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ORIGINAL PAPER

Modeling the thermoregulatory significance of differential solar absorptance in American football helmets

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Abstract

Variations in the color of youth football helmets had a statistically significant (ANOVA; $p < 0.001$) $\backsim$2-fold effect on solar absorptance, α_1 (%) in white, red, and black helmets. At the end of 30-minute of exposure to a dangerously hot outdoor environment (mean WBGT 34.3 ± 1.1 ACSM Heat-Index Black; Extreme Danger Stop Play) the internal shell temperature, T_{is} (°C) of red and black youth helmets were $\backsim$18.7 to 20.6 °C hotter than white helmets. The objective was to use the thermal modeling to estimate the thermoregulatory significance of α_1 on net-radiant heat transfers $\pm Q_n$ (W) and heat storage, $\pm X$ and the onset of exertional heat illness EHI. Players wearing black or red helmets may experience early onset of EHI. Some players wearing black or red helmets may be more susceptible to EHI. We discuss our results in relationship to the potential effect of helmet color on EHI.

Abbreviations

A_1	Surface area of the scalp involved in net-radiant heat transfer
A_2	Surface area of the interior helmet shell involved in net-radiant heat transfer
ACSM	American College of Sports Medicine
α_1	Absorptance of solar radiation (%)
°C	Degrees Celsius
C	Convective heat loss (W)
E	Cutaneous evaporative heat loss (W)
EHI	Exertional heat illness
EHS	Exertional heat stroke
EHIM	Exertional heat illness model
ε_1	Emissivity of human skin $\backsim$0.97
ε_2	Emissivity of football helmet shells $\backsim$0.95
g	Grams
J	Joules
K	Degrees Kelvin
K	Conductive heat loss (W)
λ	Wavelength (nm)
m_b	Brain mass (kg)
M_b	Body mass (kg)
M_{ex}	Metabolic heat production during exercise (W)
NDCH	Neurological disfunction and Cellular Histopathy
$+/-Q_n$	Net-radiant heat transfer (W)
R_a	Thermal radiation (W)
S	Solar Radiation
σ	Stefan-Boltzmann constant (5.673×10^{-8} W.m^{-2}K^{-1})
t	Elapse time (m)
T_a	Ambient air temperature (°C)
T_{br}	Brain temperature (°C)
T_{es}	External helmet shell temperature (°C)
T_{is}	Internal helmet shell temperature (°C)
T_{sc}	Scalp temperature (°C)
W	Units watts
WBGT	Wet bulb globe temperature (°C)
$\pm X$	Heat storage in tissues (W)

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Table 1 Spectral and physical characteristics of matt finish Riddell Victor youth football helmets (size large)

Color	Solar Absorptance, α_1 (%; $n=12$) Mean (±SD)	Emissivity (ε)	Ventilation (∽mm²; $n=4$)	Surface Area Head Model (∽mm²)	Surface Area Head Model Covered by Helmet (∽mm²)	Surface Area Memory Foam Padding (∽mm²)	Surface Area Interior Air Space (∽mm²)
White	$0.44 \pm 0.03^{\dagger}$	0.95	4,787 ± 205	63,150	49,975 (∽79%*)	39,375 (∽62%*)	9,200 (∽18.4%‡)
Red	$0.61 \pm 0.07^{\dagger}$	0.95	4,787 ± 205	63,150	49,975 (∽79%*)	39,375 (∽62%*)	9,200 (∽18.4%‡)
Black	$0.92 \pm 0.02^{\dagger}$	0.95	4,787 ± 205	63,150	49,975 (∽79%*)	39,375 (∽62%*)	9,200 (∽18.4%‡)

Note The dagger (†) symbol indicates statistically significant (One-Way ANOVA; DF = 2: $p < 0.01$) differences in solar absorptance, α_1 (%) between different colored helmets [9]. The asterisk (*) symbol represents the % of the head model surface area covered by the helmets, and the double dagger (‡) indicates the % of the interior helmet shell surface area involved in net-radiant heat transfer, Q_n (W; Eq. 2; Fig. 1) with the scalp surface

