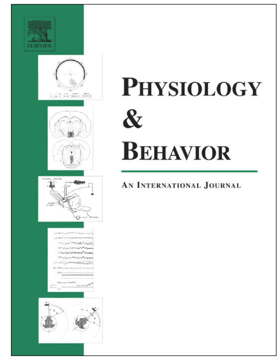

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Exposure to high solar radiation reduces self-regulated exercise intensity in the heat outdoors

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Abstract

High radiant heat load reduces endurance exercise performance in the heat indoors, but this remains unconfirmed in outdoor exercise. The current study investigated the effects of variations in solar radiation on self-regulated exercise intensity and thermoregulatory responses in the heat outdoors at a fixed rating of perceived exertion (RPE). Ten male participants completed 45-min cycling exercise in hot outdoor environments (about 31°C) at a freely chosen resistance and cadence at an RPE of 13 (somewhat hard). Participants were blinded to resistance, pedal cadence, distance and elapsed time and exercised at three sunlight exposure conditions: clear sky (mean±SD: 1072±91 W·m^{-2}; HIGH); thin cloud (592±32 W·m^{-2}; MID); and thick cloud (306±52 W·m^{-2}; LOW). Power output (HIGH 96±22 W; MID 103±20 W; LOW 108±20 W) and resistance were lower in HIGH than MID and LOW (P<0.001). Pedal cadence was lower, the core-to-skin temperature gradient was narrower, body heat gain from the sun (SHG) was greater and thermal sensation was higher with increasing solar radiation and all variables were different between trials (P<0.01). Mean skin temperature was higher in HIGH than MID and LOW (P<0.01), but core temperature was similar between trials (P=0.485). We conclude that self-regulated exercise intensity in the heat outdoors at a fixed RPE of somewhat hard is reduced with increasing solar radiation because of greater thermoregulatory strain, perceived thermal stress and SHG. This suggests that reduced self-selected exercise intensity during high solar radiation exposure in the heat may prevent excessive core temperature rise.

Key words: body temperature, exercise performance, heat stress, thermal sensation, sunlight

1. Introduction

High solar radiation exposure in the heat has been shown to reduce endurance performance in exercising individuals [1]. Nevertheless, only one study has systematically examined variations in solar radiation on endurance performance and thermoregulatory responses in the heat. Otani and colleagues [1] demonstrated that an increase in solar radiation (0, 250, 500 and 800 $W \cdot m^{-2}$) progressively reduced endurance exercise capacity and elevated thermoregulatory strain during a time-to-exhaustion test at 70% peak oxygen uptake (VO_2max) in a hot indoor environment (30°C ambient temperature [Ta], 50% relative humidity [RH]). These observations were associated with a higher mean skin temperature (Tsk) and a narrower core-to-skin temperature gradient as solar radiation increased, with a lack of rectal temperature (Tre) difference between conditions. However, given that this research employed a ceiling-mounted solar simulator at a fixed angle of 90° in an environmental chamber, it remains unclear whether similar effects are observed as a result of exposure to natural sunlight in a hot outdoor environment.

To date only one study systematically investigated the effect of different solar radiations on thermoregulatory responses during outdoor exercise in hot environments [2], though a few studies have examined this effect in cool-to-temperate environments [3,4,5]. The previous study demonstrated a greater thermoregulatory strain when exposed to a higher solar radiation (from 672 to 1107 $W \cdot m^{-2}$) associated with rising solar elevation angle (from 44° to 69°) in the morning (34±1°C Ta, 60% RH) compared with a lower solar radiation (from 717 to 0 $W \cdot m^{-2}$) associated with falling solar elevation angle (from 34° to 0°) in the afternoon (33±2°C Ta, 54% RH) during a 3-hour baseball training under a clear sky [2]. This was accompanied by a higher tympanic temperature, Tsk and heart rate (HR), a greater body heat gain from the sun (SHG) and a lower heat loss at the skin during exercise in the morning compared with the afternoon. Hence, much less evidence exists on the relationship between solar radiation and thermoregulatory responses during outdoor exercise in the heat where exertional heat-related illness most often occurs.

The rating of perceived exertion (RPE) is recognised as a good indicator of physical stress during physical activity [6]. During self-paced cycling exercise, Tucker and colleagues [7] studied the impact of Ta on self-regulated endurance performance at a fixed RPE of 16 (hard to very hard) on the Borg 6-20 RPE scale [6]. The authors reported that self-regulated exercise intensity was lower in hot (35°C) than cool (15°C) and moderate (25°C) environments, resulting from a lower power output with increasing Ta [7]. The high RPE of 16 may simulate competitive situations, but daily exercise for training and fitness is typically performed at a lower effort level. During daily exercise, an RPE between 12 and 14 [8] or 10 and 14 [9] is generally selected when individuals are allowed to self-select the exercise intensity. An RPE of 13 (somewhat hard) equates to intensities around 70% VO_2max [10] which is similar to that used in many previous studies investigating the influence of environmental conditions on endurance exercise capacity [1,11,12]. In terms of reducing the risk of exertional heat-related illness during daily exercise in hot outdoor environments, it is important to determine how different sunlight exposure conditions influence the voluntary control of endurance performance in the heat when allowing individuals to self-select exercise intensity at a fixed RPE of about 13.

The aim of the present study was therefore to investigate the effects of variations in solar radiation on self-regulated exercise intensity and thermoregulatory responses in the heat outdoors at a fixed RPE. It was hypothesized that self-selected power output would be lowered in response to the greater thermoregulatory strain as solar radiation increased in a hot outdoor environment.

2. Methods

2.1. Subjects

Ten healthy, heat-acclimatized males (mean±standard deviation [SD]; age 22±1 y, height 175±5 cm, body mass 70±12 kg, VO_2max 51.3±3.8 $mL\cdot min^{-1}\cdot kg^{-1}$) participated in this investigation. All participants were university students and were not competitive athletes and road cyclists. They trained ~2 h·day^{-1}, 3-4 days·week^{-1} which corresponded to the performance level 2 of the participant group classification by De Pauw et al. [13]. Before volunteering, all participants received written information regarding the nature and purpose of this study. Following an opportunity to ask any questions, a written statement of consent was signed. The protocol employed was approved by the local Ethics Advisory Committee of Hyogo University of Health Sciences (REF: 17036) and was conducted in accordance with principles of the Declaration of Helsinki.

