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### Interval running with self-selected recovery

Physiology, performance and perception

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1    **Abstract**

2    This study: 1) compared the physiological responses and performance during a high-intensity  
3    interval training (HIIT) session incorporating externally-regulated (ER) and self-selected (SS)  
4    recovery periods; and 2) examined the psychophysiological cues underpinning self-selected  
5    recovery durations. Following an incremental maximal exercise test to determine maximal  
6    aerobic speed (MAS), fourteen recreationally-active males completed two HIIT sessions on a  
7    non-motorised treadmill. Participants performed 12 x 30s running intervals at a target intensity  
8    of 105% MAS interspersed with 30s (ER) or SS recovery periods. During SS, participants were  
9    instructed to provide themselves with sufficient recovery to complete all 12 efforts at the  
10   required intensity. A semi-structured interview was undertaken following the completion of  
11   SS. Mean recovery duration was longer during SS ( $51 \pm 15$ s) compared to ER ( $30 \pm 0$ s;  
12    $P<0.001$ ;  $d=1.46 \pm 0.46$ ). Between-interval heart rate recovery was higher (SS:  $19 \pm 9$   $b \cdot min^{-1}$   
13   ; ER:  $8 \pm 5$   $b \cdot min^{-1}$ ;  $P<0.001$ ;  $d=1.43 \pm 0.43$ ) and absolute time  $\geq 90\%$  maximal heart rate  
14   ( $HR_{max}$ ) was lower (SS:  $335 \pm 193$ s; ER:  $433 \pm 147$ s;  $P=0.075$ ;  $d=0.52 \pm 0.39$ ) during SS  
15   compared to ER. Relative time  $\geq 105\%$  MAS was greater during SS ( $90 \pm 6\%$ ) compared to ER  
16   ( $74 \pm 20\%$ ;  $P<0.01$ ;  $d=0.87 \pm 0.40$ ). Different sources of afferent information underpinned  
17   decision-making during SS. The extended durations of recovery during SS resulted in a reduced  
18   time  $\geq 90\% HR_{max}$  but enhanced time  $\geq 105\% MAS$ , compared with ER exercise. Differences  
19   in the afferent cue utilization of participants likely explain the large levels of inter-individual  
20   variability observed.

21

22   **Key Words:** Fatigue; Exercise; Performance; Physiology; Recovery

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25

26    **Introduction**

27    High-intensity interval training (HIIT) has received considerable attention in research and  
28    applied domains given the reported benefits for general and athletic populations (Buchheit &  
29    Laursen, 2013). HIIT, characterised by the alternation of high-intensity exercise bouts with  
30    periods of lower-intensity recovery, has been advocated as a means of enhancing exercise  
31    performance with improvements likely mediated by favorable alterations in physiological  
32    parameters such as maximal oxygen uptake ( $\dot{V}O_{2\max}$ ) (MacPherson & Weston, 2015), lactate  
33    thresholds (Inoue et al., 2016), and peak power output (Ní Chéilleachair, Harrison, &  
34    Warrington, 2017). From a clinical standpoint, improvements in prognostic and diagnostic  
35    health indicators such as cardiorespiratory fitness (Weston, Taylor, Batterham, & Hopkins,  
36    2014), glucose regulation (Jolleyman et al., 2015), and vascular function (Ramos, Dalleck,  
37    Tjonna, Beetham, & Coombes, 2015) have been reported in response to HIIT.

38         The premise underpinning the cardiovascular and peripheral adaptations induced by  
39    HIIT stems from the ability of such exercise modalities to augment the duration of training  
40    spent at near-maximal intensities (Laursen & Jenkins, 2002). Specifically, time spent  $\geq 90\%$   
41    of maximal heart rate ( $T \geq 90\% HR_{\max}$ ) has been suggested to be particularly important in cases  
42    where enhancements in  $\dot{V}O_{2\max}$  are sought (Bacon, Carter, Ogle, & Joyner, 2013). The  
43    characteristics of work and recovery periods are therefore important components in the  
44    prescription of HIIT as their interaction will likely determine the acute physiological load  
45    (Buchheit & Laursen, 2013). Attempts have been made to document the physiological  
46    responses associated with HIIT formats utilising work/recovery durations (in seconds) of 15/15  
47    and 30/30 (Helgerud et al., 2007; Zuniga et al., 2011). A shared feature of such HIIT formats  
48    is the utilisation of a standardised and externally-prescribed work-to-rest ratio. Specifically,  
49    work-to-rest ratios of 1:1 are commonly adopted during HIIT incorporating short intervals  
50    (Dupont, Akakpo, & Berthoin, 2004; Wong, Chaouachi, Chamari, Dellal, & Wisløff, 2010).

