

Northumbria Research Link

Citation: Barwood, Martin, Goodall, Stuart and Bateman, Jon (2018) The effect of hot and cold drinks on thermoregulation, perception and performance: the role of the gut in thermoreception. *European Journal of Applied Physiology*, 118 (12). pp. 2643-2654. ISSN 1439-6319

Published by: Springer

URL: <http://doi.org/10.1007/s00421-018-3987-8> <<http://doi.org/10.1007/s00421-018-3987-8>>

This version was downloaded from Northumbria Research Link:
<http://nrl.northumbria.ac.uk/id/eprint/35646/>

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: <http://nrl.northumbria.ac.uk/policies.html>

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

The effect of hot and cold drinks on thermoregulation, perception and performance: the role of the gut in thermoreception

Martin J Barwood^{1*}, Stuart Goodall², Jon Bateman²

¹Department of Sport, Health and Nutrition, Leeds Trinity University, Horsforth, Leeds U.K.

²Northumbria University, Department of Sport, Exercise and Rehabilitation, Northumberland Road, Newcastle Upon Tyne, U.K.

Running head: Hot and cold drinks

This work was funded by a research grant from the European Hydration Institute

There are no conflicts of interest to declare

*Corresponding Author: Dr Martin Barwood, Dept. Sport, Health and Nutrition, Leeds Trinity University, Brownberrie Lane, Horsforth, LS18 5HD, UK. Tel: +44 (0) 113 283 7100.
Email. m.barwood@leedstrinity.ac.uk

Abstract

Purpose. Hot compared to cold drinks alter sweating responses during very low intensity exercise in temperate conditions. The thermoregulatory, perceptual and performance effects of hot compared to cold drinks in hot, dry conditions during high-intensity exercise have not been examined. **Method.** Ten participants (mean \pm SD characteristics age 25 ± 5 years, height 1.81 ± 0.07 m, body mass 73.5 ± 10.6 kg, maximal power output (P_{Max}) 350 ± 41 W), completed two conditions where they drank four boluses (ingested at -9, 15, 30 & 45 minutes respectively) of $3.2 \text{ mL}\cdot\text{kg}^{-1}$ (~960 mL total) of either a COLD (5.3°C) or a HOT drink (49.0°C), which were contrasted to a no drink CONTROL. They cycled for 60-minutes ($55\% P_{Max}$ in hot (34.4°C) dry (34% RH) ambient conditions followed by a test to exhaustion (TTE; $80\% P_{Max}$). The thermoregulatory, performance and perceptual implications of drink temperature were measured. **Results.** TTE was worse in the CONTROL (170 ± 132 s) than the COLD drink (371 ± 272 s; $p = .021$) and HOT drink conditions (367 ± 301 s; $p = .038$) which were not different ($p = .965$). Sweat responses (i.e. reflex changes in mean skin temperature (T_{msk}) and galvanic skin conductance) indicated transient reductions in sweating response after COLD drink ingestion. The COLD drink improved thermal comfort beyond the transient changes in sweating. **Conclusion.** Only COLD drink ingestion changed thermoregulation but improved perceptual response. Accordingly, we conclude a role for gut thermoreception in thermal perception during exercise in hot, dry conditions.

Keywords: cold drinks, gut thermoreception, hot drinks, thermal comfort.

List of Abbreviations

Analysis of variance (ANOVA)

American College of Sports Medicine (ACSM)

Fixed intensity (FI)

Galvanic skin conductance (GSC)

Gut comfort (GC)

Heart rate (HR)

Maximal power output (P_{Max})

Mean skin temperature (T_{msk})

Rating of perceived exertion (RPE)

Rectal temperature (T_{rec})

Relative humidity (RH)

Skin wetness (SkW)

Standard deviation (SD)

Test to exhaustion (TTE)

Thermal comfort (TC)

Thermal sensation (TS)

Wet bulb, globe, temperature (WBGT)

1 **Introduction**

2 Exercise performance and physical activity capacity are limited by dehydration (Rowell et al.
3 1974). Dehydration is exacerbated by increases in environmental temperature because of high
4 sweat rates in order to control the rise in deep body temperature (Rowell et al. 1966). This
5 problem applies to those undertaking extended exercise in both competitive and recreational
6 scenarios. It is generally accepted that modest dehydration of approximately 2% is sufficient
7 to reduce maximal aerobic exercise performance and increase the cardiovascular demand of
8 sub-maximal exercise (ACSM et al. 2007). Consequently it is advisable to maintain hydration
9 status within these limits. There is much on-going debate on the best practise for maintaining
10 hydration status in such circumstances which include *ad libitum* drinking (Armstrong et al.
11 2014), thirst driven fluid consumption (Hew-Butler et al. 2006) and fluid consumption per
12 kilogram of body mass (Noakes, 2011). The ACSM guidelines suggest drinking fluids of
13 between 15°C and 22°C, at a rate of 0.4-0.8 L.hr⁻¹ in temperate conditions and to avoid body
14 mass loss of greater than 2% irrespective of ambient conditions (ACSM et al. 2007). Such
15 guidance is of critical importance particularly during exercise in hot conditions where, if
16 adequate fluid is not ingested to balance sweat losses, deep body temperature may increase
17 disproportionately (hyperthermia), culminating in heat related illness and ultimately
18 circulatory and physical collapse (Rowell et al. 1966).

19

20 To date the temperature of ingested fluid has primarily been considered on the basis of
21 palatability (e.g. ACSM et al. 2007). However, there is evidence that hot (i.e. 50°C)
22 compared to cold drinks (i.e. 10°C, 4.5°C) could change body temperature regulation and
23 sweat rates during physical activity and possibly sports performance (Bain et al. 2012; Lee et
24 al. 2008). Continued exercise is liable to arouse a thirst response and the vast majority of

25 people would choose a cool drink to lessen their thermal discomfort from both a
26 physiological and perceptual viewpoint (Barwood, 2012). This selection probably occurs
27 because of the greater hedonic tone of cold drinks (Szytk et al. 1989). Yet, Bain et al. (2012)
28 have suggested that ingestion of hot fluids (50°C) probably *reduced* body heat storage when
29 compared to cold (1.5°C) and cool (10°C) drinks because of a disproportionate influence
30 upon sweat rate by stimulation of a gut thermoreceptor. Specifically, hot fluid ingestion
31 increased sweat production and rate beyond the thermal mass of the fluid itself but this was
32 not evident with a cold drink; although the validity of the resultant net change in body heat
33 storage has recently been challenged (Lamarche et al. 2015). These findings have important
34 implications for fluid replacement guidelines. Theoretically, in certain circumstances the
35 consequence of hot fluid ingestion may be to *reduce* the risk of heat illness by increasing
36 sweating assuming adequate fluid is available to balance the extra sweat. The studies of Bain
37 and colleagues (2012) along with Morris and colleagues (2014) are applicable to low work
38 rates where the evaporation capacity of the environment was high (i.e. low ambient
39 temperature and humidity; 23.6°C/23.7°C & 11%/32% RH). These data, coupled with
40 studies performed at rest (e.g. Nadel et al. 1970), show that the thermoregulatory responses
41 are influenced by drink temperature but the picture at higher work rates, in relation to
42 performance and at higher ambient temperatures is less clear.

