

1 **Reference:** James, C.J., Willmott, A.G.B., Dhawan, A., Stewart, C., and Gibson, O.R. (2021).
2 Increased air temperature decreases high-speed, but not total distance, in international field
3 hockey. *Temperature*. 10.1080/23328940.2021.1997535.

4
5 **Title:** Increased air temperature decreases high-speed, but not total distance, in international field
6 hockey

7
8 **Submission type:** Original research article

9
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24
25 **Suggested Running Head:** *Impact of temperature on international hockey*

26
27 **Abstract Word Count:** 245

28 **Text-Only Word Count:** 4145

29 **Tables:** 1

30 **Figures:** 5

31 **Supplementary materials:** 1 table

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42 **Abstract**

43 This study investigated the effect of heat stress on locomotor activity within international field
 44 hockey at team, positional and playing-quarter levels. Analysis was conducted on 71 matches
 45 played by the Malaysia national men's team against 24 opponents. Fixtures were assigned to
 46 match conditions, based on air temperature [COOL ($14\pm 3^{\circ}\text{C}$), WARM ($24\pm 1^{\circ}\text{C}$), HOT ($27\pm 1^{\circ}\text{C}$),
 47 or VHOT ($32\pm 2^{\circ}\text{C}$), $p < 0.001$]. Relationships between locomotor metrics and air temperature (AIR),
 48 absolute and relative humidity, and wet bulb globe temperature (WBGT) were investigated further
 49 using correlation and regression analyses. Increased AIR and WBGT revealed similar correlations
 50 ($p < 0.01$) with intensity metrics; high-speed running (AIR $r = -0.51$, WBGT $r = -0.45$), average speed
 51 (AIR $r = -0.48$, WBGT $r = -0.46$), decelerations (AIR $r = -0.41$, WBGT $r = -0.41$), sprinting efforts (AIR
 52 $r = -0.40$, WBGT $r = -0.36$), and sprinting distance (AIR $r = -0.37$, WBGT $r = -0.29$). In comparison to
 53 COOL, HOT and VHOT matches demonstrated reduced high-speed running intensity (-14-
 54 17%; $p < 0.001$), average speed (-5-6%; $p < 0.001$), sprinting efforts (-17%; $p = 0.010$) and
 55 decelerations per min (-12%; $p = 0.008$). Interactions were found between match conditions and
 56 playing quarter for average speed (+4-7%; $p = 0.002$) and sprinting distance (+16-36%; $p < 0.001$),
 57 both of which were higher in the fourth quarter in COOL *versus* WARM, HOT and VHOT. There
 58 was an interaction for 'low-speed' ($p < 0.001$), but not for 'high-speed' running ($p = 0.076$)
 59 demonstrating the modulating effect of air temperature (particularly $> 25^{\circ}\text{C}$) on pacing within
 60 international hockey. These are the data demonstrating the effect of air temperature on locomotor
 61 activity within international men's hockey, notably that increased air temperature impairs high-
 62 intensity activities by 5-15%. Higher air temperatures compromise high-speed running distances
 63 and sprint activity between matches in hockey.

64
 65 **Key words:** Hockey, Temperature, GPS, Thermoregulation, Heat stress, Speed.

67 **Abbreviations**

69	AIR	Air temperature
70	ANOVA	Analysis of variance
71	FIFA	Federation Internationale de Football Association
72	GPS	Global positioning system
73	HDOP	Horizontal dilution of precision
74	IMA	Inertial movement analysis
75	Q1, Q2, Q3, Q4	Respective playing quarters
76	R.H.	Relative humidity
77	SWC	Smallest worthwhile change
78	VHI	Very high intensity
79	WBGT	Wet-bulb globe temperature
80	WR	World Ranking

81 Introduction

82 Increased air temperature, particularly $>25^{\circ}\text{C}$, appears detrimental to running performance in elite
83 middle- and long-distance endurance events[1]. The magnitude of performance decrement is
84 proportional to both the event duration and the temperature difference *versus* purported optimal
85 conditions for endurance performance of $\sim 10\text{--}15^{\circ}\text{C}$ [2]. Increased atmospheric water vapour (i.e.
86 humidity) and exposure to solar radiation (i.e. direct sunlight) also concurrently exacerbate the
87 decrement[3,4]. Therefore, it is the interplay between high internal metabolic heat production (i.e.
88 exercise intensity), clothing, and the environment, that determines heat storage and increases in
89 body temperature, leading to performance impairment. Increased body temperature does not
90 directly impact performance, with elite endurance athletes demonstrating resistance to core
91 temperatures $>40^{\circ}\text{C}$ [5], and team-sport athletes eliciting core temperatures of $39\text{--}40^{\circ}\text{C}$ [6–8].
92 However, the combination of cardiovascular strain[9] and elevated skin temperature that occur
93 when air temperature increases impairs performance via multiple mechanisms[10], including
94 behavioural modifications of exercise intensity[11][12].

95
96 Team-sports, such as field hockey (hockey), are characterised by high aerobic demands (mean
97 $\sim 85\%$ of maximum heart rate)[13] and intermittent/repeated bouts of sprint activity (21 ± 7 per
98 game)[14]. In combination, this activity profile provides a greater thermal challenge than
99 continuous intensity exercise of the same mean intensity[15]. The effect of air temperature on
100 repeated-sprint performance is more complex than endurance performance. Increased locomotor
101 muscle temperature can enhance muscle force production[16], however, a point occurs where
102 muscle temperature related benefits acquiesce to cardiovascular and metabolic strain[17].
103 Laboratory experiments have shown elevated core and muscle temperatures to impair repeated-
104 sprint performance by $\sim 10\%$ [18], with this impairment consistent across hot-dry and hot-humid
105 environment[19]. Consequently, locomotor data from the 2014 FIFA soccer World Cup revealed
106 consistent reductions in both high-intensity activity (e.g. the number of sprints) and the distance
107 covered at high-intensity, in hot (wet-bulb globe temperature [WBGT] 34°C) *versus* cooler
108 conditions (WBGT 19°C)[20]. Ambient (air) temperature appears central to this effect, having
109 been shown to elicit a greater effect on soccer match outcomes than relative humidity[21]. Whilst
110 equivalent analyses regarding international hockey have not been published, decreased 15 m
111 repeated-sprint performance has been observed in hockey players during laboratory protocols in
112 the heat (30°C [22]).

113
114 Compared with other team-sports, modern hockey is characterised by a high average speed
115 during matches ($127\pm 15\text{ m}\cdot\text{min}^{-1}$), with considerable high-speed ($1191\pm 328\text{ m}$, $>14.5\text{ km}\cdot\text{h}^{-1}$) and
116 sprinting volumes ($401\pm 144\text{ m}$, $>19\text{ km}\cdot\text{h}^{-1}$)[14]. Hockey is therefore considered a repeated-sprint
117 activity, interspersed with low-intensity activities[13]. We have previously identified locomotor
118 outputs to reduce across playing quarters in international men's hockey[14]. We and others[23,24]
119 have also found that the volume and intensity of outputs differs between playing positions.
120 Notably, defenders accrue longer playing times ($+27\%$ *versus* forwards). However, forwards
121 display higher playing intensities ($+17\%$ average speed *versus* defenders), and perform greater
122 high-intensity and sprint activities per min ($+50\%$ sprinting distance *versus* defenders)[14].
123 Fourteen matches played by the Singapore national team ($26\text{--}33^{\circ}\text{C}$) indicated that players
124 regulate low-intensity activity ($<15\text{ km}\cdot\text{h}^{-1}$), with high-intensity activity maintained across playing

125 quarters[25]. Whether this ‘pacing’ profile is evident across varying air temperatures, and how
126 different playing positions are affected, is unknown. Unlike in other team-sports, any behavioural
127 modifications to high-intensity activity within hockey matches may be attenuated by the four-
128 quarter match structure, which affords more regular rest periods. Furthermore, hockey permits
129 unlimited substitutions, which are utilised to maintain team-level outputs[26]. Therefore, the nature
130 of any modifications to the activity profile within hockey under high air temperatures, may be
131 different to other team-sports.

132
133 The aim of this study was to investigate the effect of heat stress on whole-match locomotor
134 activity, and across playing quarters, within international men’s hockey. We hypothesised that at
135 a team level, volume and intensity metrics characterising sprint and high-intensity activity would
136 decrease with increased heat stress (characterised by air temperature, absolute and relative
137 humidity, and WBGT). Secondly, we hypothesised that high-intensity locomotor activities (i.e.
138 high-speed running, sprinting distance and sprinting efforts) of forwards would be to a greater
139 extent than defenders, given they undertake more high-intensity activities per game. Thirdly, we
140 hypothesised a reduction in high-intensity activities, during the fourth playing quarter in conditions
141 where heat stress was greater..