2.2. Experimental protocol

All participants completed an initial maximal exercise test, a familiarisation trial and three experimental trials. VO_2max was determined in a temperate environment (24-25°C Ta and 45-50% RH) using a step-wise incremental exercise test to exhaustion on an upright cycle ergometer (Monark 828E, Sweden). During this test, expiratory gases were analyzed using a breath-by-breath gas analyzer (AE300S, Minato Medical Science, Co., Ltd., Osaka, Japan). A familiarization trial was conducted under a clear sky or thin cloud conditions to ensure the participants were accustomed to the procedures employed during the investigation and to minimize learning or anxiety effects. This trial was identical to the experimental trials in all respects (see below for details). Experimental trials were undertaken outdoors on a dark asphalt pavement. There were no obstructions to shield the sun within a 100 m radius from the east, south and west sides of exercising participants, but a building located approximately 8 m from the north side of them as a windshield to minimize the impact of airflow [12]. All trials were conducted between 0900 h to 1200 h from late-July to mid-September to minimize the effects of solar elevation angle [2] and the time-of-day [14] on thermoregulatory responses. Participants performed exercise at three sunlight exposure conditions: under a clear sky (HIGH), thin cloud (MID) and thick cloud (LOW). Solar radiation during exercise averaged 1072±91, 592±32 and 306±52 W·m^{-2} in HIGH, MID and LOW trials, respectively (Table 1). Because it was difficult to keep solar radiation condition stable under thin cloud conditions, participants exercised under a white polyester tarpaulin on a day with a completely clear sky in MID trial. The polyester tarpaulin covered a 4 m × 5 m area and was 3 m tall. During exercise, participants faced the sun and received sunlight at the frontal aspect of their body to set the azimuth angle, which is the orientation of the body relative to the sun, of 0° [15]. Participants were dressed in shorts and athletic shoes in all trials. This ensemble was approximately 0.8 kg of total weight, 1.024 of the clothing area factor, 0.011 W·(m^2·°C)$^{-1}$ or 0.08 clo of the intrinsic clothing insulation and 0.004 W·(m^2·kPa)$^{-1}$ of the evaporative resistance of clothing [16]. Experimental trials were completed in a randomized order and were separated by at least 7 days to avoid an order effect. No exercise or alcohol consumption was permitted in the 24 h before the trials.

Participants entered the laboratory maintained at a comfortable temperature (24-25°C) in the morning after an overnight fast, other than plain water ingested ad libitum until 90 min before the start of the trial. Although participants were instructed to record dietary intake during the 24 h before the trial to help ensure nutritional balance, there were no restriction of the amount and content of dietary intake before the trial. Upon arrival participants first emptied their bladder and nude body mass was measured to the nearest 10 g (AD6205B, A&D Co., Ltd., Tokyo, Japan). Participants then inserted a rectal thermistor (ITP010-11, Nikkiso-Therm Co., Ltd., Musashino, Tokyo, Japan) 10 cm beyond the anal sphincter for measurement of Tre to determine core temperature. Surface skin temperature thermistor probes (ITP082-25, Nikkiso-Therm Co., Ltd., Musashino, Tokyo, Japan) were attached to four sites (chest, upper arm, thigh and calf) to enable the calculation of Tsk [17]. A HR telemetry band (Polar WearLink + Hybrid transmitter, Polar Electro Oy, Kempele, Finland) was then positioned. A skin blood flow probe (laser-Doppler flowmetry; LBF-III, Bio Medical Science Co., Ltd., Tokyo, Japan) was also secured on the medial aspect of right forearm, approximately 5 cm from the radial styloid process, to determine skin blood flow. Skin blood flow was normalized to baseline values of 100%.

Participants then went outside, walked for about 20 m to reach an upright cycle ergometer (Monark 828E, Sweden) and rested on the ergometer in a seated position for 15 min. After the 15 min, Tre and skin temperatures were recorded using a thermometer (N543R, Nikkiso-Therm Co., Ltd., Musashino, Tokyo, Japan), HR was recorded using HR monitor (RCX5, Polar Electro Oy, Kempele, Finland), skin blood flow was recorded, and blood pressure was measured using an automated sphygmomanometer (FB-300S, Fukuda Denshi Co., Ltd., Tokyo, Japan). Thermal sensation was measured using a 9-point scale [18]. Participants then began a 45-min stationary ergometer cycling test at a freely chosen pedal cadence with resistance adjusted by using the control knob to achieve and maintain an RPE value of 13 on the Borg 6-20 RPE scale corresponding to somewhat hard. Although distance feedback may not affect pacing and performance during self-paced exercise [19], given that the pacing set at the first trial may affect subsequent trials owing to perceived RPE and distance [20], the current study was designed to provide no visual and auditory information concerning resistance, pedal cadence, distance and elapsed time until participants completed the trials. Participants also received no feedback in terms of physiological and environmental indices. During exercise, resistance and pedal cadence were recorded after 3 min of exercise and thereafter every 3 min. Tre, skin temperatures and HR were recorded every 3 min during exercise. Blood pressure was assessed and skin blood flow was recorded at 10±2 min intervals to obscure elapsed time to the participants, and these data were represented at 10 min intervals. Thermal sensation was recorded after 3 min of exercise and thereafter at 10±2 min intervals like blood pressure measurements. During exercise, experimenters randomly asked participants whether they maintained an RPE of 13. Following exercise, participants returned to the laboratory and emptied their bladder, the probes were removed, and nude body mass was re-measured to allow the estimation of sweat loss. During the experimental trials, participants were free to ingest plain water maintained at about 35°C.

2.3. Environmental measurements

All environmental indices were measured every 15 min. Direct and diffuse solar radiation in the horizontal plane were measured 1.5 m above the ground and recorded using a pyranometer (MS-01, Eko Instruments Co., Ltd., Tokyo, Japan), and solar radiation (global) was estimated by summing up the values. Solar elevation angle was determined from the geographical location (34°87´ North, 134°69´ East). Ta, RH, black globe temperature (Tg) and wet-bulb globe temperature (WBGT) were measured 1.5 m above the ground and taken using a WBGT meter (WBGT-203A, Kyoto Electronics Industry Co., Ltd., Fukuchiyama, Kyoto, Japan). Air velocity was measured 1.5 m above the ground using an anemometer (AM-4214SD, Mother Tool Co., Ltd., Ueda, Nagano, Japan) facing the headwind.