43

44 Studies that have been performed at higher ambient temperatures humidities and higher
45 exercise work rates (e.g. Lee & Shirreffs, 2007; Lee et al. 2008a & b; Burdon et al. 2008;
46 Mundel et al. 2006) have not reached a consensus on the effect on sweating but do suggest a
47 possible performance improvement when cold fluid is ingested in a hot or temperate
48 environment (Burdon et al. 2010). Accordingly, it is important to consider both the perceptual
49 and biophysical (i.e. heat exchange) consequences of different temperature drinks. From the

50 perspective of thermal perception, the sensation of a hot drink stimulating the gut may
51 actually increase thermal discomfort and consequently reduce exercise capacity and
52 performance. This would contrast the hypothesised benefit of increasing sweat production
53 that would occur. This places the behavioural (i.e. thermal discomfort is a profound
54 behavioural driver; Taylor et al. 1995) and biophysical mechanisms that may influence
55 physical performance in direct conflict.

56

57 Many of those studies that have examined the performance effect of different temperature
58 drinks have not directly measured regional sweat responses and have instead used a surrogate
59 of regional sweating performance in the form of lowered skin temperature. This is despite
60 well-known discrepancies between regional sweat rates and blood flow thereby producing
61 different drivers of regional skin temperature (Smith et al. 2013; Smith & Johnson, 2016).
62 Similarly, unrealistic drinking protocols that use large volumes of fluid (e.g. Lee et al. 2008b)
63 and/or that include temperature response priming by consumption of large boluses of fluid in
64 advance of exercise (e.g. Lee & Shirreffs, 2007) with extended periods of seated rest, all
65 contribute to the confusion over any performance and thermoregulatory effect. Importantly,
66 these studies raise the possibility thermal effects but do not reflect the real world scenario
67 where preparatory periods before exercise may be short. Likewise, flavoured beverages have
68 also been used which may increase drink consumption, frequency and hedonic tone when the
69 primary variable of interest is drink temperature (e.g. Mundel et al. 2006). Lastly, it is prudent
70 to ensure only the gut thermoreceptors are targeted by a given temperature drink and care
71 must be taken to protect the skin (palm) from cooling and warming prior to beverage
72 consumption. This is especially prudent given the density of thermoreceptors on the hand that
73 may subsequently drive thermal comfort (Hensel, 1984).

74

75 Accordingly, this study aims to examine whether the ingestion of a hot drink (i.e. 50°C) is
76 beneficial to thermoregulation at rest and during exercise in hot conditions when evaporation
77 is enabled (i.e. a dry environment) when contrasted to a cold drink (i.e. 5°C) and a no-drink
78 control. We hypothesised that hot fluid ingestion would accelerate the onset of sweating and
79 increase sweat production thereby lowering skin temperature and cardiovascular strain (H₁).
80 Secondly, a hot drink would increase gut discomfort and alter thermal perception (H₂).
81 Finally, performance may be influenced by the resultant effects of drink temperature with
82 cold drinks having an ergogenic effect (H₃).

83

84 **Methods**

85 *Participants*

86 The study was approved by the University ethics committee. All participants gave written,
87 informed consent to take part. An *a priori* power analysis to see differences in TTE
88 performance indicated nine participants were required to see a moderate effect size (0.5) at an
89 80% statistical power to an alpha level of 0.05 (GPower, version 3.1, Heinrich Heine,
90 University of Dusseldorf). Twelve non heat acclimatised male volunteers were recruited to
91 allow for participant attrition. They were trained cyclists who were accustomed to maximal
92 exercise and undertook cycling training > 3 times per week. Their mean \pm SD physical
93 characteristics were age 25 ± 5 years, height 1.81 ± 0.07 m, body mass 73.5 ± 10.6 kg, body
94 surface area (Dubois & Dubois, 1915) 1.93 ± 0.2 m², maximal power output (P_{Max}) 350 ± 41
95 W. Prior to each visit, participants were asked to maintain a similar diet, and to refrain from
96 alcohol or caffeine consumption 24 hours prior. Participants arrived for each test in a
97 hydrated state (i.e. having consumed 500 mL of water within the previous two hours).

98

99 *Experimental design*

100 The participants visited the experimental facility on four separate occasions. Visit one was to
101 undertake a preliminary P_{Max} cycling test used to verify the training status and to establish the
102 sub-maximal fixed intensity (FI) threshold for the remaining three visits. They then
103 completed an exercise test in hot, dry conditions (35°C and 30% relative humidity [RH])
104 during which they consumed either HOT (50°C) or COLD (5°C) fluid or a no fluid
105 CONTROL. The order of the test conditions was randomised using a Latin square.

106

107

108 *Procedure*

109 *Preliminary Measurements*

110 Participants arrived at the laboratory and changed into their cycling kit (typically anklet
111 socks, jersey, bib shorts and cycling shoes) before height (m) and mass (kg) were measured
112 using calibrated weighing scales (Seca, Model 705 2321009, Vogel and Halke, Hamburg,
113 Germany) and a stadiometer (Holtain Ltd, Crymych, Dyfed), respectively. Participants then
114 entered the laboratory and mounted a stationary cycle ergometer (Velotron Racermate,
115 Seattle, USA) and adjusted the cycling position to suit; bike position was replicated in
116 subsequent tests for each. Participants completed a standardised warm-up before commencing
117 the P_{Max} protocol in temperate conditions (20°C, 40% RH). The participant commenced
118 cycling at 150 W at 90 revs·min⁻¹. Step increases of 25 W·min⁻¹ were added until volitional
119 exhaustion was reached or if participants were unable maintain a cadence within 10 revs·min⁻¹
120 ¹. P_{Max} was established objectively as the highest sustained power output for a minimum of 15
121 s.

122

123 *Main Experimental Trials*

124 On arrival at the Environmental Physiology laboratory (TIS Services, Hampshire, UK) the
125 participants were initially weighed naked (within a private room) and clothed (i.e. wearing
126 cycling kit) for subsequent estimation of sweat production and evaporation when coupled
127 with post-test weight measurements and fluid consumed. Participants then, in private, self-
128 inserted after instruction, a calibrated and sterilised rectal thermistor (T_{rec}) 15 cm beyond the
129 anal sphincter to measure deep body temperature during exercise. Participants were then
130 instrumented with skin thermistors, secured by micropore tape (Transpore, 3M, London,
131 Ontario, Canada), on the left hand side of the body at eight different body sites to enable the

132 estimation of mean skin temperature (T_{msk} ; Olesen, 1980); chest, scapula, bicep, hand, thigh,
133 hamstring, calf, and foot. They also donned a heart rate monitor (Polar FT1, Polar Electro Oy,
134 Kempele, Finland) before entering the environmental chamber.

