 2005). This corollary discharge constitutes a second neurophysiological link between $f_R$ and RPE. Within such a neurophysiological framework, the strong association observed between $f_R$ and RPE in the present and previous studies is unlikely to be spurious.

The strong correlation with RPE indicates that $f_R$ is a valid physiological measure of effort during self-paced exercise. This confirms and extends previous findings that, among the physiological parameters classically supposed to reflect physiological strain, $f_R$ was the only parameter associated with RPE during both continuous and intermittent self-paced exercise (Nicolò, Bazzucchi, Haxhi, et al., 2014). As suggested by these authors (Nicolò, Bazzucchi, Haxhi, et al., 2014), monitoring $f_R$ may have some advantages over RPE. $f_R$ is an objective physiological parameter that can be measured continuously during exercise. Conversely, RPE relies on self-report and can only be collected at discrete points in time.

Interestingly, we found that the power output values of the three TTs were virtually superimposed when data were normalised for the average power output of each trial. These results suggest that well-trained competitive cyclists use a similar pacing strategy across TTs of different durations. Although these findings may not apply to TTs with durations outside the range here investigated, normalised power output data similar to those observed in the present study have been reported for TTs around 1 h of duration (Skorski et al., 2015). However, it has to be acknowledged that these findings may not be generalised to recreational cyclists or untrained individuals.

## Conclusions

The present study pointed out, for the first time, that during TTs of different durations, $f_R$, but not $\dot{V}_E$, HR or $\dot{V}O_2$, shows a strong relationship and a similar time course to RPE, irrespective of exercise duration. This indicates that $f_R$ is the best correlate of RPE during self-paced exercise, at least among the parameters and for the range of durations herein investigated. Since the increase in RPE over time is recognised as being a major feature of fatigue (Enoka & Stuart, 1992; Noakes, 2004) as well as playing a pivotal role in regulating pacing during exercise (De Koning et al., 2011; Eston, 2012; Marcora, 2010; Tucker, 2009), the present findings suggest that $f_R$ is an important physiological parameter to be monitored during self-paced exercise. The mechanisms underlying the strong link between respiratory frequency and perceived exertion deserve further investigation.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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