142 **Methods**

143 **Participants**

144 Twenty-seven males from the Malaysia national hockey team (2018 world ranking [WR] #12, 2019
145 WR #11) participated in the study (age 25±4 years, stature 172±5 cm, body mass 68±6 kg, sum
146 of 7 skinfolds 45.3±10.8 mm). The study had institutional ethical approval and all analysis was
147 conducted retrospectively on anonymous data, in accordance with the Declaration of Helsinki
148 (2013).

149

150 **Design**

151 A retrospective analysis was undertaken of 71 international matches played between March
152 2018–November 2019 against 24 different opponents (WR 12±11, range 1-60). Each player
153 participated in 40±20 matches (range 9-66). Data were derived from official matches and
154 tournaments including; Hockey World Cup, Asian Games, Asian Champions Trophy, and World
155 Series Finals. In line with other similar experiments[21,27], for correlation analyses, air
156 temperature (range 9-40°C) and relative humidity (R.H.) data (range 19-100%) were extracted
157 from the Integrated Surface Database (National Oceanic and Atmospheric Administration) and
158 “weather underground” website referenced by the World Meteorological Organization. The most
159 proximal location to the corresponding stadia was utilised. Absolute humidity was calculated
160 according to established equations[28] (Absolute humidity = $\{6.112 \times \exp[(17.67 \times T)/(T + 243.5)]$
161 $\times RH \times 2.1674\}/(273.15 + T)$ where T is the dry bulb temperature and RH the relative humidity).
162 Only air temperature was used for the group analysis, given the greater number of assumptions
163 related to the estimation of WBGT using established models[29]. Temperatures were separated
164 into four conditions designed to create groups of similar sample size and distribution: cool (COOL:
165 temperature <20.0°C, n=14), warm (WARM: temperature 20.1-25.0°C, n=10), hot (HOT:
166 temperature 25.1-30.0°C, n=31), and very-hot (VHOT: temperature >30.0°C, n=16).

167 Locomotor/accelerometer data are reported as volume (i.e. total values) and intensity (i.e. relative
168 to playing time [per min]). Matches played in COOL took place in the Americas (n=6), Australasia
169 (n = 5) and Europe (n = 3) average time difference -6 hours. WARM took place in Asia (n = 7),
170 Europe (n = 3) average time difference -2 hours. HOT took place in Asia (n = 23), Australasia (n
171 = 3), Europe (n = 3) average time difference -1 hours. VHOT took place in Asia (n = 9), Australasia
172 (n = 1), Europe (n = 1), middle east (n = 5) average time difference -1 hour. Three matches in
173 WARM, twelve matches in HOT, and six matches in VHOT were played in Malaysia.

174

175 Data Collection and Processing

176 Following a 10 min central pitch localisation, data were collected using triaxial 100 Hz
177 accelerometer/10 Hz GPS units (G5, firmware v.7.40, Catapult Sports, Australia)[14]. Players
178 were familiarised with equipment from daily training and used the same device and vest where
179 possible. Units were worn throughout the warm-up (~35-min) and national anthems (4-min). For
180 one tournament (6 matches), players used different devices from the same manufacturer
181 (Catapult S5, firmware v.7.32). Measures of GPS quality; horizontal dilution of precision (HDOP:
182 0.75±0.14) and satellite number (11.6±0.8) were considered excellent by the manufacturer
183 guidelines.

184

185 Devices were downloaded using a *Catapult Sports* docking station and processed using *Openfield*
186 software (version 2.3.3, build #52841). Match data were processed live, by the same individual.
187 Data associated with large breaks in play were excluded, ensuring data used for analysis
188 pertained to periods where the game clock is running and represents 'ball-in-play time'[25]. Each
189 player's individual playing time was used to calculate intensity data. Running velocities above and
190 below 14.5 km.h⁻¹ were considered 'high-' and 'low-speed running', respectively. High-intensity
191 accelerations and decelerations were processed from GPS data (Catapult Gen2) when exceeding
192 2.0 m.s⁻². Velocity and acceleration dwell times were 1.0 and 0.4 s, respectively. Data from the
193 inertial measurement unit were used to calculate *Playerload*. Accelerations, decelerations, and
194 left/right changes of direction processed from the inertial measurement unit (IMU) were
195 categorised as '*very high-intensity*' (VHI) when exceeding 3.5 m.s⁻², and combined into a single
196 metric of multi-directional load (total VHI movements), processed using inertial movement
197 analysis ('IMA') V2[30]. Match files not meeting the following our previously described inclusion
198 criteria[14] were discarded (3 cases).

199

200 Statistical Analysis

201 Data are presented as mean±SD and were analysed using SPSS (version 26, SPSS Inc, USA)
202 with alpha set at $p < 0.05$. All outcome variables met assumptions for normality of distribution using
203 histograms, boxplots and measures of skewness and kurtosis, prior to analysis. Pearson's
204 correlation coefficient was used to identify associations between heat stress parameters and
205 locomotor activity data, at the team level (match average). Relationships were classified as; trivial:
206 0.00-0.09; *small*: 0.10-0.29; *moderate*: 0.30-0.49; *large*: 0.50-0.69; *very-large*: 0.70-0.89; *nearly-*
207 *perfect*: 0.90-0.99 and *perfect*: 1.00[31]. Linear regression was used to identify the ability of air
208 temperature and WBGT to predict locomotor activities. One-way independent ANOVA were used
209 to analyse the effect of air temperature on the team average locomotor activity, across four
210 conditions (COOL, WARM, HOT and VHOT), with Bonferroni post-hoc analyses. To determine

211 the impact of playing position and match quarters (Q1, Q2, Q3, and Q4), a total of 4335 individual
212 playing-quarter records were utilised, with players categorised as defenders (n=353), midfielders
213 (n=365), forward (n=388). Two-way between subjects ANOVA were used to investigate changes
214 between temperatures, with regards to position and two-way mixed ANOVA were also used to
215 investigate changes between temperatures across match quarters, with Bonferroni correction
216 utilised post-hoc.

218 Results

219 Effect of temperature on team locomotor activity

220 Air temperatures, humidity and WBGT of each condition are shown in Table 1. There were
221 differences in air temperature ($f=240.0$, $p<0.001$) absolute humidity ($f=19.4$, $p<0.001$) and WBGT
222 ($f=131.3$, $p<0.001$) between match conditions, but not for relative humidity ($f=1.6$, $p=0.195$). At
223 the team level (i.e. team average), significant correlation coefficients (all $r=-0.26 - 0.51$) and
224 regression equations (all $p<0.05$) were observed between air temperature, absolute humidity and
225 playing duration, average speed, high-speed running (volume and intensity), sprinting distance
226 (volume and intensity), sprinting efforts (volume and intensity), *Playerload* (volume and intensity),
227 acceleration efforts (intensity) and deceleration efforts (volume and intensity), see Table 1 and
228 Figure 1. No relationships (all $p>0.05$) were observed for the team's (average); total distance, low-
229 speed running (volume or intensity), acceleration efforts (volume) or VHI movements (volume or
230 intensity). For WBGT, significant correlation coefficients (all $r=-0.20 - 0.46$) and regression
231 equations (all $p<0.05$) were observed between air temperature and playing duration, average
232 speed, total distance, low-speed running (volume), high-speed running (volume and intensity),
233 sprinting distance (volume and intensity), sprinting efforts (volume and intensity), *Playerload*
234 (volume and intensity), acceleration efforts (intensity) and deceleration efforts (volume and
235 intensity), see Table 1 and Figure 1. No relationships (all $p>0.05$) were observed for low-speed
236 running (intensity) or VHI movements (volume or intensity).