135

136 Participants mounted the stationary cycle ergometer after which galvanic skin conductance
137 (GSC) sensors were attached to the bicep and subscapular region. These were used to
138 estimate sweating onset and rate (see measurements section). The participant sat at rest on the
139 ergometer for 10-minutes. Depending on the trial condition, the participant either ingested a
140 hot or cold drink after 1-minute of rest or did not receive any fluid (CONTROL). Further
141 drinks were ingested after 15, 30 and 45 minutes of exercise. Prior to each drink ingestion
142 point (including the corresponding point in the CONTROL condition) an absorbent pad of
143 fixed surface area was secured, using micropore tape, to the forearm and subscapular to
144 establish regional sweat volume and rate. The pad was removed after 5-minutes. On
145 commencement of this rest period and before and after drink ingestion point, participants
146 reported their subjective sensations of thermal perception (comfort and sensation), perceived
147 exertion (exercise only), skin wetness and gut comfort. Following the rest period participants
148 commenced FI exercise at 55% of P_{Max} which corresponded to 193 ± 23 W. A fan (Wahl,
149 Model ZX220, Wahl, Sterling, IL, USA) was switched on at the start of exercise and
150 provided a consistent wind speed of 2 to 2.5 $m \cdot s^{-1}$ throughout the trial; wind speed was
151 verified by an anemometer (LM-8000 Anemometer, Digital Instruments, New York, USA).

152

153 After 60-minutes of FI cycling the power output was increased to 80% of P_{Max} and
154 participants were instructed to maintain this intensity for as long as possible until exhaustion
155 occurred; this comprised the performance based test to exhaustion (TTE) phase of the trial.

156 Test duration, power output, pedal cadence and heart rate were displayed throughout the FI
157 period but were obscured during the TTE. Participants were withdrawn if their deep body
158 temperature exceeded 40°C. Upon completion of the trial the participants exited the
159 environmental chamber and were re-weighed.

160

161 *Drink Temperature Manipulation*

162 Participants ingested a fixed fluid volume of 3.2 mL.kg⁻¹ of body mass. This corresponded to
163 approximately 240 mL per bolus for a 75 kg individual and a total of ~960 mL in the HOT
164 and COLD drink conditions. The temperature of the HOT drink was established by
165 immersing two drinks bottles in to a temperature controlled water bath (Grant Instruments
166 (Cambridge) Ltd, Shepreth, U.K) set to 50°C. In order to verify the drink temperature a
167 thermistor was taped to the wall of the water bath and a second thermistor was immersed in to
168 one of the drinks bottles, which was not consumed during the trial to avoid biological
169 contamination. Temperature data were displayed on a data logger (Squirrel 1000 Series,
170 Grant Instruments (Cambridge) Ltd, Shepreth, U.K). It was assumed that the temperature
171 established in one drink corresponded to that achieved in the one that was consumed; this
172 method was verified in pilot studies. Immediately before drink consumption and in order to
173 achieve an accurate drink volume, the water was poured in to an insulated plastic beaker on a
174 weighing scale (Coline, KG-1005, Clas Ohlson, Dalarna, Sweden). To avoid warming the
175 skin of the palm and thereby confounding thermal perception subjective reports, the surface
176 of the beaker was insulated against temperature change. The participants were encouraged to
177 ingest the drink as quickly as possible to avoid substantial beverage temperature changes.

178

179 The temperature of the COLD drink was controlled via an ice bath kept in a thermoneutral
180 cupboard adjacent to the environmental chamber. A similar procedure to that described above
181 was used to verify the drink temperature but the beaker from which the drink was consumed
182 was also stored in the ice; the beaker insulator remained in the environmental chamber.
183 Thereafter the same procedure as in the HOT drinks trial was used to enable accurate drink
184 volume.

185

186 *Measurements*

187 *Skin Temperature, Deep Body Temperature and Environmental Temperature*

188 Skin temperature (T_{sk} ; EUS-UU-VL- 2-0, Grant Instruments (Cambridge) Ltd, Shepreth,
189 U.K) and deep body temperature (T_{rec} ; REC-UU-VL- 2-0, Grant Instruments (Cambridge)
190 Ltd, Shepreth, U.K) were measured by a data logger (Squirrel 2020 series, Grant Instruments
191 (Cambridge) Ltd, Shepreth, U.K) in 10 s epochs throughout the heat exposure. Between
192 participants, each skin thermistor was cleaned with an alcohol swab. Between participants the
193 rectal thermistor was sterilised using medical disinfectant (Virkon, Day-Impex Ltd,
194 Colchester, U.K). The environmental conditions were measured at the mid-point of the fork
195 of the Velotron bike using a WBGT weather station (Edale Instruments, Longstanton,
196 Cambridge, U.K).

197

198 *Galvanic Skin Conductance (GSC)*

199 GSC was used to estimate sweating onset and rate of sweat gland activation; an extension of
200 its application to sweat ion reabsorption (Amano et al. 2016). Prior to trial commencement
201 two GSC probes (GSR MLA0118-DC-12A, AD Instruments, Castle Hill, Australia) were
202 attached in a standardised array using micropore tape (Transpore, 3M, London, Ontario,

203 Canada) and a standardised amount of conductive electrode paste (MLA1095, AD
204 Instruments, Castle Hill, Australia). The probes were integrated with a biological amplifier
205 (FE116 GSR Amp, AD Instruments, Castle Hill, Australia). Before commencing data
206 collection the probes were biologically zeroed whilst attached to the participant's skin. Data
207 were collected using an analogue to digital converting system (Powerlab, 16/30 AD
208 Instruments, Castle Hill, Australia) at a resolution of 60 Hz and subsequently averaged to 10 s
209 epochs.

210

211 *Absorbent Pad Sweat Measurement*

212 Local sweat volume was established at the subscapular and forearm using a technical
213 absorbent pad (2204CW1, Technical Absorbents Ltd, Grimsby, U.K) collection technique. In
214 accordance with the methods of Morris et al. (2013), a pad of fixed surface area (64 cm²) was
215 attached to the skin. The patch consisted of an outer area and an inner area (49 cm²;) from
216 which the volume of sweat was collected and established using high-resolution scales
217 (OHAUS TS400D, precision balance, Florham Park, New Jersey, USA). The outer border of
218 the pad was used to avoid sweat tracking from an unmeasured area of the skin. Between
219 measurements of pad weight the pad was stored in an airtight Ziploc bag thereby preventing
220 sweat evaporation. The patches were assembled two minutes prior to application and applied
221 to the skin twenty seconds prior to each time point (i.e. -10, 15, 30 and 45 minutes; i.e.
222 corresponding to immediately before drink consumption). This technique correlates well with
223 ventilated sweat capsule estimates of regional sweat production (Morris et al. 2013).

224

225

226

227 *Perceptual Responses*

228 Participants underwent a standardized explanation of each perceptual scale before
229 commencing the exercise trials of the following scales:

230 RPE was measured on a 15-point likert scale (Borg, 1982). Whole body thermal perceptions
231 were measured using a 20 cm visual analogues scale for thermal sensation (TS) which ranges
232 from *Very hot* (20 cm); *Hot* (17.5 cm), *Warm* (15.0 cm), *Slightly warm* 12.5 cm), *Neutral* (10
233 cm), *Slightly cool* (7.5 cm), *Cold* (2.5 cm), *Very cold* (0 cm). The thermal comfort (TC) scale
234 ranges from: *Very comfortable* (20 cm), *Comfortable* (16 cm), *Just comfortable* (12 cm), *Just*
235 *uncomfortable* (10.5 cm), *Uncomfortable* (4 cm), *Very uncomfortable* (0 cm). On both
236 thermal perceptual scales the worded descriptions were used as a guide only (Zhang, 2003).