Table 2 Mean (±SD) internal helmet shell surface temperatures, T_{is} (°C) of white, red and black helmets recorded at five-minute intervals using infrared field thermometers [9]

Event Time t (min.)	White Helmet T_{is} (°C)	Red Helmet T_{is} (°C)	Black Helmet T_{is} (°C)
–5	25.3 ± 0.45	23.9 ± 0.70	27.7 ± 0.60
0	32.5 ± 5.8	44.3 ± 12.5	27.7 ± 13.6
5	34.7 ± 4.20	56.9 ± 7.2	49.6 ± 8.7
10	33.4 ± 3.5	50.0 ± 4.9	50.8 ± 9.6
15	41.0 ± 11.0	52.1 ± 5.8	52.8 ± 10.0
20	37.6 ± 7.5	53.8 ± 5.0	51.1 ± 15.6
25	38.2 ± 3.9	56.9 ± 2.7	54.2 ± 10.5
30	37.0 ± 2.0	55.7 ± 7.7	57.6 ± 10.1

Note measurements recorded at the -5-time interval represent baseline measurements recorded in the lab prior to outdoor exposure to mean WBGT 34.3±1.1 ACSM Heat-Index Black Extreme Danger [9].

Introduction

Wearing a football uniform, including a helmet, increases metabolic heat production and decreases radiative, evaporative, convective, and conductive modes of heat loss from the skin surface [1–8]. The transfer of atmospheric radiant environmental heat (Appendix I) through the rigid plastic/polycarbonate shell of American football helmets can cause an increase in brain temperature, T_{br} (°C) [8]. The color of the shell influences its solar absorptance, α_1 (%; i.e., the portion of solar radiation absorbed; Table 1; Appendix I) [1]. Rowe and Lopez-Macias (2022) [9] reported a statistically significant (One-Way ANOVA; DF = 2; $p < 0.001$) ∽2-fold difference in α_1 between white, red, and black youth football helmets (Table 1). At the end of 30-minute trials where helmets were exposed to a dangerously hot outdoor environment (mean WBGT 34.3 ± 1.1 °C; ACSM Heat-Index Black; Extreme Danger Stop Play) the internal shell temperature, T_{is} (°C) of red and black youth helmets were statistically significantly (One-Way ANOVA; DF = 2; $p < 0.03$) ∽18.7 to 20.6 °C, respectively, hotter than white helmets (Table 2). However, statistically significant differences in α_1 and T_{is} between helmet colors may not cause biologically significant thermoregulatory challenges for players wearing different colored helmets.

In the present study, we use the lumped parameter thermal energy budget [1, 10], in combination with our previously published data (Tables 1 and 2) to provide a first approximation thermoregulation by estimating the rate of heat gain and loss (in units watts; W) that take place at the (bald) scalp surface of a youth football player's head while wearing a helmet,

$$\text{Heat Gain} \approx \text{Heat Loss}$$

$$M_{ex} \approx \pm Q_n + E + C + K \pm X. \tag{1}$$

To maintain equilibrium, a player's active metabolic heat production, M_{ex} must be lost from the skin surface *via* the combined effects of net-radiant heat transfer, $\pm Q_n$, cutaneous evaporative heat transfer, E, convective heat transfer, C, and conductive heat transfer, K, else heat is stored, $\pm X$, in brain tissues, as evidenced by and increase in T_{br} (°C).

However, helmet characteristics influence the thermal energy budget. The present analysis focuses strictly on the effect of helmet characteristics on thermoregulation (Tables 1 and 2), therefore M_{ex} is ∽0 W. The helmet shell covers ∽79% of the head surface area (Table 1), which results in an increase in sweat production, but decreases the transfer of E to the environment by ∽20–70% [2–8; and our unpublished data]. For modeling purposes, we assume E is ∽0 W. Similarly, windspeed is minimal inside of a football helmet, thus C is ∽0 W. Memory foam padding (i.e., insulation) is in contact with ∽62% of the head surface area (Table 1). Therefore, K is negligible, ∽ 0 W. Thus, thermal energy budget (Eq. 1), can be reduced to, $\pm Q_n \approx \pm X$, where the rate of $\pm Q_n$ absorbed at the scalp surface is approximately equal to $\pm X$ stored in brain tissue.

