



Article

Perceptual Responses to Submaximal and High-Intensity Cycling Exercise in Moderate and Hot Environments

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Highlights

Public health relevance—How does this work relate to a public health issue?

- Exercise and physical work in hot environments increase physiological and perceptual strain and the risk of exertional heat illness.
- Understanding how thermal perception changes with exercise intensity may improve heat-risk assessment in occupational and athletic settings.

Public health significance—Why is this work of significance to public health?

- During 60 min of submaximal cycling, thermal sensation, thermal comfort, and perceived exertion distinguished the hot environment from the moderate environment.
- At the end of the high-intensity time-to-exhaustion test, perceptual responses did not differ significantly between conditions, despite differences in achieved metabolic intensity.

Public health implications—What are the key implications or messages for practitioners, policy makers and/or researchers in public health?

- Perceptual ratings may provide useful information during prolonged submaximal activity but may be less able to distinguish environmental strain near volitional exhaustion.
- Practitioners should use perceptual ratings together with environmental monitoring, work–rest guidance, and individual risk assessment rather than as stand-alone indicators of heat safety.

Abstract

This randomized, counterbalanced crossover study examined the effects of ambient heat on thermal sensation (TS), thermal comfort (TC), and rating of perceived exertion (RPE) during submaximal and high-intensity cycling. Eleven recreationally active men completed 60 min of cycling at a workload prescribed from 60% of VO_2max , followed by 15 min of seated recovery and a time to exhaustion (TTE) test at a workload prescribed from 90% of VO_2max , in moderate (MT: 22 °C, 45% RH) and hot (HT: 35 °C, 45% RH) conditions. During submaximal exercise, condition by time interactions were observed for TS, TC, and RPE (all $p \leq 0.05$), with greater heat sensation, discomfort, and exertion in HT. Achieved oxygen uptake during TTE corresponded to $78.7 \pm 1.9\%$ and $85.3 \pm 3.8\%$ of VO_2max in HT and MT, respectively. At exhaustion, TS, TC, and RPE did not differ significantly between conditions. Perceptual ratings differentiated the environments during prolonged submaximal exercise but not at the end of the high-intensity TTE test. This convergence should be interpreted



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cautiously because ceiling effects, the small sample, unequal TTE duration, and differences in achieved metabolic intensity may have contributed.

Keywords: heat stress; thermoregulation; perceived exertion; perceptual scales; cycling

1. Introduction

Extreme environmental heat stress imposes profound physiological and psychological strain on the human body, severely compromising exercise performance and elevating the risk of heat-related illnesses [1]. During physical exertion, metabolic heat production elevates internal body temperature. When ambient temperature exceeds skin temperature, radiative and convective heat dissipation pathways reverse, rendering evaporative cooling through sweating the primary avenue for heat loss [2]. High relative humidity further compromises this mechanism by narrowing the water vapor pressure gradient between the skin and the environment, decreasing sweat evaporation efficiency and increasing the risk of thermoregulatory failure or exertional heat stroke (EHS) [1]. To quantify this environmental thermal burden, environmental physiologists commonly utilize the Wet Bulb Globe Temperature (WBGT) index, which incorporates ambient temperature, humidity, and radiant heat load [3,4].

Maintaining fluid balance is important during exercise in the heat, and limiting body mass loss to less than 2% is commonly recommended [5]. However, more fluid is not always better. Excessive water intake during prolonged exercise can exceed renal excretory capacity and cause exercise-associated hyponatremia, defined as a plasma sodium concentration below $130 \text{ mEq}\cdot\text{L}^{-1}$, with the risk of cellular edema [6,7]. Although the systemic consequences of heat stress are well documented, less is known about how physiological strain is reflected in thermal perception during exercise.