237 Gut Comfort (GC; adapted from Gonzalez et al. 2015) was assessed using a five point likert
238 scale to describe digestive sensations in the stomach where 1 = *Very comfortable*, 3 =
239 *Average comfort* and 5 = *Very uncomfortable*. Skin wetness (SkW; adapted from Storaas and
240 Bakkevig, 1996) was used to measure the sensation of sweat accumulation on the skin using
241 an eight point categorical scale where 1 = *More dry than normal*, 4 = *Chest and back* are wet,
242 and 8 = *Sweat/water runs off many places*.

243

244 *Statistical Analysis*

245 Two of the twelve participants recruited did not complete all of the main exercise trials; data
246 are presented for n = 10. Mean \pm SD were calculated for each condition for drink temperature
247 and volume (COLD and HOT drink trials only). Drink volume was compared between
248 conditions (i.e. COLD drink vs HOT drink) using an independent samples t-test.

249

250 Mean \pm SD were calculated for all thermal (T_{msk} , T_{rec} , and HR) and perceptual (RPE, TS, TC,
251 GC and SkW) variables at nine different time points across the trial (trial start, pre and post
252 each drink ingestion [6 points], end of FI exercise and TTE end); RPE was only analysed for
253 eight time points as it was not collected at rest. The difference in sweat pad mass before and
254 following drink ingestion was calculated. Data were compared within participant, across time
255 and between condition (CONTROL, COLD and HOT drinks) using repeated measures
256 analyses of variance (ANOVA). To establish the presence of any reflex changes in
257 thermoregulatory response after drink ingestion the change in T_{msk} and T_{rec} were calculated
258 for the 3-minutes following drink ingestion (due to the potential for decay in intragastric
259 temperature 5-minutes after drink ingestion; Shi et al. 2000) and averaged across drink time
260 points. Mean GSC was established at each measurement site (i.e. bicep and subscapular).
261 Total sweat production, sweat evaporation, TTE duration, mean GSC, reflex change in T_{msk} ,
262 T_{rec} were compared between condition using a one way ANOVA. *Post-hoc* pairwise
263 comparisons were conducted to establish the direction of any significant main and interaction
264 effects with *Bonferroni* adjustment. Estimates of effect size are reported using partial eta
265 squared (η^2). Confidence intervals at the 95% level data are reported for TTE data.
266 Statistical analyses were carried out using SPSS v22 (IBM SPSS statistics, Chicago, IL,
267 USA) to an alpha level of 0.05.

268

269

270 **Results**

271 *Environmental Conditions*

272 Environmental conditions across trials were: dry bulb temperature $34.4 \pm 0.7^{\circ}\text{C}$, wet bulb
273 temperature $21.7 \pm 0.9^{\circ}\text{C}$ equating to a relative humidity of $33.9 \pm 1.4\%$. Wind speed within
274 the trials averaged $2.8 \pm 0.3 \text{ m}\cdot\text{s}^{-1}$.

275

276 *Performance Data*

277 *Time to exhaustion*

278 TTE performance averaged, $170 \pm 132 \text{ s}$, $371 \pm 272 \text{ s}$, and $367 \pm 301 \text{ s}$ in the CONTROL,
279 COLD and HOT drink conditions, respectively. Participants exercised for significantly less
280 time in the CONTROL condition (main effect for condition: $F_{(2,18)} = 4.287$, $p = .030$, $\eta p^2 =$
281 $.323$) compared to both the COLD ($p = .021$) and HOT ($p = .038$) conditions, which did not
282 differ ($p = .965$). 95% CI for TTE in the CONTROL, COLD and HOT DRINK trials was 76
283 to 265 s, 176 to 565 s, and 151 to 583 s respectively.

284

285 *Drink Volume and Temperature*

286 Drink volume in the HOT and COLD drink trials averaged $971 \pm 171 \text{ mL}$ and $930 \pm 126 \text{ mL}$,
287 respectively. Consequently, the drink volume between the HOT and COLD drink conditions
288 was not different ($t = 1.035$ $p = .328$). Drink temperature averaged $49.0 \pm 1.9^{\circ}\text{C}$ and $5.3 \pm$
289 1.7°C in the HOT and COLD drink trials respectively.

290

291

292

293 *Rectal temperature (T_{rec})*

294 Rectal temperature response is displayed in figure 1A. Rectal temperature increased steadily
295 during FI exercise and averaged $38.7 \pm 0.6^{\circ}\text{C}$ (grand mean \pm SD) by the end of this part of
296 the protocol (main effect for time, $F_{(8,72)} = 43.628$, $p = .001$, $\eta^2 = .829$). Terminal rectal
297 temperature after the TTE indicated the participants were hyperthermic (grand mean $39.0 \pm$
298 0.6°C). T_{rec} was higher, on average, in the CONTROL trial (main effect for condition $F_{(2,18)} =$
299 5.436 , $p = .014$, $\eta^2 = .377$) than both the COLD drink ($p = .019$) and HOT drink trial ($p =$
300 $.008$) which were not different ($p = .482$). This main effect for condition did not culminate in
301 an interaction effect ($F_{(16,144)} = .780$, $p = .706$, $\eta^2 = .080$). The extent of T_{rec} change in the 3-
302 minutes following drink ingestion was similar in each condition ($F_{(2,18)} = 1.492$, $p = .251$, $\eta^2 =$
303 $.142$) and averaged $0.06 \pm 0.02^{\circ}\text{C}$, $0.05 \pm 0.02^{\circ}\text{C}$ and $0.05 \pm 0.02^{\circ}\text{C}$ in the CONTROL,
304 COLD and HOT drink conditions, respectively.

305

306 ***INSERT FIGURE 1 NEAR HERE***

307

308 *Mean skin temperature (T_{msk})*

309 T_{msk} response is displayed in figure 1B. As the trial ensued the T_{msk} increased but then
310 plateaued (main effect for time: $F_{(8,72)} = 3.982$, $p = .045$, $\eta^2 = .307$). This did not happen to
311 any greater extent in any of the test conditions (no main effect for condition: $F_{(2,18)} = 1.416$, p
312 $= .269$, $\eta^2 = .136$ or interaction effect: $F_{(16,144)} = 0.775$, $p = .711$, $\eta^2 = .079$). The change in
313 T_{msk} following drink ingestion was significantly different in the 3-minutes following drink
314 ingestion ($F_{(2,18)} = 3.533$, $p = .05$, $\eta^2 = .282$) with T_{msk} remaining unchanged in the COLD
315 drink trial ($0.00 \pm 0.10^{\circ}\text{C}$) compared to the CONTROL condition which increased ($0.10 \pm$
316 0.10°C ; $p = .020$), but was not different to the HOT drink condition ($0.06 \pm 0.10^{\circ}\text{C}$; $p = .$

317 200). The CONTROL condition and the HOT drink condition were not different ($p = .273$).
318 Terminal T_{rec} and T_{msk} at the end of each stage of the protocol (i.e. rest, 55%, 80% P_{Max}) are
319 displayed in table 1.

320

321 ***INSERT TABLE 1 NEAR HERE***

322

323 *Sweat Responses*

324 *Whole body Sweat Estimation*

325 Sweat production in the CONTROL, COLD and HOT drink conditions was, 1.54 ± 0.3 L,
326 1.63 ± 0.3 L and 1.59 ± 0.2 L, respectively and was not different between conditions ($F_{(2,18)} =$
327 $.592$, $p = .564$, $\eta^2 = .050$). The volume of sweat evaporated was 1.46 ± 0.4 L, 1.52 ± 0.3 L
328 and 1.49 ± 0.2 L, respectively and was not different between condition ($F_{(2,18)} = .214$, $p =$
329 $.809$, $\eta^2 = .054$). This equated to 95 ± 13 %, 94 ± 6 % and 94 ± 7 % of sweat being
330 evaporated.