The objective of the current study was to estimate the effect of variations in helmet color and α_1 (Table 1) between white, red, and black helmets on T_{br} during training or competition in a dangerously hot environment. To achieve this objective, we had two specific goals. Firstly, we estimated the effect of helmet color and α_1 on mean-Q_n (Eq. 2, see Methods and Materials), during 30-minutes of exposure to a dangerously hot environment (Fig. 1). Secondly, we

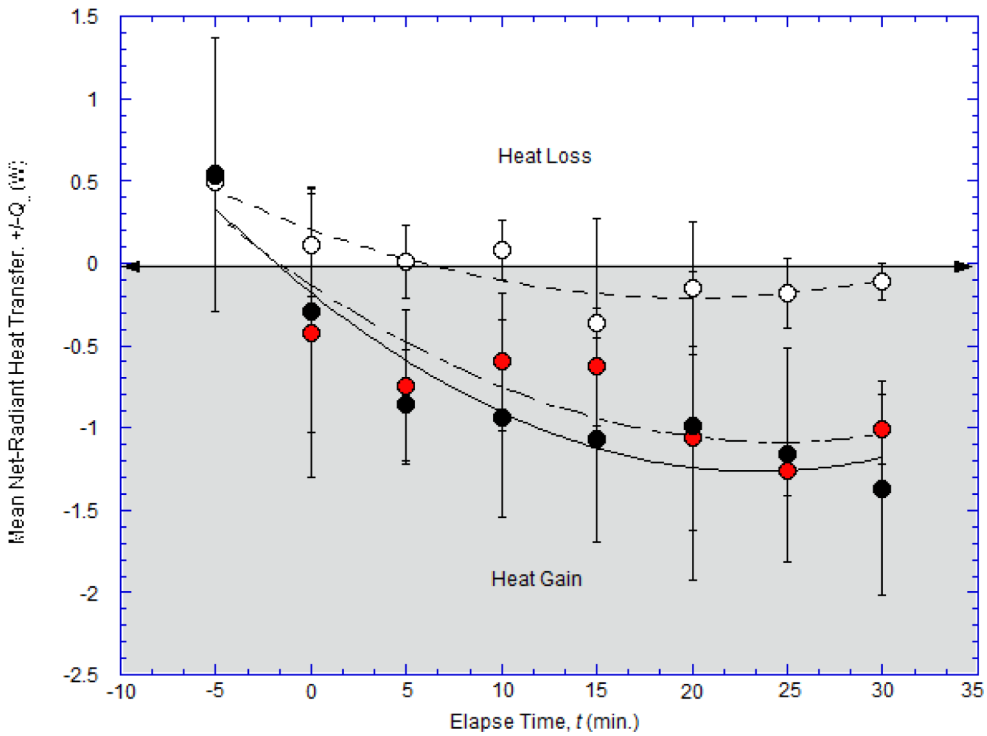

Fig. 1 Illustrates the net-radiant heat transfer, $\pm Q_n$ (W) model. During 30-minutes of practice or competition (in a dangerously hot environment, WBGT 34.3 ± 1.1 ACSM Heat-Index Black; Extreme Danger) [9], the 2.1-fold difference in α_1 between different colored football helmets resulted in negative curvilinear relationships between $\pm Q_n$ in white (white circles with dashed line), red (red circles with short and dashed lines), and black (black circles and solid line) youth football helmets and elapse time, *t* (min.). Polynomial equations describing the negative curvilinear relationship (and 95% CI) between $\pm Q_n$ and *t* are listed in Appendix II

developed the exertional heat illness model (EHIM) based on the assumption that differential mean-Q_n between white, red, and black helmets (Fig. 1) will result in differential rates of heat storage, $\pm X$ (Eq. 3; see Methods and Materials), and the onset of T_{br} characteristic of EHI in youth football players (aged 5 to 17 years old) during training or competition lasting up to 120-minutes in duration (Fig. 2). We discuss our results in relationship to the potential thermoregulatory (i.e., biological) significance of variations in helmet color and α_1 on T_{br} and the onset of EHI in youth football players (Fig. 2).