Thermal comfort (TC) is commonly defined as a psychological state reflecting an individual's satisfaction with the surrounding thermal environment [8]. While humans possess a resting thermoneutral zone between 28°C and 30°C where vasomotor adjustments and sweating are minimized [9], thermal discomfort increases outside this zone. This peripheral discomfort is tightly driven by falling skin temperatures during cold exposure and rising sweat production or skin wettedness during heat exposure [10,11]. Importantly, perceptual responses to environmental stress represent a complex central integration of multiple convergent afferent inputs, including thermal, cardiovascular, and metabolic signals [12,13]. During exercise in the heat, these signals interact to alter TC, thermal sensation (TS), and ratings of perceived exertion (RPE). However, the extent to which individuals can distinguish ambient environmental heat stress from exercise-induced physiological strain, particularly at high-intensity TTE exercise, remains unclear. Therefore, the purpose of this study was to examine the interactions among TS, TC, and RPE during submaximal steady-state cycling and high-intensity time to exhaustion (TTE) exercise performed in moderate-temperature (MT) and high-temperature (HT) environments. It is hypothesized that HT would produce greater cardiovascular and thermoregulatory strain during submaximal exercise, resulting in higher TS and RPE and lower TC than MT, whereas perceptual responses at volitional exhaustion during the high-intensity TTE test would not differ between environmental conditions.

2. Materials and Methods

2.1. Participants

An a priori power analysis was conducted using G*Power 3.1 [14] to determine the minimum sample size required for the repeated-measures design. The calculation was based on a repeated-measures ANOVA examining the condition by time interaction, with an assumed large effect size ($f = 0.40$), an alpha level of 0.05, and statistical power of 0.80. The analysis indicated that a minimum of 10 participants would be required to detect significant interaction effects. To account for potential participant attrition and missing data, 11 recreationally active men were recruited and completed all experimental trials.

Eleven recreationally active men (age: 24.0 ± 2.8 years; height: 180.2 ± 6.5 cm; body mass: 82.6 ± 7.4 kg; absolute VO_2max : 3.8 ± 0.4 L·min⁻¹) volunteered. Relative VO_2max was 45.3 ± 6.4 mL·kg⁻¹·min⁻¹. Participants completed a health-history questionnaire and had no cardiovascular, metabolic, or musculoskeletal contraindications to exercise. The >3.0 L·min⁻¹ screening threshold was used as a pragmatic eligibility criterion for the original protocol and was not treated as a body-size-independent classification of aerobic fitness. Women were not enrolled in this initial study because menstrual-cycle phase was not controlled; consequently, the findings should not be generalized to women [15]. The study was approved by the Kent State University Institutional Review Board (IRB No. 17-049; 22 February 2017), and all participants provided written informed consent.

2.2. Experimental Design

Participants visited the laboratory for three separate sessions. Session 1 served as a familiarization and baseline fitness assessment. Sessions 2 and 3 comprised experimental trials. These trials were conducted in a randomized, counterbalanced order using a Latin square design to minimize potential order effects, with each session separated by at least 72 h.

The experimental trials were conducted under hot conditions at 35 °C and 45% relative humidity and moderate conditions at 22 °C and 45% relative humidity. Wet-bulb globe temperature was not measured and could not be reliably estimated from air temperature and relative humidity alone because wet-bulb and globe-temperature data were unavailable. All trials began between 06:00 and 08:00 to minimize the influence of circadian variation in core temperature [16].

Participants received identical pretrial instructions for both conditions. They were asked to fast for 10 h, consume 3 L of water during the preceding day, and refrain from strenuous exercise, alcohol, and nicotine for 24 h. The fixed water intake was used to standardize pretrial hydration instructions but was not adjusted for body mass. Hydration status was not objectively assessed using urine-specific gravity or osmolality. Clothing was standardized to shorts and a T-shirt.

2.3. Procedures

During Session 1, anthropometric measurements and a seven-site skinfold assessment (chest, mid-axillary, suprailiac, abdomen, triceps, subscapular, and thigh) was completed using Lange calipers [17]. Participants then performed a graded exercise test on an electronically braked cycle ergometer (Velotron Dynafit Pro, Quarq/SRAM, Spearfish, SD, USA) to determine the highest attained oxygen uptake and workloads corresponding to 60% and 90% of that value. The test began at 50 W, increased by 50 W every 3 min for four stages, and then increased by 30 W every 2 min until volitional exhaustion.