237
238 *Figure 1 here*

239 *Table 1 here*

240
241 The [team] average for high-speed running volume ($f=5.5$, $p=0.002$), total sprinting efforts ($f=2.9$,
242 $p=0.041$) and total decelerations ($f=3.2$, $p=0.029$) were greater in COOL than both HOT and
243 VHOT. Full post-hoc analysis is contained in Table 1 and Figure 2. Average total distance, low
244 speed running, sprinting distance, *Playerload*, accelerations, and VHI movements did not differ
245 across temperatures ($p>0.05$). When adjusted for playing time (intensity), [team] average speed
246 ($f=7.7$, $p<0.001$), high-speed running ($f=8.6$, $p<0.001$), sprinting distance ($f=4.0$, $p=0.011$), sprint
247 efforts ($f=4.1$, $p=0.010$), *Playerload* ($f=7.3$, $p<0.001$), and deceleration efforts ($f=4.3$, $p=0.008$)
248 were all higher in COOL, than both HOT and VHOT (Table 1 and Figure 2). Low-speed running,
249 accelerations and VHI movements did not differ between temperatures ($p>0.05$). Differences for
250 each temperature condition *versus* the grand mean are displayed in Figure 3.

251
252 *Figure 2 here*

253 *Figure 3 here*

254

255 Effect of temperature on playing position

256 Differences between positions are displayed in Figure 4 and full post-hoc comparisons are
257 contained within supplementary table 1. Interaction effects were observed between playing
258 positions and temperatures for total playing duration ($f=2.9$, $p=0.009$) and total distance ($f=4.2$,
259 $p<0.001$), high-speed distance ($f=2.8$, $p=0.010$), low-speed distance ($f=3.6$, $p=0.001$), *Playerload*
260 ($f=4.2$, $p<0.001$), and total deceleration efforts ($f=3.3$, $p=0.003$). When adjusted for playing time,
261 sprinting efforts ($f=2.3$, $p=0.033$) and acceleration efforts ($f=2.4$, $p=0.027$) demonstrated
262 interaction effects.

263

264 *Figure 4 here*

265

266 Effect of temperature across playing quarters

267 Differences across playing quarters are displayed in Figure 5 and full post-hoc comparisons are
268 contained within supplementary table 1. Interaction effects were observed between playing-
269 quarter and temperatures for the [team] average high-speed running volume ($f=2.1$, $p=0.030$),
270 sprinting distance ($f=3.5$, $p<0.001$), and sprinting efforts ($f=2.3$, $p=0.015$). For intensity, interaction
271 effects were found for [team] average speed ($f=3.0$, $p=0.002$), low speed running ($f=2.4$, $p=0.011$),
272 sprinting distance ($f=3.6$, $p<0.001$), *Playerload* ($f=4.6$, $p<0.001$), acceleration efforts ($f=2.4$,
273 $p=0.009$), and deceleration efforts ($f=3.1$, $p=0.001$).

274

275 *Figure 5 here*

276

277 Discussion

278 In accordance with our first hypothesis, the team average high-intensity and sprinting distances
279 reduced with increased air temperature, absolute humidity and WBGT. Most notably, there was
280 a *large* correlation between with air temperature, and a *moderate* correlation with WBGT and
281 absolute humidity, for high-speed running per min. Relative humidity demonstrated
282 *small/insignificant* correlations suggesting this metric alone to be without merit. The largest
283 decrements in locomotor activity were found for high-intensity activities during HOT ($27\pm 1^\circ\text{C}$) and
284 VHOT ($32\pm 2^\circ\text{C}$) matches, compared with COOL ($14\pm 3^\circ\text{C}$) and WARM ($24\pm 1^\circ\text{C}$). Interestingly,
285 the performance decline did not continue to extend beyond those observed in HOT conditions,
286 suggesting this may be a 'threshold' beyond which the impact on performance does not continue
287 to worsen. Comparatively, low-intensity activities and total distance were maintained. These data,
288 derived from a highly ranked international team, also revealed greater effects of air temperature
289 on high-intensity activities of defenders and forwards, compared with midfielders.

290

291 Team whole-match responses

292 At the team level, air temperatures exceeding 25°C (i.e. HOT and VHOT conditions) elicited a
293 detrimental effect on high-intensity activities (i.e. high-speed running, sprinting distance, sprinting
294 efforts and decelerations). These metrics revealed the largest percentage changes and
295 regression models explaining large proportions of variance (Figures 1-3). These data are the first

296 to examine the specific effect of air temperature within international hockey and support previous
297 laboratory protocols that demonstrated impaired hockey skill and repeated-sprint performance in
298 the heat (30°C)[22]. Whilst ambient temperature alone (range 7–41°C) has been demonstrated
299 to be a poor predictor of international cross country cycling performance[28], data from team
300 sports e.g. hockey seemingly demonstrates different outcomes. Compared with cycling, running
301 involves lower movement speeds and higher heat production for a given metabolic rate.
302 Therefore, performance is affected at much lower ambient temperatures[32]. Moreover, we
303 identified comparable correlations for air temperature and predicted WBGT with most locomotor
304 variables. This indicates that the addition of relative humidity does not meaningfully explain a
305 greater proportion of the variance in locomotor activity within the current dataset. Indeed, the
306 effect of relative humidity is likely to be most pronounced when ambient temperature is already
307 high (i.e. 'hot-wet') and thus would elicit less effect on matches in cooler conditions, such as COOL
308 and WARM. The reduction in high-intensity activities that we observed is also congruent with
309 international soccer, where reduced sprinting efforts (~14%) and high-speed distance (~8%),
310 were observed in high, *versus* low heat stress matches played at the 2014 FIFA World Cup[20].
311 It is interesting to note this comparable trend in hockey, despite differences between the match
312 format of these team-sports, with hockey played across four, shorter playing quarters and utilising
313 unlimited substitutions giving players more frequent rest periods.

314
315 We observed no differences in total distance, however average speed ($\text{m}\cdot\text{min}^{-1}$) was significantly
316 lower during HOT/VHOT *versus* COOL conditions. The range of mean differences between COOL
317 and WARM, HOT and VHOT conditions was ~5-8 $\text{m}\cdot\text{min}^{-1}$, which may be considered meaningful
318 given the smallest worthwhile change (SWC) previously identified for this team is 3 $\text{m}\cdot\text{min}^{-1}$ [14].
319 When average speed is segregated into 'low-' (<14.5 $\text{km}\cdot\text{h}^{-1}$) and 'high-speed' (>14.5 $\text{km}\cdot\text{h}^{-1}$)
320 running intensities, we found differences between COOL and HOT/VHOT conditions for high-
321 speed, but not low-speed running. Moreover, the respective correlation and regression
322 coefficients for low-speed ($r=-0.11$) and high-speed running ($r=-0.51$) corroborate a stronger effect
323 of air temperature on high-speed running only. The reduction of high-speed running contrasts with
324 reported within-match activity profiles of team-sports, whereby both hockey[25] and soccer[33]
325 players have been shown to regulate low-intensity activity, but preserve high-speed activities
326 across playing quarters/match halves.

327
328 In soccer, whole-match sprinting output (>19.5 $\text{km}\cdot\text{h}^{-1}$) appears unaffected by heat stress[33]. We
329 similarly found the relationships with changes in sprinting (>19 $\text{km}\cdot\text{h}^{-1}$) intensity to be weaker
330 (sprinting [$\text{m}\cdot\text{min}^{-1}$] $r=-0.38$) than for high-speed running (>14.5 $\text{km}\cdot\text{h}^{-1}$). This indicates sprinting
331 may be more of a requisite activity, possibly due to the demands of the game/opponent, and it is
332 activity within the ~15-19 $\text{km}\cdot\text{h}^{-1}$ range ('striding') that players regulate between matches of higher
333 air temperatures. Such modulations of exercise intensity would serve to avoid further increases
334 in core and muscle temperature, thereby maintaining cardiovascular strain in comparison to
335 cooler conditions[7,33]. Despite high-intensity activity being associated with greater metabolic
336 heat production and heat storage[15], these actions appear critical for success in team-sports[34],
337 thus players are required to offset lower intensity activity to reduce overall intensity.

338

339 Team within-match responses

340 We hypothesised a greater reduction in high-intensity activities in Q4 of HOT and VHOT matches,
341 compared with WARM and COOL. Although thermal strain develops progressively and
342 proportionally to the volume and intensity of physical work completed[35], we did not predict
343 notable reductions during Q3, as this is preceded by a 10-min half-time break. Mechanistic
344 support for this can be derived from the work of Mohr et al[7], who observed average sprint speed
345 to be different between the first and second halves in soccer, but unmodified during the first 15-
346 min of each half, despite the $\sim 22^{\circ}\text{C}$ temperature gradient between fixtures. Whilst we did not
347 observe an interaction between temperature and playing quarter for high-speed running intensity,
348 there was an interaction for sprinting distance. This predominantly reflected increased sprinting
349 during Q4 in COOL matches (supplementary figure 2), rather than a decrement *per se* during
350 HOT and VHOT. Nevertheless, the capacity for greater sprinting in the final quarter is notable, as
351 this may be a critical period to determine the match result of team-sports[36].