51 Notwithstanding the practicality of organising training in this manner, standardised recovery  
52 durations may not always result in the highest physiological load (Gibson, Brownstein, Ball,  
53 & Twist, 2017).

54 It is well established that improvements in health and performance are maximised when  
55 the intensity of exercise is tailored to an individual's training status and physiological capacity  
56 (McPhee, Williams, Degens, & Jones, 2010). In the context of HIIT, this is often achieved by  
57 manipulating the velocity, speed or power output prescribed during work intervals (Laursen &  
58 Jenkins, 2002). Whilst the appropriateness of such practices is widely accepted, little attention  
59 has been paid to the individualisation of recovery durations. This is somewhat surprising given  
60 the large variability evident amongst individuals in the ability to recover between bouts of high-  
61 intensity exercise (Tomlin & Wenger, 2001). The extent to which standardised or externally-  
62 regulated recovery durations accommodate such differences is therefore questionable.  
63 Crucially, misjudging required recovery may compromise an individual's ability to complete  
64 a given session and/or exercise at the desired intensity. As the intensity at which work intervals  
65 are performed remains central to the effectiveness of HIIT (Munoz, Seiler, Alcocer, Carr, &  
66 Esteve-Lanao, 2015), the programming of inappropriate recovery durations may prove  
67 counterproductive.

68 The prescription of self-selected recovery durations may represent a practically useful  
69 means of individualising recovery periods during HIIT. Nevertheless, research investigating  
70 the efficacy of this approach remains relatively sparse. To date, investigations examining self-  
71 selected recovery periods have primarily utilised repeated sprint protocols, reporting  
72 conflicting results (Gibson et al., 2017; Glaister et al., 2010; Phillips, Thompson, & Oliver,  
73 2014). When instructed to self-select between-sprint recovery durations, Gibson and  
74 colleagues (2017) reported the performance of elite male youth footballers to be likely  
75 compromised and the physiological load to be likely increased during a repeated sprint protocol

76 (10 x 30 m maximal sprints). Conversely, recreationally-active males overestimated required  
77 recovery by at least 10% and were able to maintain performance during 10 x 6 s cycle sprints  
78 when self-selected recovery periods were utilised (Phillips et al., 2014). Moreover, when self-  
79 selected recovery was adopted during HIIT incorporating longer intervals (5 x 1000 m), the  
80 physiological load imposed was similar to that achieved when standardised work-to-rest ratios  
81 were prescribed, despite self-selection resulting in significantly less recovery (Edwards,  
82 Bentley, Mann, & Seaholme, 2011). The use and efficacy of self-selected recovery periods  
83 may be aided by a greater understanding of the goals and decision-making processes associated  
84 with the length of self-selected recovery periods, an area, as yet underrepresented in the  
85 literature.

86 The aim of this study was to investigate physiological, perceptual, and performance  
87 responses during HIIT incorporating 30 s work intervals, when between-interval recovery  
88 durations were self-selected and externally-regulated. Furthermore, an exploratory  
89 investigation of the decision-making processes underpinning self-selected recovery periods  
90 was performed. We hypothesised that when compared to externally-regulated recovery periods,  
91 self-selection of recovery duration would result in: 1) extended durations of recovery; 2) a  
92 reduced  $T \geq 90\% \text{ HR}_{\max}$ ; and 3) better maintenance of the target running speed.

### 93 **Methodology**

#### 94 *Participants*

95 Fourteen recreationally-active males participated (age:  $30 \pm 7$  years; stature:  $179.7 \pm 4.7$  cm;  
96 body mass:  $78.8 \pm 9.0$  kg;  $\dot{V}\text{O}_{2\text{peak}}$ :  $54.0 \pm 7.9 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ). All participants regularly  
97 participated in different forms of HIIT and disclosed no contraindications to exercise of this  
98 nature via a health screening questionnaire. Written informed consent was obtained from all  
99 participants prior to data collection. The study protocols were submitted to and approved by

100 the School of Science and Sport Ethics Committee at the University of the West of Scotland  
101 and all procedures conformed to the Declaration of Helsinki.