VO_2max was defined as the highest 30-s average attained during the graded exercise test. An $\text{RER} \geq 1.10$, $\text{RPE} \geq 17$, a plateau in VO_2 despite an increase in workload were considered supporting indicators of maximal effort. Inability to maintain the prescribed

cadence was treated as a test-termination criterion rather than evidence confirming VO_2max . Participant-level counts for the supporting indicators were not retained. Therefore, the distinction between VO_2max and VO_2peak cannot be verified retrospectively.

During Sessions 2 and 3, participants completed a 24-h dietary recall upon arrival to verify the replication of nutritional intake across trials. After obtaining initial body mass, participants changed into standardized athletic clothing and self-inserted a rectal thermistor (ITP010-11, Nikkiso-Therm Co., Ltd., Tokyo, Japan) approximately 13 cm beyond the anal sphincter to measure rectal temperature (T_{re}). Participants then completed a 10-min submaximal cycling warm-up at a self-selected intensity prior to entering the environmental chamber.

Inside the chamber (Western Environmental Chamber, Napa, CA, USA), participants completed 60 min of steady-state cycling at the fixed external workload identified during Session 1 as eliciting approximately 60% of VO_2max , rested seated for 15 min, and then completed a TTE test at the fixed workload identified as eliciting approximately 90% of VO_2max . Thus, prescription was workload-based; metabolic intensity was not continuously clamped to 60% or 90% during the environmental trials. Participants maintained 60–80 rpm. Exhaustion was defined as failure to maintain >60 rpm for 5 consecutive seconds despite standardized encouragement.

2.4. Instrumentation & Perceptual Scaling

Oxygen uptake was measured from expired gases using a metabolic cart (TrueOne 2400, Parvo Medics, Sandy, UT, USA). During the 60-min trial, data were sampled at 0–3, 12–15, 27–30, 42–45, and 57–60 min. During TTE, 30-s samples were obtained at the beginning, midpoint, and end of each participant's test. These TTE samples represented relative phases of TTE rather than standardized elapsed time points.

Heart rate was monitored by telemetry (Polar RS800 CX, Polar Electro Oy, Kempele, Finland) and analyzed at 3, 15, 30, 45, and 60 min during steady-state exercise and at the beginning, midpoint, and end of TTE. The physiological sampling schedule followed the metabolic collection windows, whereas perceptual ratings were obtained every 10 min to reduce interruption of cycling. Associations between physiological and perceptual variables were therefore interpreted only when their sampling phases aligned and not as continuously synchronized measurements.

T_{re} was recorded continuously throughout the trials using a data logger (Model N543, Nikkiso—Therm Co., Ltd., Tokyo, Japan) and analyzed at baseline (BASE) and at 3, 10, 20, 30, 40, 50, and 60 min during the steady-state bout, as well as PRE and POST during the TTE.

Body mass was measured before exercise, immediately after the 60-min bout, and after TTE using a precision electronic scale. Water was available ad libitum, and bottle mass was recorded before and after drinking. Urine loss and sweat loss were not measured; accordingly, body-mass change is reported as an outcome, and the term 'sweat dynamics' is not used.

Subjective perceptual responses were quantified every 10 min during the 60-min steady-state trial and immediately pre- and post-TTE using the following psychophysical scales: the 9-point Gagge Thermal Sensation Scale (TS; -4 = "very cold" to $+4$ = "very hot", 0 = "neutral") [10], a 9-point Thermal Comfort Scale (TC; -4 = "very uncomfortable" to $+4$ = "very comfortable") [18], and the traditional Borg 6–20 scale for the rating of perceived exertion (RPE) [12] to evaluate whole-body physical effort.