352
353 We also observed an interaction for average speed, characterised by larger reductions from Q1
354 to Q4 in VHOT ($-8 \text{ m}\cdot\text{min}^{-1}$, -6%) and HOT ($-7 \text{ m}\cdot\text{min}^{-1}$, -5%), compared with WARM ($-4 \text{ m}\cdot\text{min}^{-1}$,
355 -3%) and COOL ($-4 \text{ m}\cdot\text{min}^{-1}$, -3%). Overall, our data supports previous statements regarding the
356 within-match pacing profile in hockey[25], that high-intensity activities remain relatively consistent
357 across playing quarters, with low-intensity outputs regulated. In soccer it has been suggested that
358 such behavioural 'pacing' modifications may serve to complement technical skills during the
359 match (e.g. pass completion rate) whilst ensuring high-intensity locomotor activity is
360 maintained[20]. Similarly, others have reported a 'cool' soccer match (21°C), to display a deficit
361 in high-speed running in the second *versus* first half, which was not observed in an equivalent
362 'hot' match (43°C)[7]. Such patterns contrast with our third hypotheses and are surprising given
363 the potential for hotter conditions to induce greater fatigue. Indeed, we[14], and others[13,23,25]
364 have reported overall locomotor activity reducing in latter halves/quarters of elite hockey.
365 Interactions between locomotor activity and temperature are therefore evidently complex.
366 Possible explanations for the opposing atypical high-intensity responses of others[7] could be that
367 fatigue is induced by a higher absolute playing intensity in cooler conditions, which is greater than
368 that evoked by temperature. Pacing strategies may also be altered in the heat from the start of
369 the fixture in an anticipatory manner[11]. Nevertheless, our data demonstrates that in combination
370 with tactically driven player rotations and hockey player's modulation of low-intensity work, there
371 is a minimal decrement of high-intensity outputs across playing quarters. However, in COOL
372 conditions, players were able to increase sprinting distance in Q4 from Q3 ($+20\%$), which was
373 apparently not possible in warmer matches.

374

375 Positional responses

376 We have previously observed that forwards play shorter durations and report greater high-
377 intensity activities versus defenders, but not midfielders[14]. Thus, we hypothesised that high-
378 intensity activities of forwards would be impacted by air temperature more than defenders. In
379 contrast to our hypothesis, the volume (total distance, high- and low-speed running distances)
380 and intensity (sprinting and acceleration efforts per min) of locomotor outputs are most greatly
381 affected in both defenders and forwards, compared with midfielders. Whilst changes in average
382 speed from Q1 to Q4 were comparable in defenders ($-8 \text{ m}\cdot\text{min}^{-1}$, -7%) and forwards ($-8 \text{ m}\cdot\text{min}^{-1}$,

383 -6%), for high-speed running activity, the reduction in defenders (-25%) was considerably higher
384 than either forwards (-10%) or midfielders (-7%). Defenders may therefore acquiesce to thermal
385 strain because of longer playing durations in combination with intense activity. For forwards, the
386 impact of air temperature is likely reflecting the greater high-intensity nature of their activity[7,15].
387 Finally, whilst the locomotor outputs of forwards and defenders appear sensitive to changes in air
388 temperature, the locomotor demands for midfielders were maintained, which may elicit greater
389 physiological strain in tournaments with repeated HOT/VHOT matches.

390

391 Limitations

392 Within stadia, pitch-side measurement of air flow, solar radiation, temperature and humidity
393 throughout the game would have enhanced the precision of our analysis by enabling a more
394 precise calculation of WBGT or additional heat stress calculations[21]. Future work should
395 implement this methodological approach to improve the characterisation of the environmental
396 conditions of each match. Therefore we cannot fully discern the specific influences of other factors
397 that modify thermal equilibrium, such as solar radiation and absolute/relative humidity[28][37].
398 The collection of physiological (e.g. skin/core/muscle temperatures) and perceptual data (e.g.
399 exertion/thermal comfort/thermal sensation) would add greater mechanistic insight into the factors
400 eliciting locomotor changes across different temperatures[7], however, there remains logistical
401 challenges with collecting many of these data during competitive international fixtures.

402

403 Given the home environmental conditions of the team analysed can be categorised as equatorial,
404 (i.e., hot and humid), it is possible that some level of acclimatisation was present within the
405 players. Accordingly, a greater performance reduction may be observed in those teams residing
406 in cooler conditions, warranting further investigation. The location of the match did not appear to
407 influence our analysis given COOL presented players with the greatest time difference and travel
408 challenge. Furthermore, we highlight that match-day preparations for some, but not all VHOT
409 matches included established cooling interventions[38]. This may have mitigated larger
410 reductions in locomotor activity. Our findings also cannot extend to teams that have vastly
411 different substitution policies, for example 8-10 min rotations *versus* the 4-8 min approach typically
412 utilised by the team in this study. Finally, it is beyond the scope of this analysis to examine the
413 influence of training/competition phase, competition importance, match outcome, and opponent
414 ranking, though the authors acknowledge that these are also influencing factors in team sport
415 locomotor activity.

416

417 Practical Applications

418 The relationship between air temperature and locomotor activity within a leading international
419 men's hockey team habituating a hot climate, is noteworthy for coaches and practitioners within
420 this global sport. Average speed is a widely used metric used to compare player's locomotor
421 activity during matches and our data indicates a 10°C increase in air temperature, may elicit a 4
422 m.min⁻¹ reduction in average speed (± 5 m.min⁻¹ standard error of the estimate). This equates to
423 -3% of the grand mean (Figure 3) and is comparable to the SWC of 3 m.min⁻¹[14]. The strongest
424 relationship between volume metrics and temperature was for high-speed running, which
425 indicates just a 1°C increase in air temperature, may elicit a -11 m reduction in high-speed
426 distance across a match. Therefore, a 6°C increase is a comparable reduction (-5% versus grand

427 mean) to the SWC (66 m). Thus, these data allude to potential performance advantages from
428 implementing practical pre-competition acute [39–41] and chronic heat alleviation strategies [42–
429 44] to mitigate these declines. These strategies may include modified warm ups[45], prompt
430 cooling[46], rehydration and specific nutritional interventions[38] on/after a game day. In the
431 weeks prior, preparation such as acclimation[47], that uses controlled exercise protocols[48],
432 overdressing[49,50], hot water immersion[51], or a combination of approaches[52], can be
433 implemented to suit individual/team needs. Furthermore, our data indicate that defenders and
434 forwards appear to be the positions most impacted by increases in air temperature. Individual-
435 level heat alleviation screening may therefore be relevant for these positions, prior to tournaments
436 with heat stress (i.e. >25°C air temperature) in order to minimise decrements to locomotor output.
437 However, the maintenance of external demands for midfielders, irrespective of temperature, may
438 exacerbate physiological strain during HOT and VHOT matches, potentially impairing between-
439 match recovery. Given the high match density of hockey tournaments (often 8 games in <16
440 days), specific recovery strategies for heat stress should be considered for all players, but
441 especially for midfielders, the intention of these being to reduce exercise-heat orientated
442 detriments in physical, cognitive and perceptual parameters[53–57].

443
444 Finally, coaches should consider modifications to substitution strategies across all positions (i.e.
445 shorter rotation durations), to help mitigate expected increases in body temperature and/or
446 perceived thermal discomfort, that may result in reduced locomotor activity and/or greater
447 physiological strain. Moreover, coaches can anticipate the largest reduction in ‘striding’ activity
448 during hotter matches and may therefore wish to adjust in-possession/out of possession tactics
449 accordingly.

450
451 **Conclusion**
452 These are the first match data demonstrating the effect of air temperature on locomotor activity
453 within international men’s hockey. Increased air temperature impairs high-intensity activities by
454 5-15%. Coaches and practitioners should consider acute and chronic heat alleviation approaches
455 to mitigate performance and health consequences of competing in hot environments.

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Table Title

Table 1. Mean±SD of volume and intensity metrics for all matches and for each condition (COOL, WARM, HOT, VHOT).