102 *Experimental design and overview*

103 A randomised crossover design was used with participants attending the laboratory on three  
104 separate occasions. During the first visit,  $\dot{V}O_{2\text{peak}}$  and maximal aerobic speed (MAS) were  
105 established during an incremental exercise test on a non-motorised treadmill (Woodway Force  
106 3.0, USA). Participants then completed a HIIT protocol on each of the two remaining visits  
107 where physiological and perceptual responses were collected and participant interviews were  
108 conducted. Each session lasted no longer than 45 min, with a minimum of 48 h separating each  
109 session. Participants were requested to refrain from strenuous exercise, alcohol and caffeine  
110 intake for 24 h preceding each trial. Given the impact of alterations in diet upon performance  
111 and mood state, participants were asked to replicate dietary intake prior to each session  
112 (Jeacocke & Burke, 2010).

113 *Familiarisation and preliminary measurements*

114 Participants' stature and body mass were measured using a free-standing stadiometer (Seca  
115 Model 213, Germany) and self-zeroing digital scales (Seca Model 888, Germany),  
116 respectively. A standardised warm-up comprising 5 min jogging at a self-selected pace on a  
117 motorised treadmill (Woodway PPS 55sport-I, USA) was then performed. The non-motorised  
118 treadmill was utilised for all HIIT sessions as in addition to the physiological responses elicited,  
119 we were also interested in examining the impact of self-selected recovery periods on various  
120 measures of performance during HIIT. Given that the majority of participants had not  
121 previously utilised this apparatus, they were provided with a brief period of habituation. Having  
122 first been instructed on the correct technique, participants were tethered to a strut at the rear of  
123 the treadmill and were permitted a series of short practice runs whereby they were asked to  
124 maintain a running speed of  $7 \text{ km}\cdot\text{h}^{-1}$ . A velocity trace plotted against a line representative of

125 the target running speed was visually depicted on the user interface of the treadmill. Practice  
126 runs were ~15 s in duration and performed until participants were comfortable with the  
127 apparatus, demonstrating an ability to maintain the target running speed with minimal  
128 fluctuations.

129 The  $\dot{V}O_{2\text{peak}}$  and MAS of participants were then assessed during an incremental test to  
130 volitional exhaustion on the non-motorised treadmill (Morgan, Laurent, & Fullerkamp, 2015).  
131 Participants were instructed to perform to the best of their ability and received encouragement  
132 throughout. To help maintain the appropriate running speed, participants were again provided  
133 with real-time feedback in the form of a visual velocity trace. Participants were instructed to  
134 commence running at  $7 \text{ km}\cdot\text{h}^{-1}$  for the first minute with the target speed increasing by  $1 \text{ km}\cdot\text{h}^{-1}$   
135 every minute thereafter. Participants were instructed to maintain a consistent running speed  
136 and reminders were provided by the lead investigator when fluctuations occurred. Exact  
137 running speeds achieved were ascertained by averaging data over 20 s periods. To measure  
138 respiratory variables, participants breathed through a one-way directional valve system  
139 connected to an online gas analyser (Medgraphics Ultima, USA).  $\dot{V}O_{2\text{peak}}$  was taken as the  
140 single highest  $VO_2$  value recorded using 15-breath moving averages (Scheidler, Garver, &  
141 Hanson, 2017). Heart rate (HR) was monitored throughout the test via a chest-worn HR  
142 monitor (Polar Electro, Finland) with  $HR_{\text{max}}$  being taken as the highest value recorded. MAS  
143 was defined as the lowest running speed at which  $\dot{V}O_{2\text{peak}}$  was attained (Hill & Rowell, 1996).

144 *HIIT protocol*

145 In a counterbalanced order, participants completed an adapted version of the HIIT protocol  
146 utilised by Millet and colleagues (2003) whereby between-interval recovery was either  
147 externally-regulated at 30 s (ER) or self-selected (SS). Twelve 30 s intermittent runs at a target  
148 intensity of 105% MAS were completed during each session. Between-interval recovery  
149 periods were fixed at 30 s during ER so as to maintain a 1:1 work-to-rest ratio – a practice

150 commonly adopted during HIIT incorporating short intervals (Dupont et al., 2004; Wong et al.,  
151 2010). Running intervals commenced from a standing start with participants instructed to attain  
152 the target speed as soon as possible from the onset of each effort. Participants were not provided  
153 with any verbal encouragement. To replicate the programming of HIIT within the applied  
154 setting (Buchheit & Laursen, 2013), participants did not have access to continual feedback  
155 concerning running speed or physiological parameters during work intervals; however, a single  
156 verbal cue was provided during each interval to affirm attainment of 105% MAS. On receiving  
157 this cue, participants were instructed to “*maintain this speed as best as possible for the*  
158 *remainder of the work interval*”. During SS, participants were required to self-select the  
159 duration of their between-interval recovery periods. In this regard, participants were instructed  
160 to “*provide yourself with sufficient recovery so as to enable yourself to complete all twelve*  
161 *efforts at the required intensity*”. Instructions were carefully considered to ensure no  
162 expectation of recovery was set with the term “*sufficient*” being deemed appropriate.  
163 Participants were not provided with any verbal or visual feedback on recovery duration.