331

332 *Regional Sweat Production – Sweat Pad collection at the Subscapular and Forearm*

333 Regional sweat production increased as the trial ensued (subscapular: main effect for time:
334 $F_{(3,27)} = 39.574$, $p = .001$, $\eta^2 = .815$; forearm: main effect for time: $F_{(3,27)} = 59.568$, $p = .010$,
335 $\eta^2 = .869$). The sweat production seen at the forearm plateaued after the first sweat pad
336 collection whereas sweat volume continued to increase at the subscapular region until the
337 final measurement point. Yet, there were no differences in regional sweat production overall
338 (no main effect for condition: subscapular: $F_{(2,18)} = 1.880$, $p = .181$, $\eta^2 = .173$; forearm: $F_{(2,18)}$
339 $= 1.561$, $p = .237$, $\eta^2 = .148$) or interaction effects (subscapular: $F_{(6,54)} = .513$, $p = .796$, $\eta^2 =$
340 $.054$; forearm: $F_{(6,54)} = .738$, $p = .622$, $\eta^2 = .076$). Subscapular and forearm local sweat rates,

341 converted to $\text{g}\cdot\text{hr}^{-1}$, after each drink are presented in figure 2. The mean sweat rate across the
342 CONTROL, COLD and HOT drink conditions at the subscapular were $1.784 \pm 0.673 \text{ g}\cdot\text{hr}^{-1}$,
343 $2.072 \pm 1.066 \text{ g}\cdot\text{hr}^{-1}$, and $1.811 \pm 0.749 \text{ g}\cdot\text{hr}^{-1}$. Sweat rates at the forearm were of a similar
344 magnitude; data not shown.

345

346 ***INSERT FIGURE 2 NEAR HERE***

347

348 *Galvanic Skin Conductance*

349 GSC response at the bicep and subscapular region are displayed in figure 3A. The extent of
350 GSC was significantly greater ($t = -6.675$, $p = .001$) at the subscapular region (grand mean \pm
351 SD; $21.5 \pm 3.6 \mu\text{S}$) compared to the bicep region ($12.8 \pm 4.2 \mu\text{S}$) indicating greater proximal
352 sweating irrespective of the test condition. When the change in GSC was examined
353 immediately after drink ingestion (i.e. in the following 3-minutes) it was $0.20 \pm 0.8 \mu\text{S}$, -0.20
354 $\pm 1.74 \mu\text{S}$, and $0.30 \pm 2.2 \mu\text{S}$ in the CONTROL, COLD and HOT drink conditions,
355 respectively at the bicep and $2.2 \pm 2. \mu\text{S}$, $2.2 \pm 2.0 \mu\text{S}$, $1.3 \pm 2.2 \mu\text{S}$ at the subscapular region.
356 There was no statistical evidence that the rate of sweating was altered at either site (bicep:
357 $F_{(2,18)} = .182$, $p = .835$, $\eta^2 = .020$; subscapular: $F_{(2,18)} = .469$, $p = .663$, $\eta^2 = .050$) despite
358 visual evidence of GSC being consistently lower in the COLD drink condition at the bicep
359 (figure 3B) and a sinusoidal wave after each hot drink ingestion at the subscapular region
360 (figure 3A).

361

362 ***INSERT FIGURE 3 NEAR HERE***

363

364 *Perceptual Responses*

365 *Thermal sensation*

366 Participant's reported a similar TS at the start of each trial corresponding to the worded
367 descriptor *Slightly warm*. As the trial ensued the participant's TS increased steadily (main
368 effect for time: $F_{(10,90)} = 28.702$, $p = .001$, $\eta^2 = .761$) and reached a descriptive sensation of
369 *Hot* at the end of the FI period (grand mean \pm SD: 17.3 ± 1.5 cm) and peaked at being *Very*
370 *hot* by the end of the TTE (grand mean \pm SD: 18.7 ± 1.2 cm) yet this did not happen to any
371 differing extent in either condition (no main effect for condition: $F_{(2,18)} = 1.065$, $p = .365$, η^2
372 $= .106$) or produce an interaction effect ($F_{(20,180)} = 11.917$, $p = .160$, $\eta^2 = .163$). TS data are
373 shown in figure 4A.

374

375 ***INSERT FIGURE 4 NEAR HERE***

376

377 *Thermal Comfort*

378 Participant's reported a similar TC at the start of each trial in each condition which
379 corresponded to the worded descriptor *Just comfortable* to *Comfortable*. As the trial ensued
380 the participant's TC decreased steadily (main effect for time: $F_{(10,90)} = 38.693$, $p = .001$, $\eta^2 =$
381 $.811$) and reached a descriptive sensation of approaching *Uncomfortable* at the end of the FI
382 period (grand mean \pm SD: 6.6 ± 4.3 cm) and peaked at being more *Uncomfortable* by the end
383 of the TTE (grand mean \pm SD: 3.9 ± 3.4 cm). Participants felt less thermal discomfort (main
384 effect for condition: $F_{(2,18)} = 3.915$, $p = .039$, $\eta^2 = .303$) in the COLD drink condition than
385 the CONTROL condition ($p = .025$) and approached being different to the HOT drink
386 condition ($p = .077$). The CONTROL condition and the HOT drink trial were not different (p
387 $= .889$). An interaction effect was also evident ($F_{(20,180)} = 6.030$, $p = .002$, $\eta^2 = .202$) where

388 consistent differences were seen between the COLD drink condition and the CONTROL;
389 time point differences are shown in figure 4B.

390

391 *Gut Comfort*

392 All participants rated their GC as *Very comfortable* before the trial commenced. As the trial
393 ensued GC rating increased indicating greater discomfort (main effect for time: $F_{(10,90)} =$
394 6.078 , $p = .012$, $\eta p^2 = .403$). GC tended to be worst in the HOT drink trial (2 ± 0.3) followed
395 by the COLD drink (2 ± 0.4) and then the CONTROL condition (1 ± 0.2) although this did
396 not culminate in any differences between conditions (no main effect for condition: $F_{(2,18)} =$
397 3.078 , $p = .071$, $\eta p^2 = .255$) or an interaction effect ($F_{(20,18)} = 1.221$, $p = .241$, $\eta p^2 = .119$). It is
398 important to note that, despite some inter-individual variation in the GC responses, the mean
399 responses never exceed a rating of 2 corresponding to *Comfortable*; see figure 4C.

400

401 *Skin Wetness*

402 Despite the dry ambient conditions and convective airflow provided by the fan, as the trial
403 ensued and the participants started to sweat their sensation of SkW increased (main effect for
404 time: $F_{(10,90)} = 67.086$, $p = .001$, $\eta p^2 = .882$). At the end of the FI period SkW was rated as
405 *Sweat/water runs somewhere off* (grand mean \pm SD: 7 ± 1) and reached the descriptive rating
406 *Sweat water runs of many places* (8 ± 1). There were no differences between conditions (no
407 main effect for condition: $F_{(2,18)} = .249$, $p = .782$, $\eta p^2 = .027$) or an interaction effect ($F_{(20,18)} =$
408 1.555 , $p = .068$, $\eta p^2 = .147$). SkW responses are shown in figure 4D.