Variable	Whole data set (n=71)	Relationship with Temperature	Relationship with absolute humidity	Relationship with relative humidity	Relationship with WBGT	Regression Model (Temperature)	Regression Model (absolute humidity)	Regression Model (WBGT)	COOL (n = 14)	WARM (n = 10)	HOT (n = 31)	VHOT (n = 16)
Environmental parameters												
Temperature (°C)	25.0 ± 6.5	-	-	-	-	-	-	-	13.5 ± 3.1 ^{## ^^ vv}	23.6 ± 1.0 ^{*** ^^ vv}	27.3 ± 1.0 ^{** ## vv}	31.5 ± 2.4 ^{** ## ^^}
Absolute humidity (g.m ³)	15.9 ± 5.9	r = 0.637 ^{††}	-	-	-	-	-	-	8.7 ± 2.3 ^{## ^^ vv}	13.7 ± 3.8 ^{*** ^^ vv}	18.2 ± 4.2 ^{** ##}	19.4 ± 6.1 ^{** ##}
Relative humidity (%)	67 ± 17	r = -0.209	r = 0.581 ^{††}	-	-	-	-	-	72 ± 14	64 ± 17	70 ± 16	60 ± 20
WBGT (°C)	22.0 ± 5.4	r = 0.892 ^{††}	r = 0.848 ^{††}	r = -0.193	-	-	-	-	11.6 ± 3.0 ^{## ^^ vv}	20.4 ± 2.0 ^{** ^^ vv}	24.4 ± 2.0 ^{** ## vv}	26.9 ± 2.4 ^{** ## ^^}
Volume parameters												
Playing duration (mins)	38.8 ± 1.9	r = 0.260 [†]	r = 0.163	r = -0.063	r = 0.248 [†]	b ₀ = 36.9 b ₁ = 0.075 SEE = 1.8 min [†]	b ₀ = 38.0 b ₁ = 0.052 SEE = 1.9 min [†]	b ₀ = 37.1 b ₁ = 0.079 SEE = 1.8 min [†]	38.0 ± 1.2	38.2 ± 1.1	39.3 ± 2.2	39.2 ± 1.8
Total distance (m)	4865 ± 205	r = -0.192	r = -0.153	r = -0.003	r = -0.203 [†]	b ₀ = 5016.5 b ₁ = -6.063 SEE = 202 m	b ₀ = 4950.6 b ₁ = -5.373 SEE = 204 m [†]	b ₀ = 5018.4 b ₁ = -7.024 SEE = 202 m [†]	4962 ± 146	4808 ± 171	4837 ± 212	4869 ± 241
High-speed Running (m)	1191 ± 166	r = -0.425 ^{††}	r = -0.444 ^{††}	r = -0.106	r = -0.472 ^{††}	b ₀ = 1462.1 b ₁ = -10.831 SEE = 151 m ^{††}	b ₀ = 1391.9 b ₁ = -12.570 SEE = 149 m ^{††}	b ₀ = 1480.1 b ₁ = -13.2 SEE = 147 m ^{††}	1318 ± 103	1249 ± 113	1139 ± 173 ^{**}	1145 ± 163 [*]

Low-speed Running (m)	3664 ± 164	r = 0.184	r = 0.249 †	r = 0.100	r = 0.216 †	b ₀ = 3548.4 b ₁ = 4.627 SEE = 162 m	b ₀ = 3552.7 b ₁ = 6.977 SEE = 160 m †	b ₀ = 3533.3 b ₁ = 5.987 SEE = 161 m †	3636 ± 114	3550 ± 105	3688 ± 191	3715 ± 146
Sprinting (m)	401 ± 74	r = -0.299 †	r = -0.259 †	r = 0.005	r = -0.305 ††	b ₀ = 485.1 b ₁ = -3.381 SEE = 71 m †	b ₀ = 452.1 b ₁ = -3.226 SEE = 72 m ††	b ₀ = 483.5 b ₁ = -3.793 SEE = 71 m ††	436 ± 51	431 ± 55	383 ± 83	385 ± 69
Sprinting Efforts (n)	21 ± 3	r = -0.335 ††	r = -0.309 ††	r = -0.019	r = -0.352 ††	b ₀ = 25.2 b ₁ = -0.165 SEE = 3 ††	b ₀ = 23.8 b ₁ = -0.169 SEE = 3 ††	b ₀ = 25.2 b ₁ = -0.190 SEE = 3 ††	23 ± 2	22 ± 2	20 ± 4	20 ± 3
Playerload (a.u.)	470 ± 23	r = -0.298 †	r = -0.300 †	r = -0.063	r = -0.333 ††	b ₀ = 496.4 b ₁ = -1.075 SEE = 23 a.u. †	b ₀ = 488.7 b ₁ = -1.201 SEE = 23 ††	b ₀ = 498.4 b ₁ = -1.318 SEE = 22 ††	483 ± 19	473 ± 19	464 ± 24	466 ± 25
Acceleration Efforts (n)	50 ± 3	r = -0.199	r = -0.122	r = 0.054	r = -0.185	b ₀ = 52.2 b ₁ = -0.105 SEE = 3	b ₀ = 50.8 b ₁ = -0.072 SEE = 3	b ₀ = 51.9 b ₁ = -0.107 SEE = 3	51 ± 3	49 ± 3	50 ± 4	48 ± 3
Deceleration Efforts (n)	60 ± 4	r = -0.357 ††	r = -0.325 †	r = -0.016	r = -0.374 ††	b ₀ = 65.3 b ₁ = -0.232 SEE = 4 ††	b ₀ = 63.3 b ₁ = -0.235 SEE = 4 ††	b ₀ = 65.4 b ₁ = -0.267 SEE = 4 ††	62 ± 4	59 ± 4	59 ± 4 *	58 ± 4 *
VHI movements (n)	17 ± 2	r = -0.063	r = -0.036	r = -0.050	r = 0.051	b ₀ = 18.2 b ₁ = -0.025 SEE = 2	b ₀ = 17.5 b ₁ = -0.012 SEE = 2	b ₀ = 17.7 b ₁ = -0.016 SEE = 2	17 ± 2	18 ± 2	18 ± 2	16 ± 2
Intensity metrics												
Average speed (m.min⁻¹)	127.4 ± 5.8	r = -0.479 ††	r = -0.315 ††	r = 0.067	r = -0.459 ††	b ₀ = 138.1 b ₁ = -0.429 SEE = 5.1 m.min ⁻¹ ††	b ₀ = 132.4 b ₁ = -0.313 SEE = 5.6 m.min ⁻¹ ††	b ₀ = 137.2 b ₁ = -0.451 SEE = 5.2 m.min ⁻¹ ††	133.1 ± 3.1	127.7 ± 4.6	125.3 ± 5.1 **	126.2 ± 6.7 **
High-speed running (m.min⁻¹)	32 ± 5	r = -0.506 ††	r = -0.311 ††	r = -0.068	r = -0.449 ††	b ₀ = 41.3 b ₁ = -0.367 SEE = 4 m.min ⁻¹ ††	b ₀ = 36.2 b ₁ = -0.249 SEE = 5 m.min ⁻¹ ††	b ₀ = 40.0 b ₁ = -0.356 SEE = 4 m.min ⁻¹ ††	36 ± 3	34 ± 3	30 ± 5 **	31 ± 4 **
Low-speed running (m.min⁻¹)	95 ± 4	r = -0.110	r = -0.104	r = 0.180	r = -0.155	b ₀ = 96.6 b ₁ = -0.066 SEE = 4 m.min ⁻¹	b ₀ = 96.0 b ₁ = -0.068	b ₀ = 97.1 b ₁ = -0.100	96 ± 2	93 ± 2	95 ± 4	95 ± 5