Methods and materials

Helmets and head model

Data (Tables 1 and 2) used for thermal modeling purposes (Eqs. 1–3) were collected on three new Riddell Victor® Youth Football Helmets that were purchased directly from the manufacturer [9]. Helmet colors were chosen to represent a wide range of α_1 (Table 1) that had previously been shown to cause differential T_{is} (Table 2) during exposure to a dangerously hot environment [9]. The surface area (and portion) of the head covered by the helmets, padding and air space (Table 1) was determined by covering the head model with graph paper (marked in 1 mm^2 blocks) and then outlining the helmet, padding, and air space. The number of blocks representing each were then counted and relative portions calculated (Table 1).

Net-radiant heat transfer model

The mean (± SD) net-radiant heat transfer model, $\pm Q_n$ (Eqs. 1, 2; Fig. 1) estimates the exchange of thermal radiation (Appendix I) between a football player's scalp surface and the interior helmet shell surface (Table 2). Equation 2 was used to estimate $\pm Q_n$ [11, 12],

$$Q_n = \frac{\epsilon_1 * \{\epsilon_2 sigma * A_1 * (\bar{T}_{sc}^4 - T_{is}^4)}{1 + (1 - \epsilon_2) * (A_1/A_2)} \tag{2}$$

Here, $\bar{T}_{sc}$ (K) is the mean temperature of the athlete's scalp. No peer reviewed published data describing $\bar{T}_{sc}$ in active football players was available. A $\bar{T}_{sc}$ of ∽34.9 °C, was chosen as a reference temperature based on its previous use to model heat transfer in cricket helmets [13]. $\bar{T}_{is}$ (K) is the mean temperature of interior helmet shell (Table 2) [9]. The approximate emissivity of human skin, ε_1, and the helmet shell, ε_2, were ∽0.97 [1] and 0.95 [9], respectively (Table 1).

The Stefan-Boltzmann constant, σ is 5.673×10^{-8} W.m^{-2} K^{-1} [1]. A_1 is scalp skin surface area adjacent to the surface area of interior helmet shell, A_2 (Table 1). NOTE: + Q_n indicates radiant heat loss and -Q_n indicates radiant heat gain (Fig. 1).