409

410

411 *RPE and Heart Rate*

412 Mean \pm SD RPE response is displayed in figure 5A. Shortly after the commencement of
413 exercise the participant's RPE increased corresponding with the worded descriptor *Light*
414 (grand mean 11 ± 2). Despite no change in exercise intensity RPE increased significantly
415 throughout the FI exercise period and was 15 ± 3 at the end of this part of the protocol (main
416 effect for time: $F_{(7,63)} = 59.503$, $p = .001$, $\eta^2 = .905$). At the end of the TTE RPE was 19 ± 1
417 corresponding to the worded descriptor *Maximal exertion* but there were no significant
418 differences in any of the conditions (no main effect: $F_{(2,18)} = .808$, $p = .461$, $\eta^2 = .082$) or
419 interaction effects: $F_{(14,126)} = 1.497$, $p = .121$, $\eta^2 = .143$).

420

421 ***INSERT FIGURE 5 NEAR HERE***

422

423 Mean \pm SD HR response is displayed in figure 5B. Heart rate did not reflect the RPE
424 responses and a showed a steady increase (main effect for time: $F_{(7,63)} = 59.503$, $p = .001$, η^2
425 $= .869$) as the fixed exercise period ensued (grand mean at the end of fixed exercise: 163 ± 14
426 $\text{b}\cdot\text{min}^{-1}$). Overall HR was significantly higher in the CONTROL condition (main effect for
427 condition: $F_{(2,18)} = 3.553$, $p = .050$, $\eta^2 = .283$) than the COLD drink ($p = .039$) but only
428 approached being different to the HOT drink trial ($p = .052$). The two drink conditions were
429 not different to one another ($p = .464$) and there was no interaction effect ($F_{(14,126)} = 1.260$, p
430 $= .242$, $\eta^2 = .123$).

431

432 **Discussion**

433 This study examined whether the ingestion of a hot drink (i.e. 50°C) is beneficial to
434 thermoregulation at rest and during exercise in hot conditions when evaporation was enabled
435 (i.e. a dry environment) in contrast to a cold drink (i.e. 5°C) and a no-drink control. The
436 perceptual, thermoregulatory and performance implications of these differing drink
437 temperatures were considered with a view to informing fluid replacement guidelines. A
438 conflicting behavioural (i.e. perceptual) and thermoregulatory effect (i.e. altered sweat
439 production) was plausible since it is possible that a hot drink could increase thermal
440 discomfort through increases in temperature sensation by stimulation of the gut but actually
441 *improve* body temperature regulation by elevating sweat production (Bain et al. 2012).
442 Although highly theoretical, this in turn could have had the potential to reduce surface and
443 eventually internal body temperature. However, this would also have increased the rate at
444 which dehydration developed that could be a problem in situations where water provision is
445 limited and may only be evident over an extended period of time. Yet, we found no change in
446 the rate of sweating or the extent of dehydration after hot drink ingestion; thus, H₁ for the hot
447 drink was not supported.

448

449 By contrast, an opposing effect on sweating was possible when a cold drink was ingested. A
450 cold drink could have reduced sweat production through direct stimulation of a gut
451 thermoreceptor which has been confirmed as being present in mammals and humans (Bain et
452 al. 2012; Morris et al. 2014 & 2017; Nadel et al. 1970; Rawson & Quick, 1972). There was
453 only visual evidence for a reduction in peripheral sweating (i.e. bicep GSC) following cold
454 drink ingestion but a significant reflex reduction in T_{msk} immediately after cold drink
455 ingestion. Yet these changes were small, periodic and beyond the detection resolution of the
456 previously validated (Morris et al. 2013) sweat pad collection technique that has been shown

457 to be sensitive to change with similar protocols (Morris et al. 2013). However, it must be
458 noted that a longer collection period may have yielded different results. Nevertheless, our use
459 of the GSC as an index of change in sweat rate, which extends its use beyond that of sweat
460 ion reabsorption (Amano et al. 2016), shows promise. Indeed, the GSC data showed a
461 significant regional difference in sweat rate and descriptive changes in response to both hot
462 and cold drinks. Our use of GSC in this way is novel but requires further scrutiny.

463

464 The effects of the ingestion of these different temperature drinks on thermal comfort were
465 potentially complicated and could have been confounded by changes in palm temperature
466 without appropriate control. We were careful to avoid this methodological limitation and the
467 resultant effect was that the cold drink improves thermal comfort in a consistent manner
468 towards the end of the trial (see figure 4B) by contrast to the transient alterations in skin
469 temperature and sweating that we saw. Accordingly, we hypothesise a thermal signalling role
470 for the gut thermoreceptor in producing perceptions of thermal comfort but not thermal
471 sensation that extend beyond the reflex physiological response. The opposing effect was not
472 evident following hot drink ingestion. Collectively we suggest the high ambient temperatures
473 and exercise work rates were salient in producing the thermal comfort vote in the early part of
474 trial; therefore we only partially support H₂. The role of the gut only became salient towards
475 in the second half of the trial where relief of thermal discomfort after cold drink ingestion
476 rather than its acceleration after hot drink ingestion was only seen (see figure 4B). Given that
477 the experience of thermal discomfort is a driver of behavioural thermoregulation (Taylor et al.
478 1995) it may be that this proves to be ergogenic as has been seen in other studies (e.g. Lee et
479 al. 2008b; Mundel et al. 2006) albeit with less realistic fluid consumption volumes and
480 profiles. From a mechanistic perspective, we suggest a reciprocal role for the gut along with
481 visceral thermoreceptors in contributing to thermoreception that may only be salient after skin

482 temperature has plateaued (at $>34^{\circ}\text{C}$ in the present study; see also Nadel et al. 1970) and deep
483 body temperature has risen (i.e. $>37.8^{\circ}\text{C}$) which approximately coincides with the ingestion
484 of the second cold drink in the present study (see figures 1A & 1B). At rest and during lower
485 intensity exercise, beverage temperature has been shown to influence sudomotor responses
486 relatively independently (Bain et al. 2012; Morris et al. 2014 & 2017). We suggest that less
487 independence may be seen when internal and peripheral temperatures are raised although it is
488 also possible that the sweat response would be changed in response to drink temperature
489 outside of the thermal range of skin and rectal temperatures we saw in the present study.