							SEE = 4 m.min ⁻¹	SEE = 4 m.min ⁻¹				
Sprinting (m.min⁻¹)	10.9 ± 2.1	r = -0.367 ††	r = -0.194	r = 0.026	r = -0.290 ††	b ₀ = 13.8 b ₁ = -0.117 SEE = 1.9 m.min ⁻¹ ††	b ₀ = 12.0 b ₁ = -0.068 SEE = 2.0 m.min ⁻¹ ††	b ₀ = 13.1 b ₁ = -0.100 SEE = 2.0 m.min ⁻¹ ††	12.1 ± 1.3	11.8 ± 1.6	10.3 ± 2.3 *	10.4 ± 1.8
Sprinting efforts (n.min⁻¹)	0.6 ± 0.1	r = -0.404 ††	r = -0.235 †	r = 0.011	r = -0.359 ††	b ₀ = 0.7 b ₁ = -0.006 SEE = 0.1 n.min ⁻¹ ††	b ₀ = 0.6 b ₁ = -0.004 SEE = 0.1 n.min ⁻¹ ††	b ₀ = 0.7 b ₁ = -0.005 SEE = 0.1 n.min ⁻¹ ††	0.6 ± 0.0	0.6 ± 0.1	0.5 ± 0.1 *	0.5 ± 0.1 *
Playerload (a.u.)	12.3 ± 0.7	r = -0.467 ††	r = -0.297 †	r = 0.004	r = -0.417 ††	b ₀ = 13.7 b ₁ = -0.052 SEE = 0.7 a.u. min ⁻¹ ††	b ₀ = 12.9 b ₁ = -0.037 SEE = 0.7 a.u. min ⁻¹ ††	b ₀ = 13.5 b ₁ = -0.052 SEE = 0.7 a.u. min ⁻¹ ††	13.0 ± 0.6	12.6 ± 0.6	12.1 ± 0.7 **	12.2 ± 0.7 *
Acceleration efforts (n.min⁻¹)	1.3 ± 0.1	r = -0.293 †	r = -0.256 †	r = 0.087	r = -0.293 ††	b ₀ = 1.4 b ₁ = -0.005 SEE = 0.1 †	b ₀ = 1.4 b ₁ = -0.005 SEE = 0.1 ††	b ₀ = 1.4 b ₁ = -0.006 SEE = 0.1 ††	1.4 ± 0.1	1.3 ± 0.1	1.3 ± 0.1	1.3 ± 0.1
Deceleration efforts (n.min⁻¹)	1.6 ± 0.1	r = -0.408 ††	r = -0.347 ††	r = -0.007	r = -0.406 ††	b ₀ = 1.8 b ₁ = -0.009 SEE = 0.1 ††	b ₀ = 1.7 b ₁ = -0.008 SEE = 0.1 ††	b ₀ = 1.4 b ₁ = -0.006 SEE = 0.1 ††	1.7 ± 0.1	1.6 ± 0.1	1.5 ± 0.1 *	1.5 ± 0.1 *
VHI movements (n.min⁻¹)	0.5 ± 0.1	r = -0.168	r = -0.127	r = 0.021	r = -0.148	b ₀ = 0.5 b ₁ = -0.002 SEE = 0.1	b ₀ = 0.5 b ₁ = -0.002 SEE = 0.1	b ₀ = 0.5 b ₁ = -0.002 SEE = 0.1	0.5 ± 0.1	0.5 ± 0.1	0.5 ± 0.0	0.4 ± 0.1

† denotes significant correlation with temperature (p<0.05). †† denotes significant correlation with temperature (p<0.01). * denotes significant difference from COOL (p<0.05), ** denotes significant difference from COOL (p<0.01). # denotes significant difference from WARM (p<0.05), ## denotes significant difference from WARM (p<0.01). ^ denotes significant difference from HOT (p<0.05), ^^ denotes significant difference from HOT (p<0.01). High-speed running = >14.5 km.h⁻¹, low-speed running =<14.5 km.h⁻¹ and sprinting =>19 km.h⁻¹. Acceleration and deceleration efforts =>2 or <-2 m. s⁻², respectively. VHI movements = sum of all movements in the horizontal plane (i.e. accelerations, decelerations, and left / right changes of direction), when >3.5 or <-3.5 m s⁻².

Figure Captions

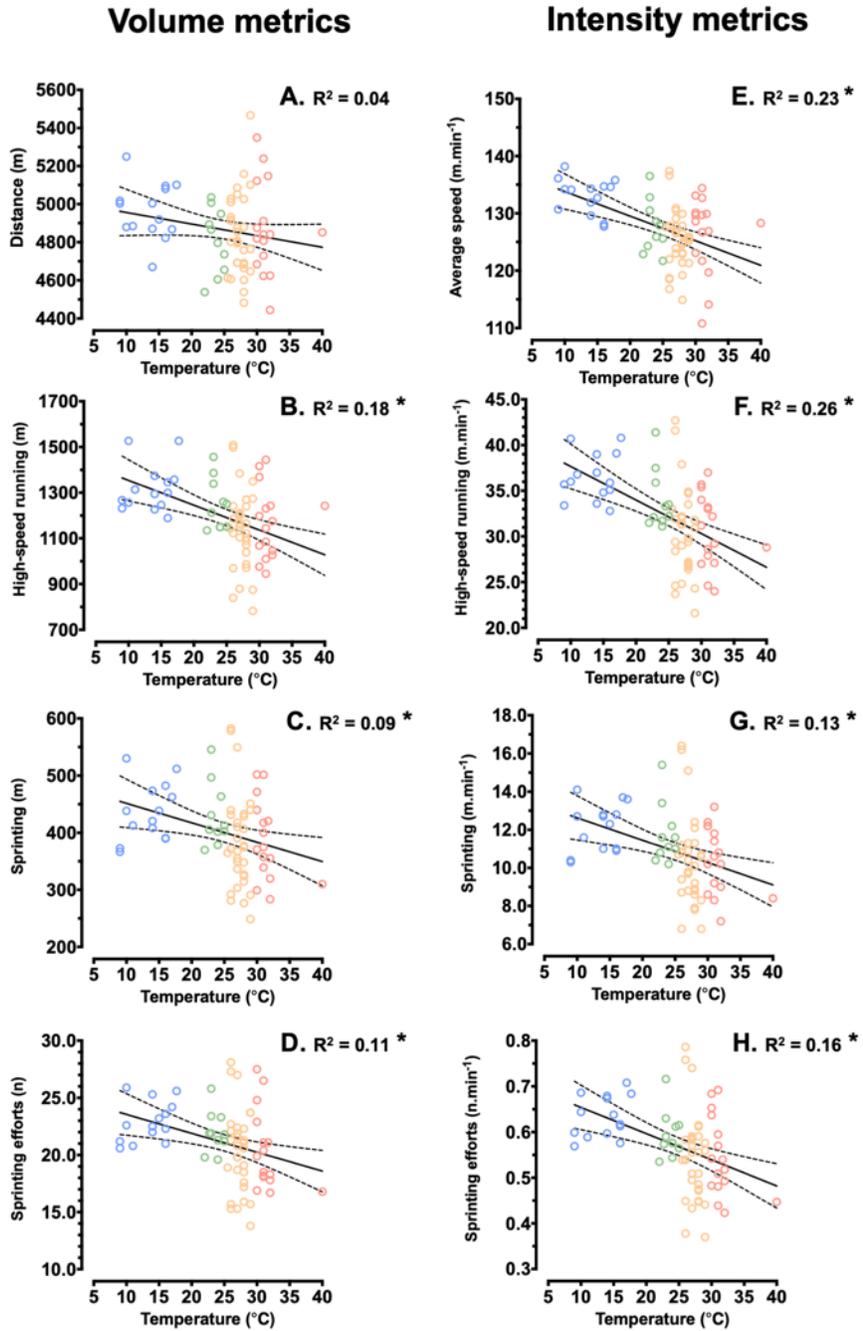


Figure 1. Panel of scatter plots demonstrating the relationship between temperature and volume (panels A-D) and intensity (panels E-H) metrics.

* denotes $p < 0.05$. High-speed running = $> 14.5 \text{ km.h}^{-1}$ and sprinting = $> 19 \text{ km.h}^{-1}$.