2.4. Calculations

SHG was calculated using the following equation [5]:

$$\mathrm{SHG} = A_\mathrm{P}\cdot\alpha_\mathrm{k}\cdot\frac{I_\mathrm{m}}{\sin\theta_\mathrm{s}} - \frac{I_\mathrm{dvk}}{2\sin\theta_\mathrm{s}} + \frac{A_\mathrm{r}}{A_\mathrm{D}}\ (SA - A_\mathrm{sh})\cdot\alpha_\mathrm{k}\cdot\frac{I_\mathrm{dvk}}{2}\quad \mathrm{W}$$

where, A_P is the projected area in m^2 (calculated using the equation below); α_k is the absorbance of skin for solar radiation (assumed to be 0.54 [5]); I_m is global solar radiation in $\mathrm{W\cdot m^{-2}}$; θ_s is the solar elevation angle in degrees; I_dvk is diffuse solar radiation in $\mathrm{W\cdot m^{-2}}$; $\frac{A_\mathrm{r}}{A_\mathrm{D}}$ is the effective radiative area of the body (assumed to be 0.7 for sitting person [21]); SA is the body surface area in m^2 (calculated using the equation below); A_sh is the area of the clothing in m^2 (assumed to be 14% of SA for shorts). The projected area (A_P) was calculated using the following equation [15]:

$$A_\mathrm{P} = 0.043\sin\theta_\mathrm{s} + 2.997\cos\theta_\mathrm{s}\sqrt{(0.02133\cos^2 az + 0.0091\sin^2 az}\quad \mathrm{m}^2$$

where, az is the azimuth angle. Since participants faced the sun at various az, A_P was calculated at 0°. Body surface area (SA) was calculated using the following equation [22]:

$$SA = 0.202\text{BM}^{0.425} \times \text{height}^{0.725} \quad \text{m}^2$$

where, BM is the body mass in kg; height is height of the participants in m. Convective heat transfer coefficient (h_c) was calculated using the following equation [21]:

$$h_c = 8.3\text{v}^{0.6} \quad \text{W}\cdot(\text{m}^2\cdot\text{K})^{-1}$$

where, v is the air velocity in m·s^{-1}. Radiative heat transfer coefficient (h_r) was calculated using the following equation [21]:

$$h_r = 4\varepsilon\sigma\frac{Ar}{A_D}[237.2+(t_{cl}+T_r)/2]^3 \quad \text{W}\cdot(\text{m}^2\cdot\text{K})^{-1}$$

where, ε is the area weighted emissivity of the clothing body surface (assumed to be 0.95 [5]); σ is the Stefan-Boltzmann constant, 5.67×10^{-8} in W·(m^2·K^4)$^{-1}$; t_{cl} is the mean temperature of the clothed body in °C (calculated using the iteration method [21]); T_r is mean radiant temperature in °C using the equation below. Mean radiant temperature (T_r) was calculated using the following equation [23]:

$$T_r = [(T_g+273)^4+2.5\times10^8\times\text{v}^{0.6}(T_g-T_a)]^{0.25}-273 \quad °\text{C}$$

where, T_g is the black globe temperature in °C; T_a is the ambient temperature in °C. Combined heat transfer coefficient (h) was calculated using the following equation [21]:

$$h = h_c + h_r \quad \text{W}\cdot(\text{m}^2\cdot\text{K})^{-1}.$$

Dry or sensible heat loss at the skin (DHL) was calculated using the following equation [21]:

$$\text{DHL} = (\text{Tsk}-T\text{o})/[R_{cl}+(1/f_{cl}h)] \quad \text{W}\cdot\text{m}^{-2}$$

where, Tsk is mean skin temperature in °C; T_o is the operative temperature calculated using the equation below; R_{cl} is the thermal resistance of clothing [0.011 W·(m^2·°C)$^{-1}$ for shorts]; f_{cl} is the clothing area factor (1.024 for shorts). The operative temperature (T_o) was calculated using the following equation [21]:

$$T_o = (h_rT_r+h_cT_a)/(h_r+h_c) \quad °\text{C}.$$

Evaporative heat transfer coefficient (h_e) was calculated using the Lewis Relation [21]:

$$h_e = 16.5h_c \quad \mathrm{W \cdot (m^2 \cdot kPa)^{-1}}.$$

Evaporative heat loss at the skin (EHL) was calculated using the following equation [21]:

$$\mathrm{EHL} = [w(P_{sk,s} - P_a)]/[R_{e,cl} + (1/f_{cl}h_e)] \quad \mathrm{W \cdot m^{-2}}$$

where, w is skin wettedness (assumed to be completely wet of 1.0 for fully acclimated individuals [21]); $P_{sk,s}$ is the partial water vapor pressure at the skin in kPa (assumed to be the saturated water vapor pressure [P_{sa}] at Tsk which was calculated using equation below); P_a is the water vapor pressure in the ambient air in kPa (calculated using the equations below); $R_{e,cl}$ is evaporative heat transfer resistance of the clothing layer [0.004 W·(m^2·kPa)$^{-1}$ for shorts]. The saturated water vapor pressure (P_{sa}) was calculated using Antoine's equation [21]:

$$P_{sa} = 0.1\exp[18.956 - 4030.18/(\mathrm{T}+235)] \quad \mathrm{kPa}$$

where, T is a temperature (°C). P_a was calculated using the following equation [21]:

$$P_a = P_{sa} \times \mathrm{RH} \quad \mathrm{kPa}$$

where, RH is the relative humidity in %. Total heat loss at the skin (THL) was estimated using the following equation [21]:

$$\mathrm{THL} = \mathrm{DHL} + \mathrm{EHL} \quad \mathrm{W \cdot m^{-2}}.$$

Absolute humidity was calculated using the following equation [21]:

$$\text{Absolute humidity} = 2.17 \cdot P_a/\mathrm{T} \quad \mathrm{kg \cdot m^{-3}}$$

where, T is a temperature (K). Power output was calculated using the following equation:

$$\text{Power output} = \text{resistance} \times \text{cadence} \times \text{flywheel distance} \quad \mathrm{kpm \cdot min^{-1}}$$

where, resistance is in kp, cadence is in rev·min^{-1} (rpm) and flywheel distance is 6 m·rev^{-1} for a Monark ergometer. Power output in kpm·min^{-1} was converted to power output in watts (W) by dividing by 6.116 (i.e. 1 W = 6.116 kpm·min^{-1}) which was then corrected plus 8% for frictional losses at the chain and drive train [24]. Total sweat loss was estimated using the following equation:

$$\text{Total sweat loss} = \text{body mass loss} + \text{the volume of water ingested} \quad \mathrm{L}.$$