2.5. Statistical Analysis

All statistical analyses were conducted using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Distributional form and influential observations were examined graphically, sphericity was evaluated using Mauchly's test, and Greenhouse–Geisser corrections were applied when appropriate. Separate two-way repeated-measures ANOVAs were used for physiological and perceptual outcomes during the 60-min trial. Follow-up pairwise comparisons from these ANOVAs were not adjusted for multiplicity and should therefore be interpreted as exploratory. Statistical significance was set at $p \leq 0.05$.

For TTE, separate two-way repeated-measures ANOVAs were used for oxygen uptake, HR, and body mass (2 conditions $\times$ 3 phase) and for Tre, TS, TC, and RPE. Energy and macronutrient intake were also compared using paired-samples t-tests. Exploratory Pearson correlations examined ending HR in relation to the duration spent in four mutually exclusive Tre categories. The categories were less than 38.0 °C, 38.0–38.4 °C, 38.5–38.9 °C, and ≥ 39.0 °C. The four correlations within each environment were adjusted using Holm's method. Because category durations were components of the same exercise period, they were mathematically interdependent and were not interpreted as independent tests of distinct mechanisms. Data are presented as mean $\pm$ standard error (SE).

3. Results

3.1. Dietary Intake and Exercise-Intensity Verification

No statistically significant differences were detected between the MT and HT conditions in reported total energy intake ($p = 0.429$), carbohydrate intake ($p = 0.918$), fat intake ($p = 0.405$), or protein intake ($p = 0.398$). These non-significant findings do not demonstrate dietary equivalence but indicate that no differences between conditions were detected in the present sample. The achieved percentages of $\text{VO}_{2\text{max}}$ during the submaximal and high-intensity trials are presented in Table 1. During TTE, the achieved oxygen uptake corresponded to $85.3 \pm 3.8\%$ of $\text{VO}_{2\text{max}}$ in MT and $78.7 \pm 1.9\%$ in HT. These descriptive values indicate that the prescribed fixed workloads did not elicit identical relative oxygen uptake across the two environments.

Table 1. Achieved oxygen uptake relative to maximal oxygen uptake during the submaximal and high-intensity protocols in moderate (MT) and hot (HT) environments.

	Submaximal Trial	TTE Trial
MT	57.2 ± 1.9	85.3 ± 3.8
HT	60.7 ± 1.6	78.7 ± 1.9

Data are presented as mean $\pm$ standard error (SE). MT (moderate temperature: 22 °C, 45% RH); HT (high temperature: 35 °C, 45% RH).

3.2. Perceptual Responses

3.2.1. Submaximal Exercise

A significant condition by time interaction was observed for TS during the 60-min submaximal exercise protocol ($F = 6.252$, $p \leq 0.001$, $\eta p^2 = 0.385$). A significant effect of time was also observed in both MT ($F = 7.670$, $p \leq 0.001$, $\eta p^2 = 0.434$) and HT ($F = 34.901$, $p \leq 0.001$, $\eta p^2 = 0.777$). TS differed from baseline at all exercise time points in both conditions. In HT, TS increased from baseline and remained higher than in MT throughout the exercise period. The between-condition differences were observed at each exercise time point but not at baseline ($p = 0.588$) (Table 2).

Table 2. Thermal sensation, thermal comfort, and rating of perceived exertion during 60 min of submaximal cycling.