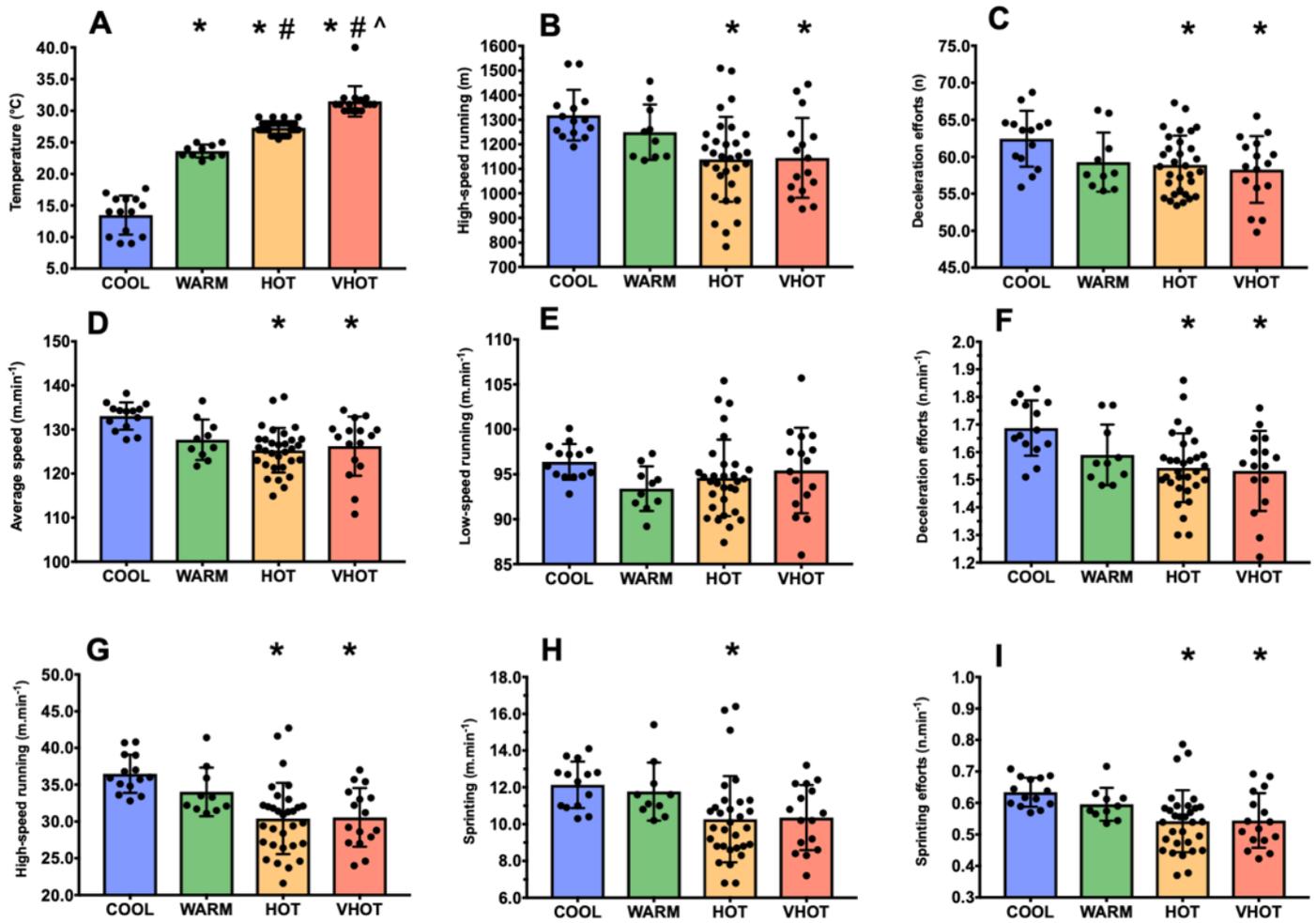


Figure 2. Mean \pm SD panel of selected volume (panels B&C) and intensity (panels D-I) metrics depicting responses across conditions (COOL, WARM, HOT, VHOT).

Filled circles depict individual data points. * denotes significant difference from COOL ($p < 0.05$), # denotes significant difference from WARM ($p < 0.05$), ^ denotes significant difference from HOT ($p < 0.05$). High-speed running = $> 14.5 \text{ km.h}^{-1}$, low-speed running = $< 14.5 \text{ km.h}^{-1}$ and sprinting = $> 19 \text{ km.h}^{-1}$. Acceleration and deceleration efforts = > 2 or $< -2 \text{ m.s}^{-2}$, respectively.

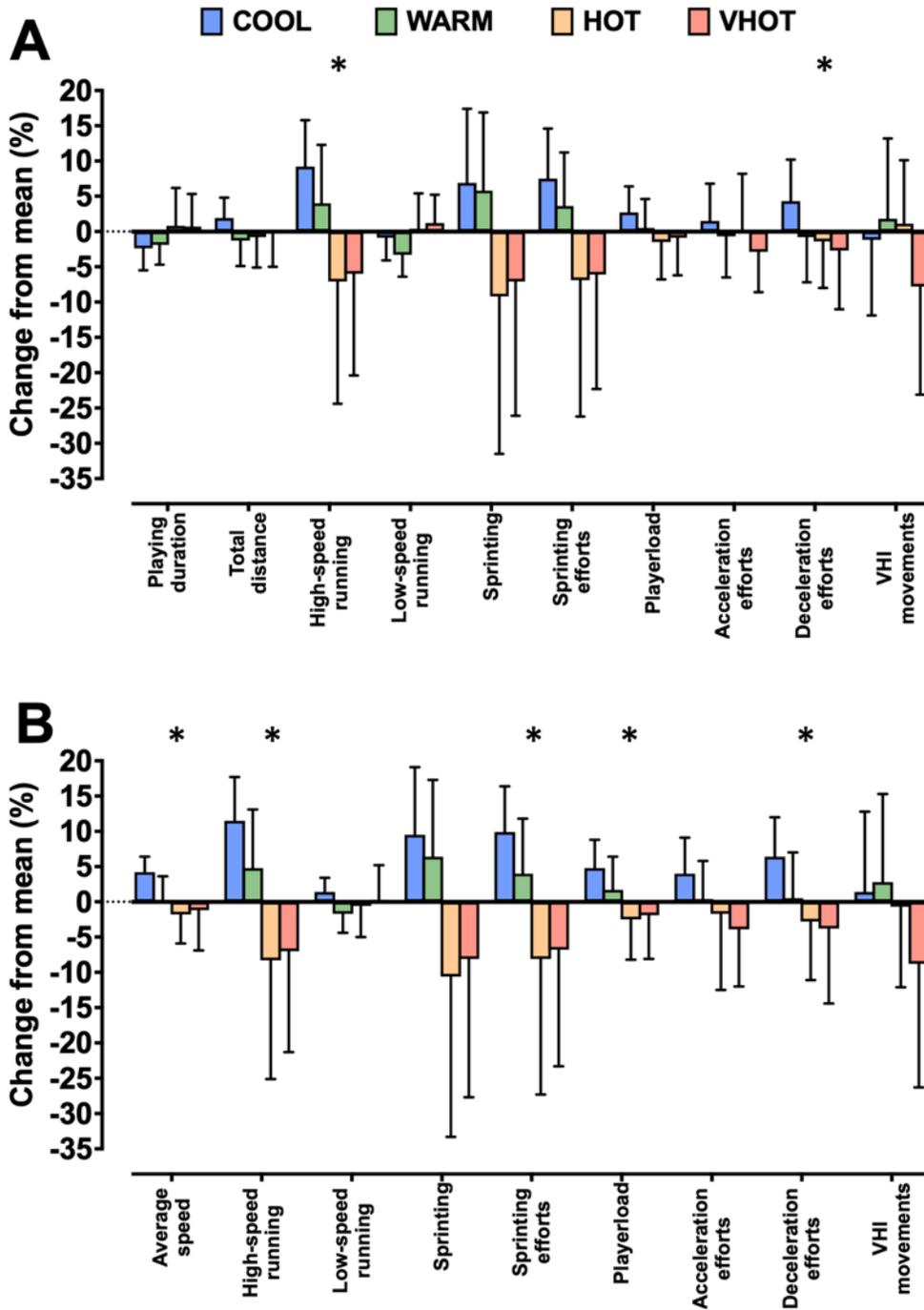


Figure 3. Summary figure outlining the change (%) in volume (A) and intensity (B) metrics in COOL, WARM, HOT and VHOT from the group mean.

* denotes main effect of temperature for each variable ($p < 0.05$). High-speed running = $>14.5 \text{ km}\cdot\text{h}^{-1}$, low-speed running = $\leq 14.5 \text{ km}\cdot\text{h}^{-1}$ and sprinting = $>19 \text{ km}\cdot\text{h}^{-1}$. Acceleration and deceleration efforts = ≥ 2 or $\leq -2 \text{ m}\cdot\text{s}^{-2}$, respectively. VHI movements = sum of all movements in the horizontal plane (i.e. accelerations, decelerations, and left / right changes of direction), when >3.5 or $<-3.5 \text{ m}\cdot\text{s}^{-2}$.