164 *Outcome measurements*

165 *Physiological*. HR data was collected at a sampling rate of 1 Hz with the absolute  $T \geq 90\%$   
166  $HR_{max}$  during each session recorded. Heart rate recovery (HRR), defined as the absolute  
167 difference between HR taken at the start and end of each recovery period (Buchheit, Simpson,  
168 Haddad, Bourdon, & Mendez-Villanueva, 2012) was recorded whilst the cardiovascular drift  
169 ( $HR_{drift}$ ) in peak and recovery HR was also analysed. Peak  $HR_{drift}$  was defined as the difference  
170 between the HR recorded at the end of the first and final work intervals. Recovery  $HR_{drift}$  was  
171 defined as the difference between the HR recorded at the end of the first and final recovery  
172 periods.

173 Blood lactate concentrations ( $[La^-]_b$ ) were assessed prior to the warm-up, immediately  
174 after, and 5 min post-HIIT. Fingertip blood samples were collected in 20  $\mu l$  capillary tubes

175 and analysed within 30 min of collection using a commercially available bench top analyser  
176 (Biosen C Line, Germany).

177 *Performance.* Mean recovery duration during SS was calculated. Running speed data were  
178 obtained during each repetition of the HIIT protocol at a sampling rate of 4 Hz. Mean running  
179 speed was calculated for each 30 s work interval whilst the relative time  $\geq$  105% MAS ( $T \geq$   
180 105% MAS) was determined.

181 *Perceived exertion.* Differential ratings of perceived exertion (d-RPE) were collected within 2  
182 min of completion of each HIIT session (McLaren, Smith, Spears, & Weston, 2017; Weston,  
183 Seigler, Bahnert, McBrien, & Lovell, 2015). Participants used the centiMax scale (CR100) to  
184 differentiate between local muscle (RPE-muscular) and central (RPE-breathlessness) effort  
185 experienced during each protocol. A measurement of total exertion (RPE-total) was also  
186 obtained. Participants were instructed on the correct use of the scale during habituation  
187 sessions and ratings were collected in a counterbalanced manner to eliminate order effects.

188 *Semi-structured interview.* Participants completed a semi-structured interview  $\sim$ 10 min after  
189 the SS trial. A list of open-ended questions were used to guide the interview and assess  
190 participants' goals for the HIIT session as well as the internal/external cues utilised during the  
191 decision-making process. Prior to the commencement of the study, questions were reviewed  
192 and adapted by a researcher experienced in qualitative research so as to ensure that they would  
193 not lead participants to particular responses. All interviews were conducted by the lead  
194 researcher in a quiet room and lasted  $14 \pm 4$  min (range: 10-21 min). With the permission of  
195 participants, interviews were audio recorded. Whilst all participants were interviewed,  
196 malfunctions with audio recordings occurred with two participants resulting in modest data  
197 attrition ( $n = 12$  interviews were analysed).

198 *Statistical and thematic analyses*

199 Data were checked for normality using the Shapiro-Wilk test and were deemed appropriate for  
200 parametric analyses ( $P > 0.05$ ). Differences between trials were examined using paired sample  
201 t-tests with mean differences and 95% confidence intervals (CI) for real change calculated.  
202 Mean standardised differences are reported as Cohen's  $d$  and are reported alongside the  
203 standard error of the effect size estimate. Mean standardised differences were interpreted as  
204 small ( $d \geq 0.2$ ), moderate ( $d \geq 0.5$ ), and large ( $d \geq 0.8$ ) (Cohen, 1992). Statistical significance  
205 was set at  $P \leq 0.05$  and unless otherwise stated, quantitative data are presented as means and  
206 standard deviations (mean  $\pm$  SD). All statistical procedures were completed using Statistical  
207 Package for Social Sciences (SPSS 22.0, IBM, USA).