Mean arterial pressure was calculated using the following equation:

$$\text{Mean arterial pressure} = (\text{systolic pressure} - \text{diastolic pressure})/3 + \text{diastolic pressure} \quad \text{mmHg}.$$

2.5. Statistical analysis

Data are presented as mean±SD. The IBM SPSS (version 21; IBM Corp., Armonk, N.Y., USA) was used for all statistical analyses. The significance level was set at $P<0.05$. The normality of the data and the homogeneity of variance between the trials were tested using Shapiro-Wilk's test and Levene's test, respectively. Non-parametric data were analyzed using Kruskal-Wallis test (solar radiation, Ta, RH, air velocity, WBGT, Tr) and Friedman's two-way ANOVA (EHL, thermal sensation). When a significant difference was found, the pairwise comparisons were tested using Mann-Whitney U test or Wilcoxon's signed-rank test. In all other cases, data collected once per trial were analyzed using a one-way ANOVA with repeated measures, and data collected over time were analyzed using a two-way ANOVA with repeated measures (3 trials [solar radiation] × time). Pair-wise differences between trials were evaluated using one-way ANOVAs with a Bonferroni adjustment applied for multiple comparisons. Effect size for non-parametric paired samples were calculated as Pearson's r (r) using the average of the cross-products of z-scores; an r of 0.1 to <0.3 and ≥0.3 to <0.5 has been suggested to represent a small and medium treatment effect, respectively, while an r ≥0.5 represents a large treatment effect [25]. Cohen's d (d) was used as a measure of effect size for parametric paired samples; a d of 0.2 to <0.5 and ≥0.5 to <0.8 has been suggested to represent a small and medium treatment effect, respectively, while a d ≥0.8 represents a large treatment effect [25].

3. Results

Pre-exercise body mass (*P*=0.652) and the initial Tre (*P*=0.925), Tsk (*P*=0.404) and HR (*P*=0.728) after 15 min of seated rest in hot outdoor environments were not different between trials, suggesting that participants began each trial in a similar physiological state.

3.1. Environmental conditions

Solar radiation was higher (*P*<0.001) on HIGH trial than on MID (*P*<0.001; *r*=0.86) and LOW (*P*<0.001; *r*=0.86) trials and on MID trial than LOW trial (*P*<0.001; *r*=0.86) (Table 1). There were no differences between trials in solar elevation angle (*P*=0.066), Ta (*P*=0.211) and WBGT (*P*=0.095). RH was higher (*P*<0.001) on LOW trial than on HIGH (*P*<0.001; *r*=0.40) and MID (*P*<0.001; *r*=0.37) trials. RH and absolute humidity were higher (both *P*<0.001) on LOW trial than on HIGH (RH *P*<0.001; *r*=0.40: absolute humidity *P*<0.05; *d*=0.65) and MID (RH *P*<0.001; *r*=0.37: absolute humidity *P*<0.01; *d*=0.73) trials. Air velocity was slower (*P*<0.05) on MID trial than on HIGH (*P*<0.01; *r*=0.29) and LOW (*P*<0.05; *r*=0.26) trials. Tr was higher (*P*<0.001) on HIGH trial than on MID (*P*<0.001; *r*=0.74) and LOW (*P*<0.001; *r*=0.80) trials. All environmental conditions showed no main effect of time within trials.

3.2. Self-regulated exercise intensity

Power output was lowered with increasing solar radiation and showed a main effect of trial (*P*<0.001); it was lower on HIGH trial (95.5±21.6 W) than on MID (103.1±20.3 W; *P*<0.001; *d*=0.37) and LOW (108.1±20.1 W; *P*<0.001; *d*=0.60) trials, and MID trial tended to be lower than LOW trial (*P*=0.060; *d*=0.26), although there was no interaction (*P*=0.611) (Figure 1A). Moreover, a main effect of trial was observed in the percentage change in power output from 3 min (*P*<0.001) which was lower on HIGH trial than on MID (*P*<0.05; *d*=0.41) and LOW (*P*<0.001; *d*=0.53) trials, although there was no interaction (*P*=0.386) (Figure 1B). The percentage change in power output from 3 min was lower at 39 to 45 min than the initial value in HIGH trial (P<0.05). There was a main effect of trial on the selected resistance during exercise (P<0.05) which was lower on HIGH trial (1.36±0.27 kp) than on MID (1.44±0.24 kp; P<0.01; d=0.31) and LOW (1.49±0.32 kp; P<0.001; d=0.44) trials, albeit no interaction was observed (P=0.671) (Figure 1C). The selected resistance was lower at 39 to 45 min than the initial value in HIGH trial (P<0.05). Although there was no interaction (P=0.357) in pedal cadence during exercise, a main effect of trial was apparent in pedal cadence (P<0.001) which was different between all trials (HIGH [64.5±5.1 rpm] vs. MID [66.0±4.2 rpm] P<0.001; d=0.32: HIGH vs. LOW [67.7±3.8 rpm] P<0.001; d=0.70: MID vs. LOW P<0.001; d=0.44) (Figure 1D).

3.3. Body temperature responses

There was no interaction (P=0.347) and main effect of trial (P=0.485) in Tre during exercise (Figure 2A). Tre was higher at 21 to 45 min in HIGH trial, at 27 to 45 min in MID trial and at 42 and 45 min in LOW trial than the initial value (all P<0.05). A main effect of trial was shown in Tsk during exercise (P<0.001) which was higher on HIGH trial than on MID (P<0.001; d=0.51) and LOW (P<0.001; d=0.74) trials, albeit no interaction was observed (P=0.165) (Figure 2B). Tsk was higher at 3 to 45 min than the initial value in HIGH trial (P<0.05). Although there was no interaction (P=0.227) in Tre-to-Tsk gradient, a main effect of trial was observed in Tre-to-Tsk gradient during exercise (P<0.001) which was narrower with increasing solar radiation and different between all trials (HIGH vs. MID P<0.01; d=0.48: HIGH vs. LOW P<0.001; d=0.72: MID vs. LOW P<0.05; d=0.42) (Figure 2C).