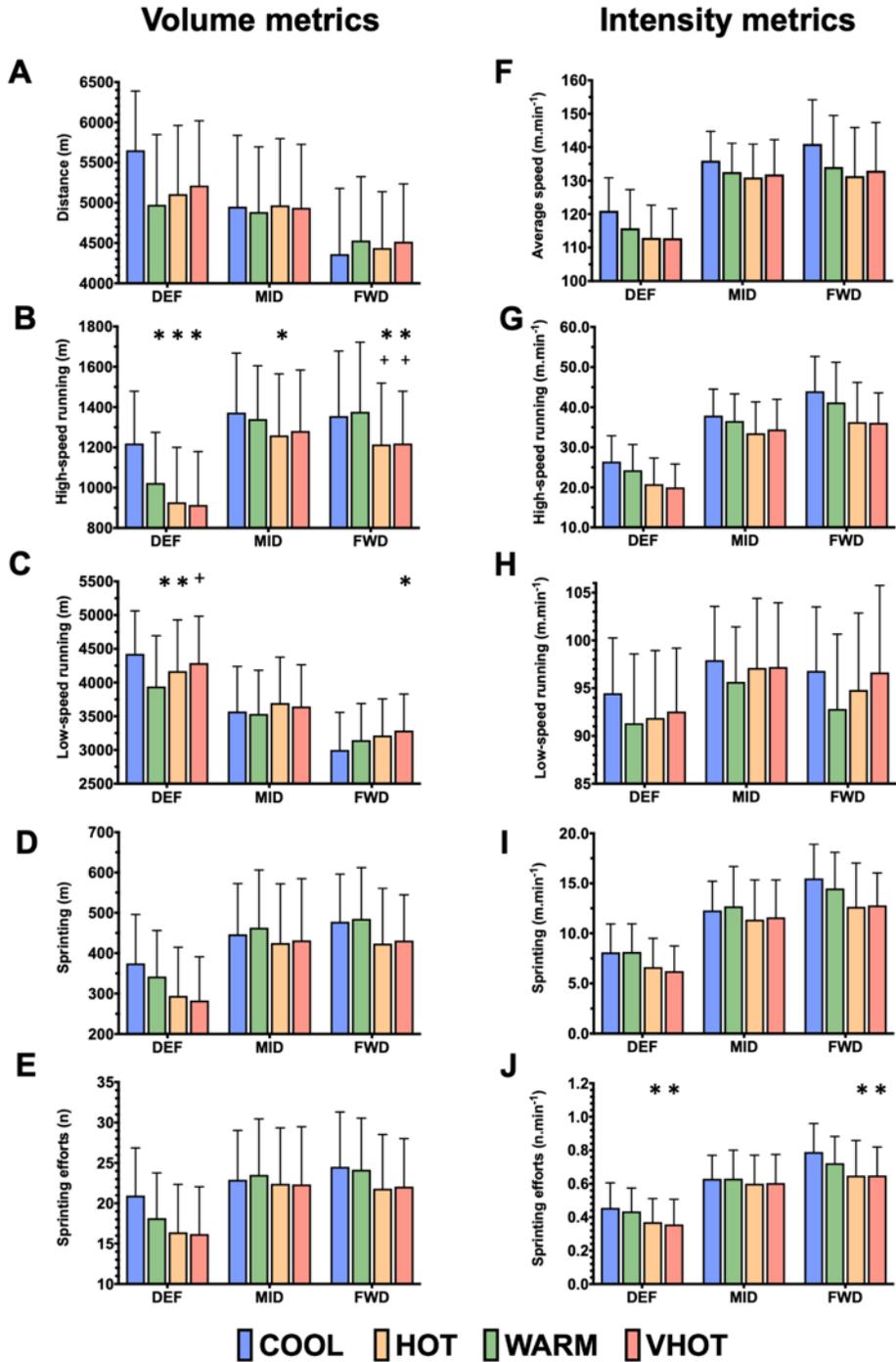


Figure 4. Mean \pm SD panel of positional responses across conditions (COOL, WARM, HOT, VHOT).

* denotes within position difference from COOL ($p < 0.05$), + denotes within position difference from WARM ($p < 0.05$). High-speed running = $> 14.5 \text{ km.h}^{-1}$, low-speed running = $\leq 14.5 \text{ km.h}^{-1}$ and sprinting = $\geq 19 \text{ km.h}^{-1}$.

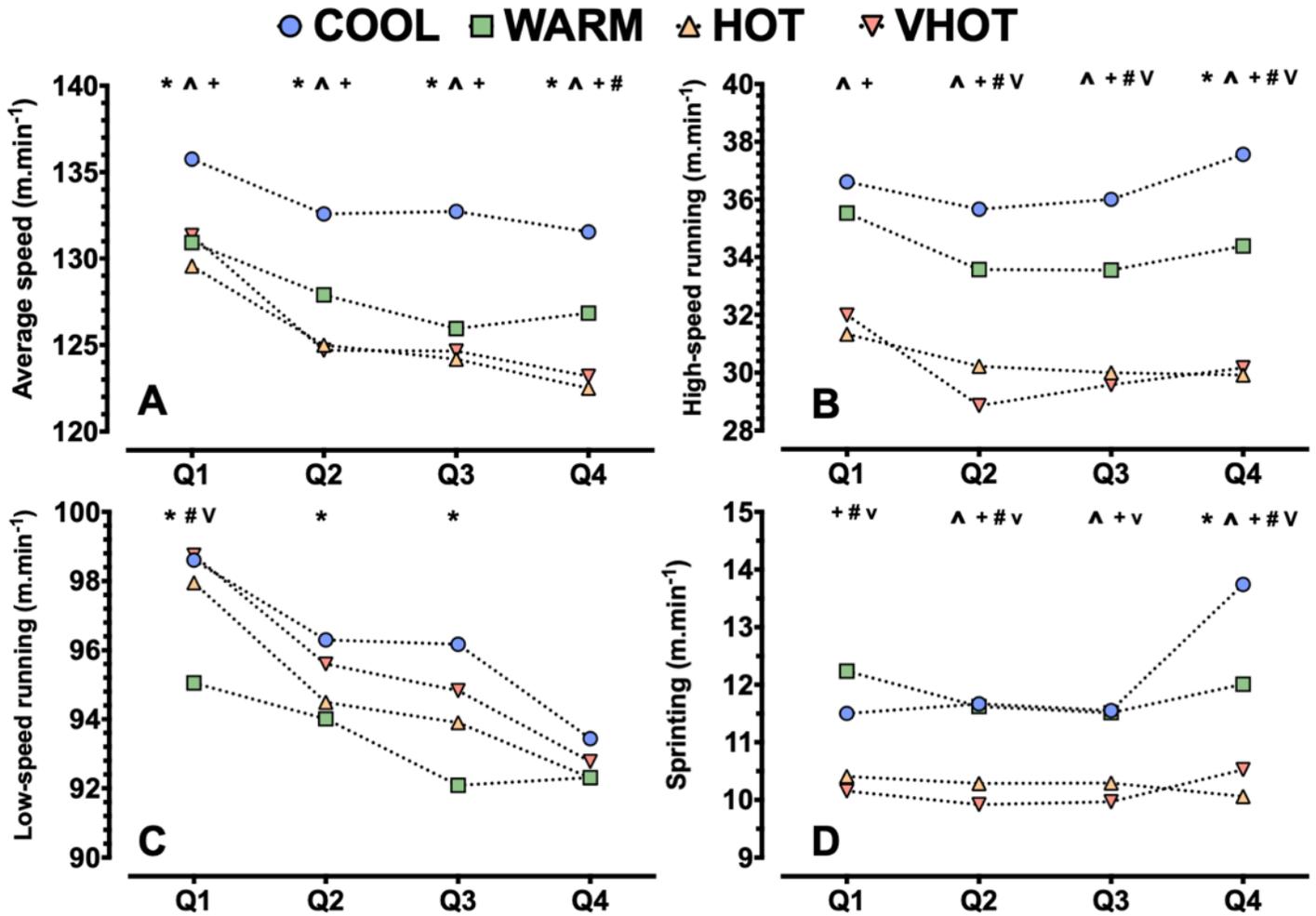


Figure 5. Panel of A - average speed (m.min⁻¹), B - high speed running (m.min⁻¹), C - low speed running (m.min⁻¹), and D - sprinting distance (m.min⁻¹) responses across playing quarters and conditions (circle =COOL, square =WARM, triangle =HOT, nabla =VHOT). Error bars removed for clarity.

* denotes a difference between COOL and WARM, ^ denotes a difference between COOL and HOT, + denotes a difference between COOL and VHOT, # denotes a difference between WARM and HOT, v denotes a difference between WARM and VHOT, all p<0.05. High-speed running = >14.5 km.h⁻¹, low-speed running =<14.5 km.h⁻¹ and sprinting =>19 km.h⁻¹.