208 Qualitative data were analysed using concurrent deductive and inductive content  
209 analysis (Sparkes & Smith, 2013) whereby the analysis was based upon two *a priori* research  
210 themes (goals and internal/external cues) whilst remaining open to emergent findings within  
211 participants' responses. Firstly, the audio-recordings were transcribed verbatim and  
212 subsequently double-checked to ensure accuracy. Close reading of the text was then  
213 undertaken by the lead researcher to ensure familiarity with the data. Raw data units were then  
214 created from participants' words before being grouped into categories and then higher order  
215 themes. During analysis, internal homogeneity (that data within a category share clear  
216 characteristics) and external heterogeneity (clear differences exist between different  
217 categories) was sought (Patton, 2001). In order to ensure the trustworthiness of the  
218 aforementioned analyses, the lead and second researchers discussed and confirmed the  
219 allocation of raw data units to specific categories through constructive debate.

220 **Results**

221 Physiological, performance, and perceptual data are presented in Table I.

222 *Physiological*

223 No differences were observed in  $T \geq 90\% HR_{max}$  between conditions ( $P = 0.075$ ); however,  $T$   
224  $\geq 90\% HR_{max}$  was increased to a moderate extent during ER compared to SS ( $d = 0.52 \pm 0.39$ ;  
225 95% CI -11-207 s). Mean HRR was lower during ER compared to SS ( $P < 0.001$ ) with a large  
226 effect size being evident ( $d = 1.43 \pm 0.43$ ; 95% CI 7-15  $b \cdot min^{-1}$ ). No differences were observed  
227 in peak  $HR_{drift}$  between conditions ( $P = 0.272$ ); however, peak  $HR_{drift}$  was reduced to a small  
228 extent during ER compared to SS ( $d = 0.31 \pm 0.38$ ; 95% CI -2-8  $b \cdot min^{-1}$ ). Recovery  $HR_{drift}$  was  
229 greater during ER compared to SS ( $P < 0.01$ ) with a large effect size being evident ( $d = 0.96 \pm$   
230 0.40; 95% CI 6-23  $b \cdot min^{-1}$ ). The HR dynamics of a representative participant during ER and  
231 SS is in Figure 1. No differences were observed between conditions in  $[La^-]_b$  at any time point.

### 232 *Performance*

233 Mean recovery duration was longer ( $P < 0.001$ ) during SS compared to ER with large effect  
234 sizes being evident ( $d = 1.46 \pm 0.46$ ; 95% CI 13-30 s; Figure 2). Mean running speed was  
235 greater ( $P < 0.05$ ) during SS compared to ER with a medium effect size being evident ( $d = 0.73$   
236  $\pm 0.38$ ; 95% CI 0.07-0.64  $km \cdot h^{-1}$ ). Relative  $T \geq 105\% MAS$  was greater ( $P < 0.01$ ) during SS  
237 compared to ER with a large effect size being evident ( $d = 0.87 \pm 0.40$ ; 95% CI 5-27%).

### 238 *Perceptual*

239 No differences in RPE-breathlessness ( $P = 0.134$ ) were observed between conditions; however,  
240 RPE-breathlessness was increased to a small extent in ER compared to SS ( $d = 0.43 \pm 0.38$ ;  
241 95% CI -2-12 AU). No differences were observed in RPE-muscular ( $P = 0.442$ ) between  
242 conditions; however, RPE-muscular was reduced to a small extent during ER compared to SS  
243 ( $d = 0.21 \pm 0.38$ ; 95% CI -15-7 AU). No differences were observed between conditions in  
244 RPE-total ( $P = 0.338$ ); however, RPE-total was increased to a small extent during ER compared  
245 to SS ( $d = 0.27 \pm 0.38$ ; 95% CI -4-10 AU).

### 246 *Qualitative data*

247 In relation to the objectives of participants during SS, three distinct types of goal were  
248 identified: performance-related, outcome-related, and those related to the maintenance of a  
249 positive affective state (Figure 3). Performance goals included the maintenance of the  
250 appropriate running speed across each work interval ( $n = 7$ ) whilst outcome goals related to the  
251 completion of the session ( $n = 10$ ) as well as the optimisation of the physiological stimulus for  
252 training adaptations to be achieved ( $n = 5$ ). Other objectives highlighted by participants were  
253 to remain comfortable and avoid unnecessary physiological stress ( $n = 5$ ) and to generally feel  
254 good ( $n = 1$ ).

255 When determining when to recommence the next high-intensity interval, participants  
256 were found to use a range of afferent feedback cues (Figure 3). Amongst these, the stabilisation  
257 of respiratory rate ( $n = 10$ ) and the magnitude of the drop in HR occurring between intervals  
258 ( $n = 6$ ) were commonly mentioned as being pivotal in determining the length of recovery.  
259 Additional cues related to feelings of muscular recovery ( $n = 6$ ), general feelings of being ready  
260 to recommence the next interval ( $n = 7$ ), and subjective feelings of being comfortable again ( $n$   
261 = 1).