3.4. Heat transfer

SHG during 45 min exercise was greater with increasing sunlight (P<0.001) and different between all trials (HIGH vs. MID P<0.001; d=5.67: HIGH vs. LOW P<0.001; d=7.66: MID vs. LOW P<0.001; d=3.96) (Figure 3A and Table 1). The projected area was not different between trials (P=0.094) (Table 1). DHL was lower and EHL was higher during 45 min exercise on HIGH trial than on MID (DHL P<0.01; d=2.26: EHL P<0.05; r=0.66) and LOW (DHL P<0.001; d=2.47: EHL P<0.05; r=0.66) trials (Figure 3B). There was no difference between trials in THL (P=0.442) during 45 min exercise (Figure 3C).

3.5. Body fluid balance

The volume of water ingested was 455±268, 392±302 and 430±302 mL in HIGH, MID and LOW trials, respectively, and was not different between trials (P=0.505). Body mass loss was 0.2±0.3 kg in all trials (P=0.723). Total sweat loss was 0.65±0.14, 0.57±0.17 and 0.68±0.11 L in HIGH, MID and LOW trials, respectively, and was not different between trials (P=0.117).

3.6. Cardiovascular responses

Neither an interaction (HR P=0.879: mean arterial pressure P=0.701: skin blood flow P=0.389) nor a main effect of trial (HR P=0.687: mean arterial pressure P=0.140: skin blood flow P=0.353) was apparent in HR, mean arterial pressure and skin blood flow during exercise (Figure 4A, B and C). HR was higher at 3 to 45 min than the initial value in all trials (all P<0.01). The average HR during exercise was 71±14%, 69±14% and 70±16% HRmax in HIGH, MID and LOW trials, respectively (P=0.716). Mean arterial pressure was higher at 10 to 40 min than the initial value in HIGH and MID trials (both P<0.05).

3.7. Thermal sensation

A main effect of trial was shown in thermal sensation during exercise (P<0.001) which was higher with increasing sunlight and different between all trials (HIGH vs. MID P<0.001; r=0.48: HIGH vs. LOW P<0.001; r=0.59: MID vs. LOW P<0.01; r=0.32) trials, although there was no interaction (P=0.293) (Figure 5). Thermal sensation was higher at 3 to 45 min than the initial value in all trials (all P<0.01).

4. Discussion

The present study demonstrated a lower power output as solar radiation increased during 45 min cycling exercise, owing to a lower self-selected resistance and pedal cadence proportionally to solar radiation, and therefore confirmed our experimental hypothesis. A novel finding in the current study is therefore that self-regulated exercise intensity in hot outdoor environments is lowered with increasing solar radiation when an individual's perceived effort is somewhat hard. The finding of a lower power output was accompanied by a higher Tsk and thermal sensation, a narrower Tre-to-Tsk gradient and a greater SHG during exercise as solar radiation increased, with no impact of radiation intensity on Tre, whole-body sweat rate, THL and cardiovascular responses of HR, mean arterial pressure and skin blood flow. These observations are consistent with previous results of Otani and colleagues [1] in a hot indoor environment. Based on the findings of Otani et al. [1] and the current study, high solar radiation exposure, which is greater than 800 $W{\cdot}m^{-2}$ corresponding to under a clear sky, in the heat might reduce endurance performance because of a greater thermoregulatory strain in conjunction with a higher skin temperature and a narrower core-to-skin temperature gradient.

In the current study, neither Ta nor WBGT was different between trials, albeit RH in LOW trial was higher and air velocity in MID trial was lower than the other trials. However, given that the differences in air velocity between MID trial and both HIGH and LOW trials were only 1.2±1.1 $km{\cdot}h^{-1}$ and 1.1±1.4 $km{\cdot}h^{-1}$, respectively, these differences between trials would have almost no impact on self-selected exercise intensity and thermoregulatory responses; this result is probably due to performing exercise under the tarpaulin only in MID trial. In addition, since Maughan and colleagues [11] demonstrated that neither endurance exercise capacity nor thermoregulatory responses in hot indoor environment (30°C Ta) were different between 40% and 60% RH trials, the difference in RH between trials within these ranges in this study would also have negligible effects on the voluntary control of exercise intensity and thermoregulatory strain. The rate of SHG is influenced by several factors, including solar radiation, solar elevation angle, the projected area, soil albedo and the colour and insulation of the clothing [26]. Although the present study did not measure soil albedo like previous studies [2,5], given that the surface of this asphalt pavement was dark-colored which is low solar reflectance, it might have a moderate impact on the difference in SHG between trials. Also, since the clothing condition was the same in each trial, it may not influence the result of SHG between trials. Regarding the influence of solar elevation angle and the projected area on SHG, given that these were approximately 55° and 28% in all trials, respectively, a greater SHG as solar radiation increases would be largely influenced by the intensity of solar radiation alone.

In the current study, a greater rate of decrease in power output towards the end of exercise was observed with increasing solar radiation that might be associated with the combined effect of a gradually lower pedal cadence throughout exercise and a greater decline in resistance during the later stages of exercise in response to increasing solar radiation. Although no research has investigated the impact of different levels of solar radiation on self-paced cycling performance in hot outdoor environments, many previous studies examined how Ta manipulations influence pacing strategy and thermoregulatory responses during indoor [7,27,28,29,30] and outdoor [31] self-paced cycling time-trials. These studies demonstrated a lower power output in a hot environment (≥30°C) compared with cool-to-temperate environments, resulting from a combination of several factors mediated by a higher thermal strain, including increases in Tre, Tsk, HR, thermal sensation and RPE. In line with these previous studies, the present study demonstrated a lower power output in a relatively higher thermal stress condition as HIGH trial than a lower thermal stress condition as MID and LOW trials, albeit Ta was almost identical between trials. This may indicate that high solar radiation exposure per se reduced effects on self-regulated exercise intensity when perceived effort is somewhat hard, even though Ta is constant in the heat.