Variable	Time	MT		HT	
		Mean	SE	Mean	SE
Thermal Sensation	Baseline	0.91	0.30	0.18	0.41
	3 min	0.55 *	0.52	1.73 *,#	0.65
	10 min	1.00 *	0.89	2.18 *,#	0.60
	20 min	1.27 *	1.10	2.55 *,#	0.82
	30 min	1.45 *	1.04	2.64 *,#	1.03
	40 min	1.64 *	0.92	3.00 *,#	0.89
	50 min	1.64 *	1.03	3.18 *,#	0.98
	60 min	1.27 *	1.19	3.18 *,#	0.98
Thermal Comfort	Baseline	1.00	1.95	1.45	1.97
	3 min	1.18	1.40	0.27 #	1.10
	10 min	0.55	1.37	−0.45 †,#	1.29
	20 min	0.73	1.01	−1.00 †,#	1.27
	30 min	0.18	1.33	−1.64 †,#	1.29
	40 min	−0.36 †	1.80	−2.09 †,#	1.22
	50 min	−0.55 †	1.51	−2.36 †,#	1.29
	60 min	−0.36 †	1.63	−2.82 †,#	1.17
Rating of Perceived Exertion	Baseline	6.0	0.0	6.0	0.0
	3 min	9.2 *	0.6	9.2 *	0.4
	10 min	10.5 *,†	0.5	11.3 *,†	0.3
	20 min	11.5 *,†	0.6	12.9 *,†,#	0.3
	30 min	12.4 *,†	0.5	14.1 *,†,#	0.5
	40 min	13.1 *,†	0.5	15.3 *,†,#	0.5
	50 min	13.4 *,†	0.5	16.2 *,†,#	0.6
	60 min	13.9 *,†	0.7	16.8 *,†,#	0.6

Data are presented as mean $\pm$ standard error (SE). MT, moderate temperature (22 °C, 45% RH); HT, high temperature (35 °C, 45% RH). * $p \leq 0.05$ versus baseline within the same condition. † $p \leq 0.05$ versus 3 min within the same condition. # $p \leq 0.05$, significantly different between MT and HT at the same time point.

A significant condition by time interaction was observed for TC during the 60 min submaximal exercise protocol ($F = 5.857$, $p \leq 0.001$, $\eta p^2 = 0.369$). A significant effect of time was also observed in both MT ($F = 2.850$, $p = 0.011$, $\eta p^2 = 0.222$) and HT ($F = 20.413$, $p \leq 0.001$, $\eta p^2 = 0.671$). In MT, TC was lower at 40 min ($p = 0.039$), 50 min ($p = 0.017$), and 60 min ($p = 0.039$) than at 3 min. In HT, TC was lower than at 3 min from 10 min onward, with differences observed at 10 min ($p = 0.022$), 20 min ($p = 0.004$), 30 min ($p < 0.001$), 40 min ($p < 0.001$), 50 min ($p = 0.001$), and 60 min ($p < 0.001$). TC was lower in HT than MT at all exercise time points (all $p \leq 0.05$), whereas no difference was observed at baseline ($p = 0.472$) (Table 2).

A significant condition by time interaction was observed for RPE during the 60 min submaximal exercise protocol ($F = 8.850$, $p \leq 0.001$, $\eta p^2 = 0.469$). Significant effects of time were observed in MT ($F = 67.516$, $p \leq 0.001$, $\eta p^2 = 0.871$) and HT ($F = 106.078$, $p \leq 0.001$, $\eta p^2 = 0.942$). In both conditions, RPE increased significantly from baseline and was also higher after 3 min (all $p \leq 0.001$). RPE was higher in HT than MT at 20 min ($p = 0.016$), 30 min ($p = 0.031$), 40 min ($p = 0.003$), 50 min ($p = 0.001$), and 60 min ($p = 0.002$). No between-condition difference was observed at baseline ($p = 1.000$) or 3 min ($p = 0.095$) (Table 2).

3.2.2. Time to Exhaustion Exercise

During TTE, a significant condition by time interaction was observed for TS ($F = 11.267$, $p = 0.007$, $\eta p^2 = 0.530$). TS increased from PRE to POST in MT ($p = 0.007$) but did not change in HT ($p = 1.000$). TS was higher in HT than MT at PRE ($p \leq 0.001$), whereas no between-condition difference was observed at POST ($p = 0.242$).

A significant condition by time interaction was also observed for TC during TTE ($F = 5.400$, $p = 0.042$, $\eta p^2 = 0.351$). TC decreased from PRE to POST in MT ($p = 0.018$) but did not change significantly in HT ($p = 0.181$). No between-condition differences were observed at PRE ($p = 0.084$) or POST ($p = 0.542$).