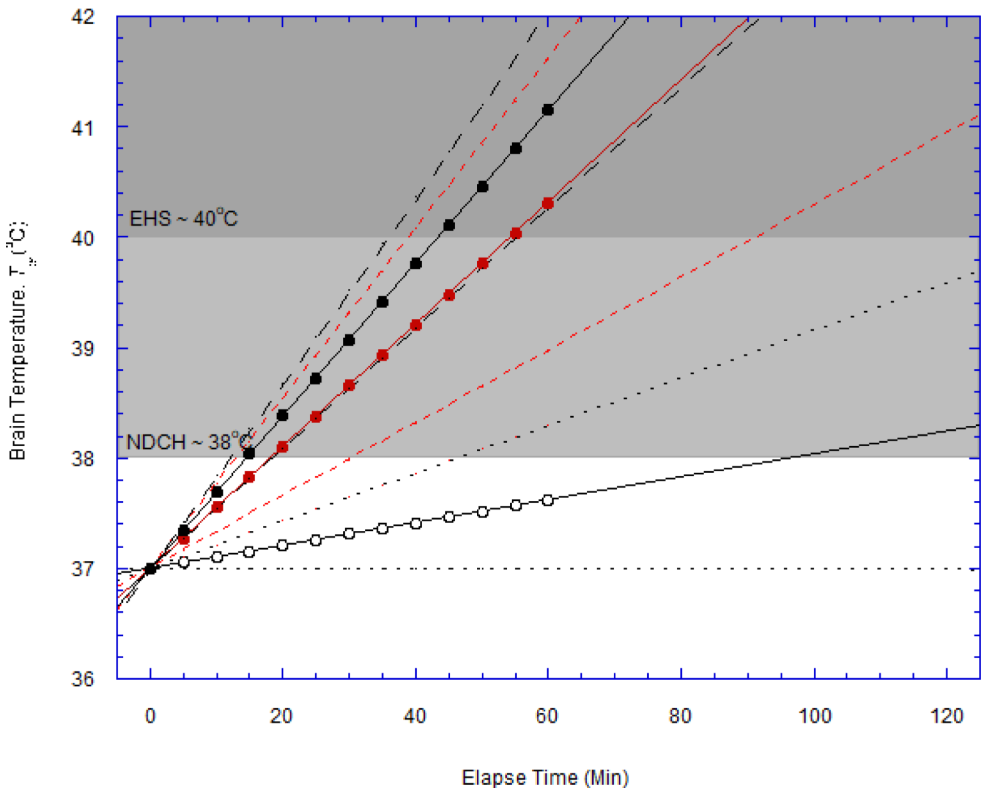

Fig. 2 Illustrates the linear exertional heat storage, ±X (Eq. 3) modeled. Helmet color had a functionally significant effect on brain temperature, T_{br} (°C) during 120-minutes of training or competition in dangerously hot environmental conditions (WBGT 34.3 ± 1.1 ACSM Heat-Index Black; Extreme Danger) [9]. Football players wearing black helmets (black circles and black solid lines; 95% CI black dashed lines) or red helmets (red circles and red solid line; 95% CI red dashed lines) may experience the onset of increases in brain temperature, T_{br} ∽38 °C (°C) characteristic of neural disfunction and cerebral histopathy (NDCH; light-grey shaded area) and T_{br} ∽40 °C characteristic of exertional heat stroke (SH; dark grey shaded area) earlier than players wearing white helmets (white circles and solid line; 95% CI black dotted lines). Linear equations describing the positive increase in T_{br} (and 95% CI) with elapse time are listed in Appendix III

Exertional heat storage model

The exertional heat storage model, ±X (Eqs. 1 and 3; Fig. 2), estimates the differences in time required for youth football players who are wearing different colored helmets (Table 1), to experience the onset of elevated T_{br} characteristic of EHIs during training and competition in dangerously hot environmental conditions. Equation 3 (Eq. 3) describes the basic heat storage relationship [14], as applied to brain tissues rather than core body tissues,

$$X = 3630 * (dT_{br}/\mathrm{d}t) * mb. \tag{3}$$

Here, 3630 J.kg^{-1}°C^{-1} is the specific heat of brain tissue [1], dT_{br} (°C) is the estimated change in T_{br} recorded in 5-minute intervals, dt (s) is the duration of the event measured in seconds (s), and m_b is ∽25% of estimated brain mass of a 12- to 14-year-old players. The m_b of a 12- to 14-year-old players with a mean body mass of ∽45.8 ± 5.2 kg was estimated based on the allometric equation, $m_b = 0.085 * M_b^{0.66}$ [15]. To estimate the change in brain temperature, T_{br} (°C) resulting from helmet color and differential α_1 (Table 1), we rearranged Eq. 3 to solve for dT_{br}, where dT_{br} = (X *dt)/(3630* m_b) [10].