In the heat outdoors, Otani and colleagues [2] reported a higher tympanic temperature, Tsk and HR, a lower THL and a greater SHG in a higher than a lower solar radiation condition during exercise. Meanwhile, in cool-to-temperate outdoor environments, increases in Tsk [3,5], HR [5] and whole-body sweat rate [4,5] were reported in a higher compared with a lower solar radiation conditions during exercise, with no difference in Tre [5]. On the basis of these observations, skin temperature is well reflected by variations in solar radiation during outdoor exercise regardless of environmental conditions. It is recognized that thermoregulatory limitations for causing a reduction in endurance performance in individuals exercising in the heat are the attainment of high core temperature, resulting in a reduced central neural drive to the exercising muscles [32], and high skin temperature [33,34]. Especially, skin temperature of greater than approximately 35°C can induce the early onset of fatigue and therefore reduce endurance exercise capacity in hot environments owing to the narrowed temperature gradient between the body core and the skin [1,33], which requires a greater skin blood flow and thus elevates cardiovascular strain [34]. This greater cutaneous blood flow during exercise has been shown to provoke elevated HR for a given stroke volume [35] and reducing left ventricular filling [36], and to lower blood flow to the exercising muscles [37], which limits oxygen delivery to, and removal of heat from, these tissues. In the current study, Tsk was gradually higher with increasing solar radiation. This rise in skin temperature would be largely influenced by a gradually greater SHG and contribute to a gradually narrower Tre-to-Tsk gradient in proportion to solar radiation. Although the current study showed no differences in cardiovascular responses of HR, mean arterial pressure and skin blood flow between trials, a narrow Tre-to-Tsk gradient might have negative effects on self-regulated endurance performance in response to increasing cardiovascular strain as solar radiation increases. Hence, a higher skin temperature and a narrower Tre-to-Tsk gradient with increasing solar radiation would evoke reductions in self-regulated exercise intensity at an RPE of 13 as solar radiation increases. Meanwhile, despite both core and skin temperatures contributing to the regulation of thermoregulatory behavior, skin temperature is a more than capable controller because core temperature changes more slowly than skin temperature during the early stages of exercise [38]. Schlader and colleagues [38] showed that a combination of high Tsk and thermal sensation in the first few minutes of exercise reduced the initial selection of exercise intensity during self-paced cycling exercise. Therefore, a relatively lower self-regulated exercise intensity from the early stages of exercise as solar radiation increases may be related to a relatively higher initial Tsk and thermal sensation with increasing solar radiation.

The present study observed the absence of difference in Tre between conditions regardless of a lowering of endurance performance with increasing solar radiation that is consistent with Otani et al. [1]. It is therefore noteworthy that variations in solar radiation might have modest effects on a rise in Tre during exercise in hot environments when environmental conditions other than solar radiation are almost similar. To date there is no research demonstrating this result, but a similar response was shown by several researchers [27,29,30]. These studies observed a lower power output in hot than cool environments during self-paced cycling time-trials, although Tre changed in a similar fashion between trials. This response is explained by the role of the central nervous system in maintaining thermal homeostasis during exercise: the brain selects a lower power output in response to a rise in core temperature [29] to avoid an excessive rise in core temperature [30]. Meanwhile, several studies demonstrated that high thermal sensation per se decreased the voluntary control of exercise intensity with the absence of Tre difference between various cooling interventions during cycling exercise under indoors heat stress conditions [39,40]. Therefore, a higher thermal sensation and skin temperature at the commencement of exercise reduced the initial selection of exercise intensity with increasing solar radiation, and thereafter a progressive increase in thermal sensation and skin temperature after that caused a greater rate of fall in self-regulated exercise intensity with elapsed time as solar radiation increases which might result in no Tre difference between trials. Meanwhile, it is possible that a higher EHL in HIGH trial attenuated an increase in Tre compared with the other trials although THL was similar between trials. On the basis of these observations, the current study would suggest that solar radiation rises skin temperature and thermal sensation with increasing its intensity that results in a greater rate of fall in self-regulated exercise intensity from the first few minutes of exercise as solar radiation increases even at a fixed RPE of 13, and these responses may offset a rise in Tre greatly in inverse relation to increasing solar radiation. This finding might be related to maintaining thermal homeostasis during exercise by the central nervous system because the brain causes high thermal sensation in response to afferent feedback from high skin temperature and thereafter selects a lower power output as solar radiation increases. In terms of preventing and mitigating the risk of exertional heat-related illness during daily exercise in hot outdoor environments, this lower self-regulated exercise intensity when individuals are exposed to high solar radiation in the heat may be important to attenuate excessive core temperature rise.

In the present study, participants performed 45 min of self-regulated cycling at an RPE of 13 to simulate the rate of daily exercise. However, if an exercise is performed at an RPE of 16 like previous studies [7,39], a rate of decrease in power output and increases in Tre, skin temperature and HR towards the end of exercise would be greater in all solar radiation conditions than the results of the current study because of a greater initial exercise intensity. Moreover, this study chose the average solar elevation angle of about 55° because the greatest SHG was obtained when it is approximately 55° in quietly standing humans [26] and exercising individuals in the morning [2], but the relationship between this angle and SHG was unclear in sitting humans. Although our subjects faced toward the sun during exercise, this would be the greatest perceived thermal stress from the sun and result in a higher thermal sensation compared with another orientation of the body relative to the sun. Given that a higher thermal sensation reduces power output during self-paced exercise [39], this body-to-Sun orientation would influence self-regulated exercise intensity. Nevertheless, how solar elevation angle and body-to-Sun orientation influence the effect of solar radiation on exercise performance and thermoregulatory responses is unknown yet. Also, participants in MID trial exercised under a white polyester tarpaulin on a day with a completely clear sky to make thin cloud conditions because it was hard to keep solar radiation condition stable under that conditions. This intervention might make a different spectral content compared with HIGH and LOW trials and not be enough to simulate thin cloud conditions in real life settings. Hence, further studies need to elucidate these influences.

In conclusion, the current study demonstrates that self-regulated exercise intensity in the heat outdoors is reduced with increasing solar radiation when an individual's perception of effort is somewhat hard, resulting from a lower power output, resistance, and pedal cadence. These responses are mainly accompanied by a greater thermoregulatory strain and perceived thermal stress as solar radiation increases in relation to a higher skin temperature and thermal sensation, a narrower core-to-skin temperature gradient and a greater SHG during exercise with increasing solar radiation, with no effect of radiation intensity on core temperature. This finding suggests that reduced self-regulated exercise intensity when individuals are exposed to high solar radiation might be important to prevent excessive core temperature rise and thus the risk of developing exertional heat-related illness during outdoor exercise in the heat under a clear sky.

Disclosure

The authors for this manuscript have nothing to disclose.

Conflict of interest

No conflicts of interest, financial or otherwise, are declared by the authors. The present study was not supported by any specific grant.