For RPE, neither a condition by time interaction ($F = 0.239$, $p = 0.635$, $\eta p^2 = 0.023$) nor a main effect of condition ($F = 0.331$, $p = 0.578$, $\eta p^2 = 0.032$) was observed. A significant main effect of time was observed ($F = 205.952$, $p < 0.001$, $\eta p^2 = 0.954$), with RPE increasing significantly from PRE to POST ($p \leq 0.001$) (Table 3).

Table 3. Perceptual responses before and after the high-intensity time-to-exhaustion test.

Variable	Time	MT		HT	
		Mean	SE	Mean	SE
Thermal Sensation	PRE	0.09	0.94	1.55 [#]	0.82
	POST	1.09 *	1.04	1.55	0.93
Thermal Comfort	PRE	0.91	1.45	−0.27	1.01
	POST	−0.64 *	1.43	−1.00	2.15
Rating of Perceived Exertion	PRE	7.0	0.5	7.2	0.5
	POST	17.5 *	0.5	17.9 *	0.7

Data are presented as mean $\pm$ standard error (SE). MT, moderate temperature (22 °C, 45% RH); HT, high temperature (35 °C, 45% RH). * $p \leq 0.05$ versus PRE within the same condition. [#] $p \leq 0.05$ between MT and HT at the same time point.

3.3. Body Weight (BW)

No condition by time interaction was observed for body weight ($F = 0.152$, $p = 0.860$, $\eta p^2 = 0.015$). The main effect of condition was also not significant ($F = 0.979$, $p = 0.346$, $\eta p^2 = 0.089$), whereas a significant main effect of time was observed ($F = 5.510$, $p = 0.012$, $\eta p^2 = 0.355$). Post hoc pairwise comparisons showed that body weight decreased from 82.8 ± 2.3 kg at Pre to 82.5 ± 2.3 kg ($p = 0.019$).

3.4. Heart Rate and Rectal Temperature Correlations

In MT, the correlations of ending HR with time at $T_{re} < 38.0$ °C ($r = -0.629$, unadjusted $p = 0.038$) and $38.0 \sim 38.49$ °C ($r = 0.619$, unadjusted $p = 0.042$) did not remain significant after Holm adjustment (both adjusted $p = 0.152$; Figure 1). No other MT correlation was significant.

In HT, ending HR was negatively correlated with time at $T_{re} < 38.0$ °C ($r = -0.774$, $p = 0.012$) and positively correlated with time at $38.5 \sim 39.0$ °C ($r = 0.737$, $p = 0.030$; Figure 2). No other HT correlation was significant. These small-sample correlations are exploratory and the category durations are mathematically dependent.

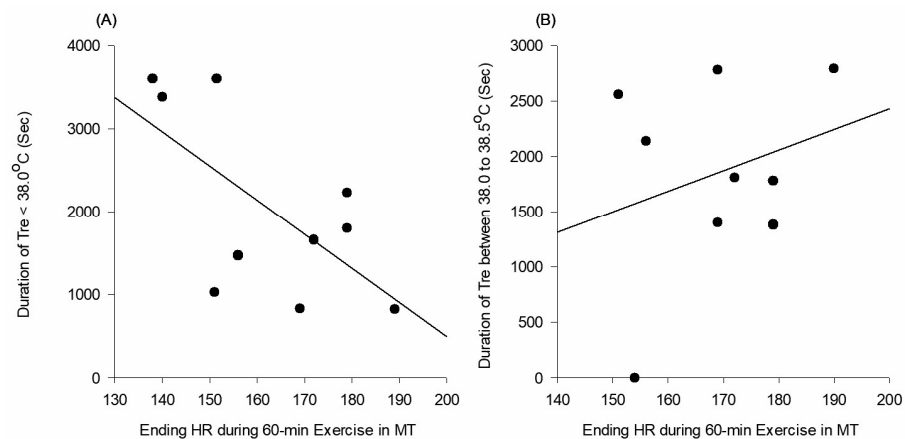


Figure 1. Correlations between ending heart rate (HR) and Tre categories during 60-min exercise in the moderate temperature (MT) condition. (A) Relationship between ending HR and the duration for which Tre exceeded 38.0 °C. (B) Relationship between ending HR and the duration for which Tre remained between 38.0 and 38.5 °C.