490

491 These data have clear implications for fluid replacement guidelines. We show, through
492 consistent evidence of a greater thermal strain (i.e. higher T_{rec} and HR; see figures 1A & 5B)
493 and greater post trial dehydration ($2.1 \pm 0.3\%$ body mass loss) in the control condition, that
494 failing to ingest fluid to replace that lost to sweat will increase the risk of dehydration and
495 heat-illness; this agrees with many other studies (e.g. Casa et al. 2000; Galloway & Maughan,
496 2000). The temperature of that fluid, in the small volumes consumed in the present study, is
497 less important as the consequent effect on the thermoregulatory responses was negligible. It is
498 probable that the associated change in gastric temperature following hot or cold drink
499 ingestion was only transient (Shi et al. 2000) thereby reflecting the thermoregulatory response
500 we see here. Larger volumes of hot or cold fluid may sit in the gut and result in a more
501 pronounced thermoregulatory change (e.g. Lee et al. 2008b) and an *ad libitum* consumption
502 profile may have resulted in more fluid being consumed (e.g. Mündel et al. 2006). Given the
503 choice, the vast majority of persons would select a cool drink to alleviate the thermal burden
504 from a perceptual and physiological perspective (Barwood, 2012) and we find no refuting
505 evidence to counter this idea when fluid consumption profile keeps hydration status within a
506 1% limit. Indeed, a cold drink has the potential to alleviate thermal discomfort to a greater

507 extent than not drinking or compared to a hot drink (see figure 4B) although we were not
508 aware of any individual preference for cold over hot fluid. Nevertheless, it is probable that the
509 hedonic tone of the cold drink when consumed in the hot environment is central to this result
510 (Szylyk et al. 1989).

511

512 We also make the important addition of a valid exercise performance measure following hot
513 and cold drink ingestion by contrast to the no drink control; previous studies have primarily
514 focussed on cold drink ingestion. The magnitude of performance difference between
515 ingesting (i.e. hot or cold drink) and failing to ingest any fluid (i.e. the control) was
516 approximately 54%; H_3 is rejected. The extent of dehydration estimated by body mass loss
517 was roughly half in the drink trials (COLD drink: $0.9 \pm 0.3\%$; HOT drink: $0.9 \pm 0.4\%$) of that
518 seen in the control trial (i.e. $2.1 \pm 0.3\%$). The approximate 1.2% difference is implicated in
519 the higher thermal strain and poor performance that was seen in the control condition. These
520 data also suggest that we were able to achieve fluid replacement levels that are in line with
521 the ACSM fluid replacement guidelines (ACSM et al. 2007) and demonstrate that we
522 achieved a realistic, and therefore valid, fluid consumption profile. Indeed, the extent of
523 dehydration did not exceed the threshold for measured body mass loss (i.e. approximately
524 2%) which correlates with the increase in plasma osmolality (Cheuvront and Kenefick, 2014)
525 and is suggested to drive the thirst response. Hence a “no drink” condition was a plausible
526 control. The drink conditions were carefully titrated to avoid hyper or hypohydration and met
527 the sweating requirements of the ambient conditions to reduce dehydration to 1%.

528

529 **Conclusions and Recommendations**

530 The present study suggests that there is no negative thermoregulatory or performance effect
531 associated with ingesting hot or cold drinks when exercise is performed in a hot, dry

532 environment. Indeed, both drinks sustained performance to a similar magnitude compared to
533 a no drink control. There is some tentative evidence that cold drinks may enhance thermal
534 comfort beyond the resultant physiological response of transient reductions in T_{msk} and
535 peripheral sweating that were seen here. Potentially, thermoreceptor signals from the gut
536 become more salient as thermal profile approaches becoming hyperthermic but are not
537 accelerated when hot fluid is ingested. It is clear that it is critical that at least some fluid is
538 ingested to offset dehydration.

539

Acknowledgements

540 This work was funded by a research grant from the European Hydration Institute

541 There are no conflicts of interest to declare.

542

- 544 1. Armstrong LE, Johnson EC, Kunces LJ, Ganio MS, Judelson DA, Kupchak BR et al
545 (2014) Drinking to thirst versus drinking ad libitum during road cycling. *Int J Athl*
546 *Train* 49(5):624-631. doi: 10.4085/1062-6050-49.3.85.
- 547 2. Amano T, Gerrett N, Inoue Y, Nishiyasu T, Havenith G Kondo N (2016)
548 Determination of the maximum rate of eccrine sweat glands' ion reabsorption using
549 the galvanic skin conductance to local sweat rate relationship. *Eur J Appl Physiol.*
550 116(2): 281-290. doi: 10.1007/s00421-015-3275-9.
- 551 3. American College of Sports Medicine, Sawka MN, Burke LM, Eichner ER,
552 Maaughan RJ, Montain SJ et al (2007) American College of Sports Medicine position
553 stand: exercise and fluid replacement. *Med Sci Sports Exerc.* 39(2):377–390. doi:
554 10.1249/mss.0b013e31802ca597.
- 555 4. Bain AR, Lesperance NC, Jay O (2012) Body heat storage during physical activity is
556 lower with hot fluid ingestion under conditions that permit full evaporation. *Acta*
557 *Physiol Scand.* 206 (2): 98-108. doi: 10.1111/j.1748-1716.2012.02452.x.
- 558 5. Barwood MJ. Hot drinks all round (2012) *Acta Physiol Scand.* 206: 94-95. doi:
559 10.1111/j.1748-1716.2012.02458.x
- 560 6. Borg GAV. Psychophysical basis of physical exertion (1982) *Med Sci Sports Exerc.*
561 14:377-381.
- 562 7. Burdon CA, O'Connor HT, Gifford JA, Shirreffs SM, Chapman P, Johnson N (2010)
563 Effect of drink temperature on core temperature and endurance cycling performance
564 in warm, humid conditions. *J Sport Sci.* 28(11):1147-1156. doi:
565 10.1080/02640414.2010.489197.

- 566 8. Burdon CA, O'Connor HT, Gifford JA, Shirreffs SM (2010) Influence of beverage
567 temperature on exercise performance in the heat: a systematic review. *Int J Sport Nutr*
568 *Exerc Metab.* 20(2):166-174. doi:10.1123/ijsnem.20.2.166
- 569 9. Casa DJ, Maresh CM, Armstrong LE, Kavouras SA, Herrera JA, Hacker FT (2000)
570 Intravenous versus oral rehydration during a brief period: responses to subsequent
571 exercise in the heat. *Med Sci Sports Exerc.* 32(1):124-33. doi: 10.1097/00005768-
572 199805001-01889.
- 573 10. Chevront SN, Kenefick RW (2014) Dehydration: physiology, assessment, and
574 performance effects. *Comp Physiol.* 4:257–285. doi: 10.1002/cphy.c130017.
- 575 11. DuBois D, DuBois EF (1915) The measurement of the surface area of man. *Int Arch*
576 *Med.* 15:868-81.
- 577 12. Galloway S, Maughan R (2000) The effects of substrate and fluid provision on
578 thermoregulatory and metabolic responses to prolonged exercise in a hot environment.
579 *J Sport Sci.* 18:339-351. doi: 10.1080/026404100402403
- 580 13. Gonzalez JT, Fuchs CJ, Smith FE, Thelwall PE, Taylor R, Stevenson EJ, et al (2015)
581 Ingestion of glucose or sucrose prevents liver but not muscle glycogen depletion
582 during prolonged endurance-type exercise in trained cyclists. *Am J Physiol: End*
583 *Metab.* 309: E1032-E1039. <https://doi.org/10.1152/ajpendo.00376.2015>
- 584 14. Hensel H, Schafer K (1984) Thermoreception and temperature regulation in man. In:
585 Ring EFJ, Phillips B (eds) *Recent advances in medical thermology.* Plenum Press,
586 New York pp. 51-64.
- 587 15. Hew-Butler T, Verbalis JG, Noakes TD (2006) International Marathon Medical
588 Directors Association. Updated fluid recommendation: position statement from the
589 International Marathon Medical Directors Association (IMMDA). *Clin J Sport Med.*
590 16(4): 283–292.