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Figure captions

Figure 1. Effects of variations in solar radiation on power output (A), the percentage change in power output from 3 min (%ΔPower output; B), resistance (C) and pedal cadence (D). **P*<0.05−0.001 denote a main effect of trial between HIGH trial and both MID and LOW trials. †*P*<0.001 denotes a main effect of trial between all trials. %ΔPower output and resistance were lower at 39 to 45 min than the initial value in HIGH trial (both *P*<0.05).

Figure 2. Changes in rectal temperature (Tre; A), mean skin temperature (Tsk; B) and the core-to-skin temperature gradient (Tre-to-Tsk; C) during exercise. **P*<0.001 denotes a main effect of trial between HIGH trial and both MID and LOW trials. †*P*<0.05 denotes a main effect of trial between all trials. Tre was higher at 21 to 45 min in HIGH trial, at 27 to 45 min in MID trial and at 42 and 45 min in LOW trial than the initial value (all *P*<0.05). Tsk was higher at 3 to 45 min than the initial value in HIGH trial (*P*<0.05).

Figure 3. Effects of variations in solar radiation on body heat gain from the sun (SHG; A) and dry (DHL; B), evaporative (EHL; B) and total (THL; C) heat losses at the skin during exercise. **P*<0.001 denotes a main effect of trial between all trials. †*P*<0.05 denotes a main effect of trial between HIGH trial and both MID and LOW trials.

Figure 4. Changes in heart rate (HR; A), mean arterial pressure (MAP; B) and skin blood flow (SkBF; C) during exercise. HR was higher at 3 to 45 min than the initial value in all trials (all *P*<0.01). MAP was higher at 10 to 40 min than the initial value in HIGH and MID trials (both *P*<0.05).

Figure 5. Thermal sensation (TS) response to exercise in environment with different solar radiations. **P*<0.01 denotes a main effect of trial between all trials. TS was higher at 3 to 45 min than the initial value in all trials (all *P*<0.01).

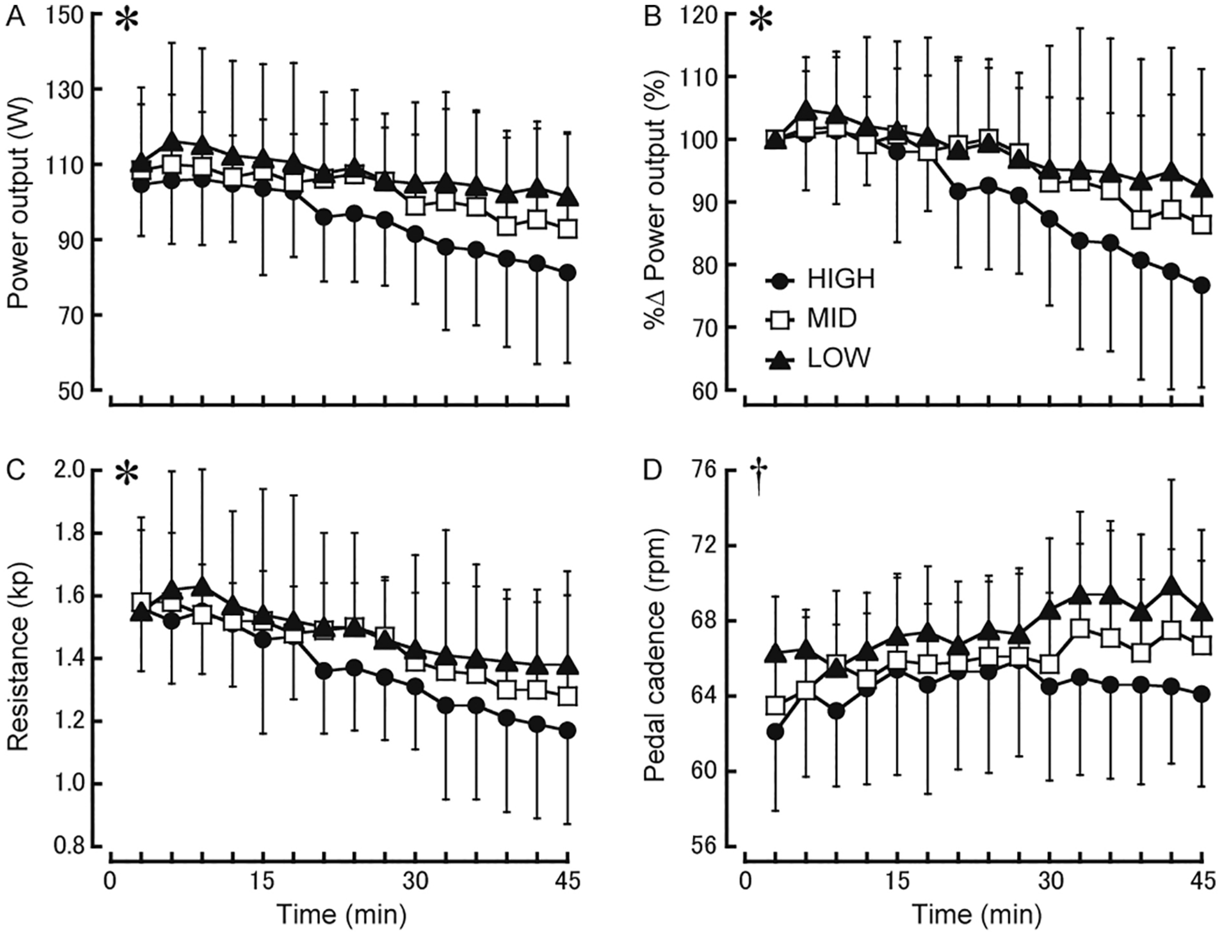

A
B
C
D
Power output (W)
%Δ Power output (%)
Resistance (kp)
Pedal cadence (rpm)
Time (min)
HIGH
MID
LOW
*
†
150
130
110
90
70
50
120
100
80
60
2.0
1.8
1.6
1.4
1.2
1.0
0.8
76
72
68
64
56
0
15
30
45