## 262 **Discussion**

263 In agreement with our hypotheses, the self-selection of between-interval recovery durations  
264 resulted in the following: 1) significantly extended durations of recovery; 2) a moderately  
265 reduced  $T \geq 90\% \text{ HR}_{\max}$ ; and 3) an enhanced ability to perform at the target running speed. The  
266 present study is also the first to examine the goals and decision-making processes underpinning  
267 self-selected recovery intermissions. Whilst our relatively small sample size and the  
268 exploratory nature of the qualitative arm of the investigation compromises our ability to  
269 provide firm conclusions surrounding the psychophysiological mechanisms, our qualitative  
270 data may provide an insight into the disparate responses observed during HIIT incorporating  
271 self-selected recovery periods. Specifically, differences in the afferent cues used and goal

272 orientations of participants may explain the large inter-individual variability shown to exist in  
273 the performance and physiological and perceptual responses.

274 *Physiological, performance, and perceptual responses*

275 Central to the effectiveness of HIIT is the ability to maximise the duration of training  
276 undertaken at high relative intensities (Laursen & Jenkins, 2002). Where enhancements of  
277 cardiorespiratory fitness are sought,  $T \geq 90\% HR_{max}$  may be important (Bacon et al., 2013). In  
278 the present investigation, we report the  $T \geq 90\% HR_{max}$  to have been moderately lower ( $d =$   
279  $0.52 \pm 0.39$ ) during SS compared to ER. Consequently, when HIIT is utilised as a conditioning  
280 tool for the enhancement of  $\dot{V}O_{2max}$ , our data suggest the use of self-selected recovery periods  
281 to be potentially unfavorable. The moderately reduced  $T \geq 90\% HR_{max}$  observed during SS  
282 may be viewed as a direct consequence of the extended recovery taken during this condition.  
283 Indeed, self-selected recovery durations were 21 s (95% CI 13-30 s) longer than the 30 s  
284 afforded during ER and coincided with a significantly greater mean HRR. Given the passive  
285 nature of these recovery periods, the impact of extended recovery durations upon participants'  
286 HR dynamics is unsurprising (Figure 1). Whilst peak  $HR_{drift}$  was comparable between  
287 conditions, recovery  $HR_{drift}$  was significantly reduced when between-interval recovery periods  
288 were self-selected. Additionally, inspection of individual responses revealed that the recovery  
289 HR (recorded at the end of each recovery period) of several participants ( $n = 5$ ) declined as the  
290 session continued, a finding which may be explained by our qualitative data (Figure 3).

291 Notwithstanding the importance of peripheral feedback in the regulation of effort (St  
292 Clair Gibson, Swart, & Tucker, 2017), our findings suggest a reliance on cardiopulmonary  
293 sources of afferent information when self-selecting recovery periods. Indeed, qualitative data  
294 revealed six participants waited for their HR to recover to a rate they perceived to be sufficient  
295 to commence the next effort. Additionally, 10 participants suggested that the stabilisation of  
296 respiratory rate was their major cue for initiating the next interval. Such data may therefore

297 help explain the extended recovery periods adopted during SS and the concomitantly greater  
298 HRR. Although disputed within the literature (Inzlicht & Marcra, 2016), the integrative  
299 governor theory suggests that exercise regulation is the result of a dynamic competition  
300 between physiological and psychological drives (St Clair Gibson, 2017). Specifically, this  
301 model suggests that individuals who have a strong physiological protective drive will likely  
302 always complete a given exercise event but will do so in a manner by which excessive  
303 disruption to bodily homeostasis is avoided. In the current investigation, the completion of  
304 HIIT sessions ( $n = 10$ ) and completion of sessions whilst maintaining a comfortable state ( $n =$   
305 5) were identified as common goals set by participants. Interestingly, all participants who cited  
306 the completion of HIIT sessions as their objective were also found to have utilised HR and/or  
307 respiratory rate when gauging their perceived readiness to commence the next interval.