- 591 16. Lamarche DT, Meade RD, McGinn R, Poirier MP, Friesen, BJ, Kenney, GP (2015)
592 Temperature of ingested water during exercise does not affect body heat storage. *Med*
593 *Sci Sports Exerc.* 2015;47(6):1272-1280. doi: 10.1249/MSS.0000000000000533
- 594 17. Lee JK, Maughan RJ, Shirreffs SM (2008a) The influence of serial feeding of drinks
595 at different temperatures on thermoregulatory responses during cycling. *J Sport Sci.*
596 26(6):583-590. doi: 10.1080/02640410701697388
- 597 18. Lee JK, Shirreffs SM, Maughan RJ (2008b) Cold drink ingestion improves exercise
598 endurance capacity in the heat. *Med Sci Sports Exerc.* 40:1637–1644. doi
599 10.1249/MSS.0b013e318178465d
- 600 19. Lee JK, Shirreffs SM (2007) The influence of drink temperature on thermoregulatory
601 responses during prolonged exercise in a moderate environment. *J Sport Sci.*
602 25(9):975-985. doi: 10.1080/02640410600959947
- 603 20. Morris NB, Bain AR, Cramer MN, Jay O (2014) Evidence that transient changes in
604 sudomotor output with cold and warm fluid ingestion are independently modulated by
605 abdominal, but not oral thermoreceptors. *J Appl Physiol.* 116(8):1088-1095. Doi:
606 10.1152/jappphysiol.01059.2013
- 607 21. Morris NB, Cramer MN, Hodder SG, Havenith G, Jay O (2013) A comparison
608 between the technical absorbent and ventilated capsule methods for measuring local
609 sweat rate. *J Appl Physiol.* 114(6):816-823. Doi: 10.1152/jappphysiol.01088.2012
- 610 22. Morris NB, Filingeri D, Halaki M, Jay O (2017) Evidence of viscerally-mediated cold
611 defence thermoeffector responses in man. *J Physiol.* 595(4): 1202-1204. Doi:
612 10.1113/JP273052
- 613 23. Mündel T, King J, Collacott E, Jones DA (2006) Drink temperature influences fluid
614 intake and endurance capacity in men during exercise in a hot, dry environment. *Exp*
615 *Physiol.* 91(5):925-933. Doi: 10.1113/expphysiol.2006.034223

- 616 24. Nadel ER, Horvath SM, Dawson CA, Tucker A (1970) Sensitivity to central and
617 peripheral thermal stimulation in man. *J Appl Physiol* 29: 603-609.
- 618 25. Noakes TD (2011) Changes in body mass alone explain almost all of the variance in
619 the serum sodium concentrations during prolonged exercise. Has commercial
620 influence impeded scientific endeavour? *Br J Sports Med.* 45(11):475–7. Doi:
621 10.1136/bjism.2010.075697
- 622 26. Olesen BW (1980) How many sites are necessary to estimate a mean skin
623 temperature? In: Hales JRS (ed) *Thermal Physiology*. Raven Press: New York, pp. 33-
624 38.
- 625 27. Rawson RO, Quick KP (1972) Localization of intra-abdominal thermoreceptors in the
626 ewe. *J Physiol.* 222:665–667.
- 627 28. Rowell LB (1974) Human cardiovascular adjustments to exercise and thermal stress.
628 *Physiol Rev.* 54:75–159.
- 629 29. Rowell LB, Marx HJ, Bruce RA, Conn RD, Kusumi, F (1966) Reductions in cardiac
630 output, central blood volume, and stroke volume with thermal stress in normal men
631 during exercise. *J Clin Invest.* 45:1801-1806.
- 632 30. Shi X, Bartoli W, Horn M, Murray R (2000) Gastric emptying of cold beverages in
633 humans: effect of transportable carbohydrates. *Int J Sport Nutr Exerc Metab.*
634 10(4):394-403. <https://doi.org/10.1123/ijsnem.10.4.394>
- 635 31. Smith CJ, Johnson JM (2016) Responses to hyperthermia. Optimizing heat dissipation
636 by convection and evaporation: neural control of skin blood flow and sweating in
637 humans. *Auton Neuroscience: Basic Clin.* 196:25-36. Doi:
638 10.1016/j.autneu.2016.01.002
- 639 32. Smith CJ, Kenney WL, Alexander LM (2013) Regional relation between skin blood
640 flow and sweating to passive heating and local administration of acetylcholine in

641 young, healthy humans. *Am J Physiol Regul Integr Comp Physiol*. 304:R566-R573.
642 Doi: 10.1152/ajpregu.00514.2012

643 33. Storaas G, Bakkevig MK (1996) Correlation between measured skin wettedness and
644 subjective sensations of skin wetness. In: Shaprio Y, Moran DS, Epstein Y. *The*
645 *Proceedings of the 7th International Conference on Environmental Ergonomics*
646 (ICEE). Freund Publishing House, Tel Aviv, Israel, pp 131–134.

647 34. Szlyk PC, Sils IV, Francesconi RP, Hubbard RW, Armstrong LE (1989) Effects of
648 water temperature and flavouring on voluntary dehydration in men *Physiol Behav*.
649 45:639-647. [https://doi.org/10.1016/0031-9384\(89\)90085-1](https://doi.org/10.1016/0031-9384(89)90085-1)

650 35. Taylor NA, Allsopp NK, Parkes DG (1995) Preferred room temperature of young
651 versus aged males: the influence of thermal sensation, thermal comfort, and affect. *J*
652 *Gerontol A Biol Sci Med Sci*. 50:M216–M221. Doi:
653 10.1093/gerona/50A.4.M216

654 36. Zhang H (2003) Human thermal sensation and comfort in transient and non- uniform
655 thermal environments. PhD thesis. Berkeley: University of California. doi:
656 <https://escholarship.org/uc/item/11m0n1wt>

657
658

659 **Figure Legends**

660 Figure 1 A-B. Mean \pm SD T_{rec} , and T_{msk} responses after each drink ingestion (condition
661 dependent) during rest, fixed intensity exercise (55% P_{Max}) and TTE end after 80% P_{Max}
662 cycling; main effects for condition are indicated on each panel where applicable; n = 10.

663 Figure 2 A-B. Mean \pm SD local sweat rate at the subscapular and forearm regions after each
664 drink (condition dependent) during rest, fixed intensity exercise (55% P_{Max}) and TTE end
665 after 80% P_{Max} ; n=10.

666 Figure 3 A-B. Mean GSC at the subscapular and forearm regions after each drink (condition
667 dependent) during rest and fixed intensity exercise (55% P_{Max}), SD data are omitted for
668 clarity; n=10.

669 Figure 4 A-D. Mean \pm SD TS, TC, GC and SkW after each drink during rest, fixed
670 intensity exercise (55% P_{Max}) and TTE end after 80% P_{Max} . Main effects for conditions are
671 indicated on each panel where applicable, brackets indicate near significance and * indicate
672 time point specific differences; n=10.

673 Figure 5 A-B. Mean \pm SD RPE and HR responses after each drink during rest, fixed intensity
674 exercise (55% P_{Max}) and TTE end after 80% P_{Max} . HR data are displayed to corresponding
675 time points for RPE; main effects for condition are indicated on each panel where applicable;
676 n=10.