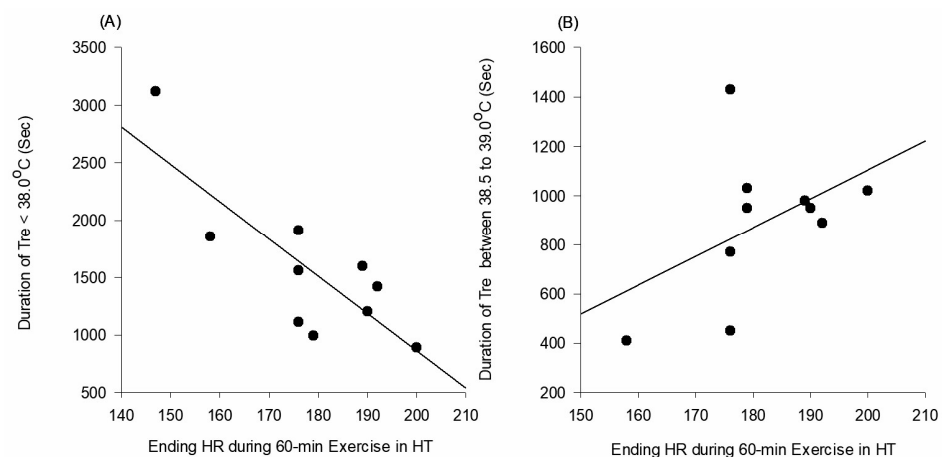


Figure 2. Correlations between ending heart rate (HR) and Tre categories during 60-min exercise in the high temperature (HT) condition. (A) Relationship between ending HR and the duration for which Tre remained < 38.0 °C. (B) Relationship between ending HR and the duration for which Tre remained between 38.5 and 39.0 °C.

4. Discussion

The principal observation was a phase-dependent pattern in perceptual responses. TS, TC, and RPE differentiated HT from MT during prolonged submaximal cycling, whereas between-condition differences were not statistically significant at the end of the high-intensity TTE test. This study extends earlier work by assessing the same participants across sequential steady-state and TTE phases while collecting thermal, exertional, and physiological measures [19]. The end-TTE convergence does not, however, establish a distinct psychophysical masking mechanism. Ceiling effects of the bounded scales, limited power, shorter TTE in HT, and lower achieved relative oxygen uptake in HT are plausible alternative explanations. Previous studies have shown that perceptual scales respond to thermal exposure at rest and during activities with relatively low metabolic demands [10,20,21].

The present findings are consistent with these studies. During submaximal exercise, participants continued to perceive differences in thermal sensation and thermal comfort between the two environmental conditions, while ratings of perceived exertion increased progressively. The crossover comparison further suggests that these perceptual ratings can

reflect changes in strain during prolonged cycling. However, the findings do not establish their diagnostic accuracy for identifying heat illness.

The submaximal results showed the effect of environmental heat on perceived strain. Participants reported greater thermal sensation, greater discomfort, and higher RPE in HT as exercise progressed. We interpret this pattern as a perceptual response to the increasing difficulty of dissipating metabolic heat. At 35 °C, the small temperature gradient between the skin and surrounding air limits dry heat loss and increases reliance on sweat evaporation [2]. Maintaining skin blood flow under these conditions can reduce central blood volume and contribute to a progressive increase in heart rate. The HR and Tre correlations observed in HT are consistent with this explanation, although the small sample and exploratory analysis prevent them from establishing cardiovascular drift directly. The exploratory HR and Tre correlations were consistent with greater cardiovascular strain as core temperature increased, particularly in HT. After Holm correction for multiple comparisons, the two correlations observed in MT were no longer statistically significant. In contrast, the HT correlations involving time below 38.0 °C and time between 38.5 and 39.0 °C remained significant.