308 In line with the moderately reduced  $T \geq 90\% \text{ HR}_{\max}$ , we found a small non-significant  
309 reduction in RPE-breathlessness following SS compared to ER. Interestingly, no differences  
310 in RPE-total were evident between the two conditions. Given the slightly reduced  
311 cardiorespiratory load perceived when self-selected recovery periods were adopted, RPE-total  
312 during SS may have been mediated by a perceived increase in peripheral demand. Indeed,  
313 although non-significant, a small effect size indicated RPE-muscular to be slightly greater  
314 during SS compared to ER. Interestingly, although McLaren et al., (2017) have previously  
315 reported greater  $[La^-]_b$  to coincide with increased perceptions of peripheral demand, no  
316 differences in  $[La^-]_b$  were evident between conditions at any time point post-HIIT. An  
317 alternative explanation for the slightly greater RPE-muscular observed during SS may reside  
318 in the greater time above 105% MAS in this trial. Although  $[La^-]_b$  remained unchanged  
319 between the two conditions, the faster running speeds attained during SS are likely to have  
320 imposed a greater stress on the musculoskeletal system, thereby offering a partial explanation  
321 for the slightly greater peripheral demand perceived by participants during this condition.

322 Furthermore, results from the present study would suggest that the afferent feedback  
323 influencing subject's decision to commence exercise as identified in the qualitative analysis  
324 were undetected by the d-RPE scales. Whilst easy to administer, our data may question the  
325 usefulness of such approaches when attributing exertion to specific physiological systems.

326         Although resulting in a moderately reduced  $T \geq 90\% \text{ HR}_{\max}$  ( $d = 0.52 \pm 0.39$ ), self-  
327 selected recovery periods facilitated an enhanced  $T \geq 105\% \text{ MAS}$  and the attainment of  
328 significantly higher running speeds (~3%). Our findings are consistent with those of Seiler and  
329 Hetlelid (2005) who documented a 2% increase in running performance during HIIT (six 4 min  
330 work periods) when recovery durations were increased from 1 to 2 min. Two possible  
331 explanations may be offered. Firstly, the extended recoveries may have allowed for greater  
332 recovery of phosphocreatine stores. Secondly, whilst target intensities of 105% MAS were set,  
333 actual running speed was self-regulated by participants in an autonomous manner. The  
334 disparate mechanical output profiles exhibited during the work intervals of SS and ER may  
335 therefore highlight the adoption of pacing strategies and differences in the central neural drive  
336 provided to the exercising muscles (Mendez-Villanueva, Hamer, & Bishop, 2007). In addition  
337 to knowledge regarding the demands of the activity, muscle activation and recruitment is a  
338 consequence of the available between-interval recovery (Billaut, Bishop, Schaerz, & Noakes,  
339 2011). It could be suggested that when recovery periods are externally-regulated during HIIT,  
340 pacing tactics aimed at the prevention of significant homeostatic disturbance and premature  
341 exercise termination may be adopted (Tucker, 2009). Conversely, a greater neural drive might  
342 be allocated to a task when between-interval recovery periods are self-selected; however, this  
343 remains speculative and represents an avenue for future research.

344 *Inter-individual variability*

345 Whilst we set out to document the responses observed within a homogenous group of  
346 recreationally-active males, the very nature of self-regulation exposes our results to high levels

347 of inter-individual variability. Consequently, the primary limitation of the current study resides  
348 in our ability to extrapolate our results to different populations. For instance, the range in mean  
349 self-selected recovery durations was substantial (30-88 s) as were physiological and  
350 performance responses. Indeed, the range in  $T \geq 90\% HR_{max}$  was substantially greater during  
351 SS (27-772 s) compared to ER (152-642 s). A potential explanation for such variation may  
352 reside in the different goal orientations of participants (Figure 3). For example, participants  
353 who set outcome goals such as the completion of the HIIT series ( $n = 10$ ) are likely to have  
354 “managed” the session differently to those who aimed to optimise the physiological load  
355 required for training adaptations to be achieved ( $n = 5$ ) (St Clair Gibson et al., 2017).  
356 Furthermore, performance-related goals such as the maintenance of the specified running speed  
357 across each work interval ( $n = 7$ ) were also commonly set; when participants’ attention is on  
358 the maintenance of performance, longer recoveries are likely to be taken. In support of these  
359 suggestions, Phillips et al., (2014) reported self-selected recovery durations during a repeated  
360 cycle sprint protocol to be overestimated by at least 10% when participants were instructed to  
361 take sufficient recovery so that they were able to replicate the performance achieved during a  
362 criterion sprint.

363 *Practical applications*

364 As self-selected recovery periods resulted in a moderately reduced  $T \geq 90\% HR_{max}$  ( $d = 0.52 \pm$   
365 0.39) during HIIT, such modes of recovery may be unfavorable when enhancements of aerobic  
366 fitness are sought. However, in instances where maintaining the prescribed intensity is the  
367 aim, self-selected recovery may be beneficial. Such examples may include tapering periods  
368 whereby the primary goal is to minimise accumulated fatigue from previous training through  
369 reductions in training volume and frequency with the maintenance of training intensity (Pyne,  
370 Mujika, & Reilly, 2009).