The exertional heat storage model makes the following four assumptions. Firstly, the duration of training or competition was 120-minutes. Secondly, players started the with a T_{br} of 37 °C. Thirdly, the low α_1 (Table 1) and approximately neutral mean-Q_n of the white helmet (Fig. 1) allows its use as a negative control to estimate minimum dT_{br} resulting from +X (Fig. 2; Eq. 3). Fourthly, a T_{br} of ∽38 °C for a duration of 30- to 60-minutes can cause neurological dysfunction and cerebral histopathology (NDCH; i.e., moderate EHI), and a similarly sustained increase in T_{br} of ∽40 °C can cause register cerebral hyperthermia characteristic of exertional heat stroke EHS (i.e., severe EHI) [16–23].

Data analyses

Data analyses and graphing was performed using KaleidaGraph 4.5 (Synergy Software, Reading, PA. USA). Data is available on request.

Results

Net-radiant heat transfer model

Measurements of T_{is} recorded in controlled laboratory conditions (ambient air temperature, $T_a \backsim 24$ °C; at $t = -5$ min; Table 2), were less than T_{sc} of 34.9 °C (Eq. 2). Similarity in mean-Q_n, between the white, red, and black helmets, of $\backsim 0.49 \pm 0.02$, 0.54 ± 0.05, and 0.53 ± 0.01, respectively, indicated net-radiant heat loss from the scalp surface regardless of color. Conversely, during the outdoor trials [9], high α_1 (Table 1) caused mean-T_{is} of black and red helmets (Table 2) to be $\backsim 15.7 \pm 3.0$ and 16.5 ± 4.0 °C greater than T_{sc}, respectively (Eq. 2). Because of the large temperature gradient between T_{ia} and T_{sc}, mean-Q_n of the red and black helmets, of -1.14 ± 0.17 W and -1.27 ± 0.15 W, respectively, ranged from $\backsim 7.8$ to 8.7-times greater than the mean-Q_n recorded in the white helmet (Fig. 1). The high α_1 of red and black football helmets caused a net-radiant heat gain at the scalp surface (Fig. 1), which may affect T_{br}. However, the low α_1 of the white helmet (Table 1) caused mean T_{is} (Table 2) to remain within 1.4 ± 3.0 °C of T_{sc} (Eq. 2) throughout outdoor trials [9]. The small temperature gradient between T_{is} (Table 2) and T_{sc} resulted in mean-Q_n of -0.086 ± 0.17 W, which remained close to thermal neutrality ($\backsim 0$ W; Fig. 1). Therefore, the low α_1 of the white football helmet buffered heat gain at the scalp surface (Fig. 1) and may facilitate heat loss.

Exertional heat storage model

Based on reduced thermal energy budget (Eq. 1; $\pm Q_a \approx \pm X$) a portion of the difference in mean-Q_n between red and white, and black and white helmets, of -0.77 ± 0.21 and -0.96 ± 0.11 W, respectively, will be stored in brain tissues throughout the duration of the event. Youth football players wearing black or red helmets may experience the onset of elevated T_{br} characteristic of NDCH and EHS (Fig. 2) more rapidly than players wearing white helmets (Fig. 2). For example, players wearing black helmets might experience the onset of T_{br} characteristic of NDCH in $\backsim 12$ to 18 min and EHS in $\backsim 35$ to 56 min (Fig. 2). Similarly, players wearing red helmets might experience the onset of T_{br} characteristic of NDCH in $\backsim 14$ to 30 min and ESH in $\backsim 38$ to 56 min (Fig. 2). Because of the early onset of EHI, players wearing black or red helmets are at a greater risk of morbidity and mortality from NDCH and EHS in a dangerously hot environment. On the contrary, players wearing white helmets might experience the onset of T_{br} characteristic of NDCH in $\backsim 48$ min but would not be at risk of mortality from ESH for the duration of the practice or competition lasting 120-minutes (Fig. 2).

Discussion

The results strongly suggested that the combination of statistically significant ($p \leq 0.03$) differences in α_1 (Table 1) and T_{is} (Table 2), between white, red, and black youth football helmets (Table 1) may cause biologically significant thermoregulatory challenges for youth football players (Figs. 1 and 2). Although speculative, when compared to white helmets, greater α_1 (Table 1), hotter T_{is} (Table 2) and the 7.8 to 8.7-times greater (negative) mean-Q_n (Fig. 1) of red and black helmets has the potential to cause a rapid rate of heat storage and the early onset of elevated T_{br}, characteristic of moderate to severe EHI (Fig. 2).