These findings should be interpreted cautiously because the sample was small, the durations within the temperature categories were mathematically interdependent, and ending HR may have been influenced by unmeasured factors. The correlations therefore do not provide direct evidence of cardiovascular drift or demonstrate that changes in HR or Tre caused the observed differences in TS, TC, or RPE.

During TTE, internal sensory inputs associated with effort may have reduced the relative influence of ambient thermal cues [22–24]. However, nociceptor activity, central motor command, corollary discharge, metabolic acidosis, and sensory integration were not measured. These mechanisms should therefore be considered possible explanations rather than pathways demonstrated by the present findings. The pattern may also reflect the limits of the perceptual scales themselves. Post TTE RPE values approached the upper end of the Borg scale in both conditions, leaving little room to distinguish additional strain. Interpretation is further complicated by the difference in achieved oxygen uptake between MT and HT despite the use of fixed external workloads.

Taken together, these factors provide more plausible explanations than a single masking mechanism. This possible ceiling effect has practical implications for occupational and athletic heat safety. When perceptual ratings approach the upper limits of their scales during high-intensity exercise, workers and athletes may have difficulty recognizing additional strain imposed by the thermal environment. Decisions regarding exercise modification, rest, or withdrawal should therefore not rely on subjective discomfort or exertion alone. Perceptual ratings are better used in combination with established environmental indices, work and rest guidelines, and physiological observations appropriate to the activity and setting. Nevertheless, the present findings do not establish which specific monitoring methods should be required.

Limitations

Several limitations constrain interpretation. The most important limitation is that the TTE trials were matched by external workload rather than by the metabolic intensity actually achieved in each environment. VO_2 during TTE averaged 85.3% of $\text{VO}_{2\text{max}}$ in MT and 78.7% in HT, indicating that the fixed workloads did not produce equivalent metabolic intensities. In addition, TTE duration was not retained as an analysis outcome. We therefore cannot determine whether exposure duration differed between conditions or whether any such difference influenced the final perceptual ratings. Accordingly, the similar ratings

observed at exhaustion may reflect perceptual convergence, ceiling effects of the scales, differences in physiological demand, or other unmeasured factors.

The small and homogeneous sample presents another limitation. With only 11 young, recreationally active men, the correlations are particularly vulnerable to individual observations, and the results may not apply to women, older adults, sedentary individuals, or clinical populations. The hydration procedure also limits interpretation because the 3 L recommendation was not adjusted for body mass, water intake during exercise was allowed ad libitum, and hydration status, urine loss, and sweat loss were not measured. In addition, WBGT was unavailable, physiological and perceptual measurements were collected at different intervals, and the proposed neural and metabolic explanations were not assessed directly. These design features should be addressed before the findings are used to guide heat monitoring during high-intensity exercise.

5. Conclusions

Thermal sensation, thermal comfort, and perceived exertion differentiated hot from moderate conditions during prolonged submaximal cycling in this small crossover study. At the end of the high-intensity TTE test, differences in perceptual ratings were not statistically significant. This convergence may reflect ceiling effects, limited power, unequal exposure duration, or differences in achieved metabolic intensity and should not be interpreted as proof that heat signals were masked. Perceptual ratings may complement established environmental and physiological monitoring, but the present data do not support their use as stand-alone indicators of heat safety.

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Data Availability Statement: The data will be made available in accordance with federal guidelines and requirements for data sharing.

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Abbreviations

The following abbreviations are used in this manuscript:

BW	Body Weight
EHS	Exertional Heat Stroke
HR	Heart Rate
RER	Respiratory Exchange Ratio
RPE	Rating of Perceived Exertion

TC	Thermal Comfort
Tre	Rectal Temperature
TS	Thermal Sensation
TTE	Time-to-Exhaustion
VO ₂	Oxygen Uptake
VO _{2max}	Maximal Oxygen Uptake
WBGT	Wet Bulb Globe Temperature

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