371 *Conclusions*

372 When afforded autonomy over between-interval recovery durations during an acute bout of  
373 HIIT, recreationally-active males adopted longer recovery periods than the 30 s permitted  
374 during an externally-prescribed trial. A moderately reduced  $T \geq 90\% HR_{max}$  but enhanced  
375 running performance was therefore exhibited in response to self-selected recovery periods. Our  
376 findings were subject to large levels of inter-individual variability with qualitative data  
377 highlighting a wide variety of goal orientations and sources of afferent information utilised by  
378 participants. Consequently, our findings should not be interpreted as being generalisable and  
379 additional research is required to elucidate the efficacy of such training modalities within  
380 individuals of varying demographics.

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491 **Tables****Table I.** Physiological, performance and perceptual responses elicited during externally-regulated (ER) and self-selected (SS) recovery conditions (n = 14)

	Externally-regulated recovery (ER)	Self-selected recovery (SS)
<i>Physiological</i>		
T $\geq$ 90% HR <sub>max</sub> (s)	433 $\pm$ 147 (27-772)	335 $\pm$ 193 (152-642)
Mean HRR (b·min <sup>-1</sup> )	8 $\pm$ 5 (2-20)	19 $\pm$ 9 (6-34) ***
Peak HR <sub>drift</sub> (b·min <sup>-1</sup> )	20 $\pm$ 6 (11-30)	18 $\pm$ 10 (4-38)
Recovery HR <sub>drift</sub> (b·min <sup>-1</sup> )	20 $\pm$ 9 (5-36)	6 $\pm$ 20 (-31-35) **
[La <sup>-</sup> ] <sub>b</sub> baseline (mmol·L <sup>-1</sup> )	1.01 $\pm$ 0.33 (0.55-1.64)	1.04 $\pm$ 0.30 (0.53-1.66)
[La <sup>-</sup> ] <sub>b</sub> post-HIIT + 0 min (mmol·L <sup>-1</sup> )	9.39 $\pm$ 3.16 (5.74-16.50)	8.78 $\pm$ 3.59 (3.44-15.25)
[La <sup>-</sup> ] <sub>b</sub> post-HIIT + 5 min (mmol·L <sup>-1</sup> )	7.15 $\pm$ 2.61 (4.12-14.60)	6.95 $\pm$ 2.92 (2.83-12.60)
<i>Performance</i>		
Mean recovery duration (s)	30 $\pm$ 0 (30-30)	51 $\pm$ 15 (30-88) ***
Mean running speed (km·h <sup>-1</sup> )	12.37 $\pm$ 0.93 (10.54-13.62)	12.72 $\pm$ 1.11 (11.15-14.50) *
T $\geq$ 105% MAS (%)	74 $\pm$ 20 (31-96)	90 $\pm$ 6 (46-95) **
<i>Perceptual</i>		
RPE-breathlessness (AU)	85 $\pm$ 12 (55-100)	80 $\pm$ 10 (68-98)
RPE-muscular (AU)	71 $\pm$ 17 (37-95)	75 $\pm$ 19 (25-95)
RPE-total (AU)	87 $\pm$ 11 (55-100)	84 $\pm$ 11 (60-95)

Data are presented as mean  $\pm$  SD (range). T  $\geq$  90% HR<sub>max</sub>, absolute time  $\geq$  90% of maximal heart rate; HRR, magnitude of between-interval heart rate recovery; HR<sub>drift</sub>, cardiovascular drift; T  $\geq$  105% MAS, relative time  $\geq$  105% of maximal aerobic speed; RPE, rating of perceived exertion. \* Significant difference (P < 0.05) from ER; \*\* significant difference (P < 0.01) from ER; \*\*\* significant difference (P < 0.001) from ER.

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499 **Figures**

500

501 **Figure 1.** Heart rate dynamics of a representative subject during externally-regulated (ER; A)  
502 and self-selected (SS; B) recovery conditions.

503

504 **Figure 2.** Durations of between-effort recovery adopted across each recovery interval during  
505 externally-regulated (ER) and self-selected (SS) recovery conditions ( $n = 14$ ). Data are  
506 presented as mean  $\pm$  SD.

507

508 **Figure 3.** Psychophysiological cues and goals reported by participants during semi-structured  
509 interviews to have underpinned self-selected recovery durations ( $n = 12$ ).

510