Figure 1

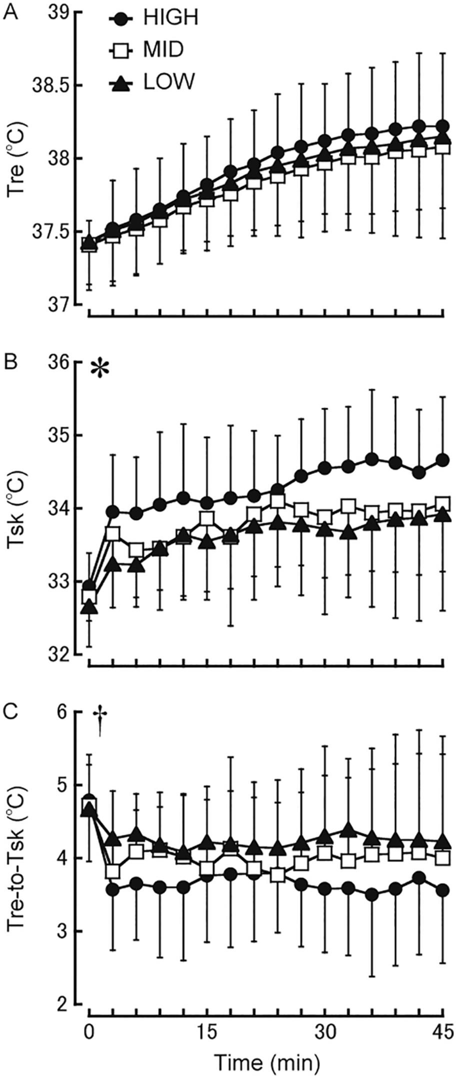
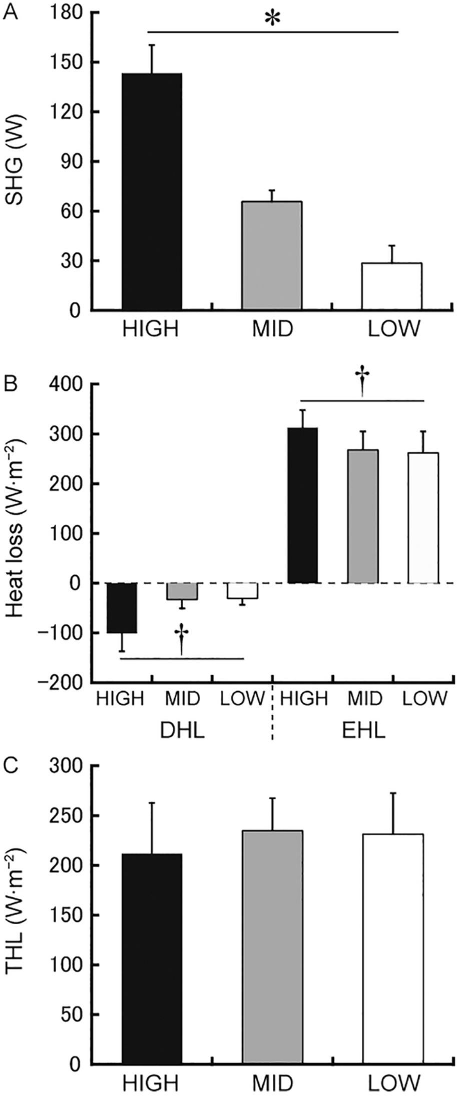

A
B
C
HIGH
MID
LOW
Tre (°C)
Tsk (°C)
Tre-to-Tsk (°C)
39
38.5
38
37.5
37
36
35
34
33
32
6
5
4
3
2
*
†
0
15
30
45
Time (min)

Figure 2



A
180
150
120
90
60
30
0
SHG (W)
*
HIGH
MID
LOW
B
400
300
200
100
0
−100
−200
Heat loss (W·m⁻²)
†
HIGH
MID
LOW
HIGH
MID
LOW
DHL
EHL
C
300
250
200
150
100
50
0
THL (W·m⁻²)
HIGH
MID
LOW

Figure 3

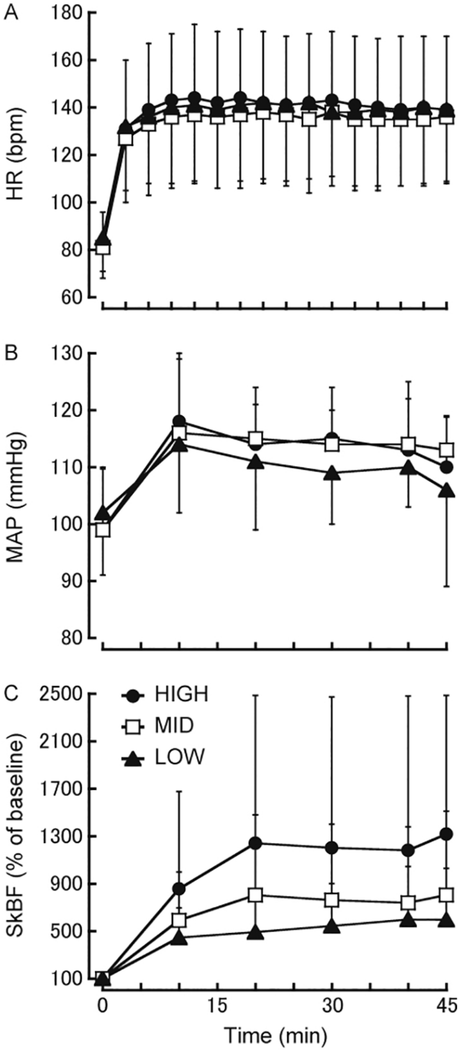
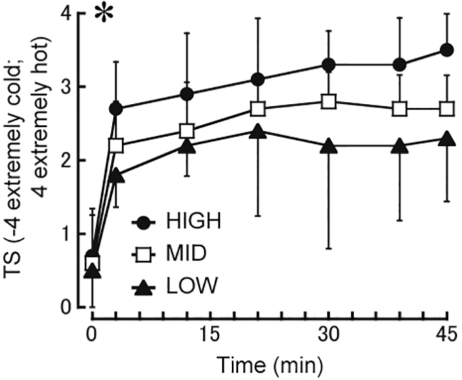

A
180
160
140
120
100
80
60
HR (bpm)
B
130
120
110
100
90
80
MAP (mmHg)
C
2500
2100
1700
1300
900
500
100
SkBF (% of baseline)
HIGH
MID
LOW
0
15
30
45
Time (min)

Figure 4



*
TS (-4 extremely cold; 4 extremely hot)
0
1
2
3
4
HIGH
MID
LOW
0
15
30
45
Time (min)

Figure 5