The reduced thermal energy budget assumes that evaporative water loss, E is $\backsim 0$ W. However, like heat storage (Eqs. 1 and 3; Fig. 2) players wearing red or black helmets may have greater sweating rates from the scalp than players wearing white helmets. Differential sweating rates were estimated during 120-minutes of training or competition by assuming a sweating rate $\backsim$ equivalent to the difference in mean-Q_n between red, black and white helmets (Figs. 1 and 2), the latent heat of vaporization of water ($\backsim 2420$ J.g^{-1}) and assuming an equal sweating rate across the total surface area of the head (Table 1). Players wearing red or black helmets might lose water via sweat from the head at a rate $\backsim 2.0$ g.min^{-1} to $\backsim 13$ g.min^{-1} greater than players wearing white helmets. Therefore, players wearing red or black helmets may also be more susceptible to dehydration (i.e., mild EHI) than those wearing white helmets.

Most EHI occur in preseason training lasting greater than one-hour when environmental conditions are hot and players are less conditioned [16, 18, 19, 22, 23]. Some players are more susceptible to EHI than others. For example, poorly hydrated large players offensive and defensive linemen characterized by high body mass index (BMI > 30) are more likely to experience EHI than smaller players [16, 23]. Although speculative, differential rates of heat storage in brain tissues (Eq. 3; Fig. 2) and/ or increased sweating rate may make larger players wearing helmets characterized by high α_1 (Table 1) may be more susceptible to EHI. In closing, susceptibility to EHI results from a complex combination of behavioral choices (hydration), interindividual anatomical and physiological variations (body size and composition), and helmet color and α_1 may influence heat storage in the brain and the onset of EHI (Fig. 2).

Conclusions

1. Football helmet color and α_1 (Table 1) influences heating of the helmet shell.

2. Rapid heating of the helmet shell (Table 2) may influence radiant heating of the scalp surface (Fig. 1).
3. Helmets characterized by high α_1 may cause a greater rate heat storage in brain tissues and the early onset of EHI (Fig. 2).
4. White helmets characterized by low α_1 may reduce the risk of EHI (Fig. 2).

Appendix I

Atmospheric electromagnetic radiation	Wavelength, λ (nm)
Solar Radiation, S	≈300– 4000*
Visible Light	≈ 400– 700
Near Infrared	≈ 700– 2500*
Terrestrial Thermal Radiation, R_a	≈ 4000– 106*‡

Approximate wavelengths, λ (nm), of solar, S and terrestrial thermal radiation, R_a [1]

Appendix II

Variable	Helmet	Second-order polynomial	R
Q_n (W)	White	$y=2.92\times10^{-7}\,t^2-0.000698t+0.21$	0.91
	Red	$y=4.37\times10^{-7}\,t^2-0.0013t-0.13$	0.91
	Black	$y=5.47\times10^{-7}\,t^2-0.0015t-0.18$	0.95

Second-order polynomial equations describing the relationship between net-radiant heat transfer, Q_n (W) and increasing elapse time, t (s) in white, red, and black football helmets (Fig. 1)

Appendix III

Variable	Helmet color	Line	Linear equations	R
T_{br} (°C)	White	Upper-Limit	$y=0.021\,t+37$	1
		Mean	$y=0.0103\,t+37$	1
		Lower-Limit	$y=9.3\times10^{-5}t+37$	1
	Red	Upper-Limit	$y=0.077\,t+37$	1
		Mean	$y=0.055\,t+37$	1
		Lower-Limit	$y=0.033\,t+37$	1
	Black	Upper-Limit	$y=0.085\,t+37$	1
		Mean	$y=0.069\,t+37$	1
		Lower-Limit	$y=0.054\,t+37$	1

Linear equations describing the increase in T_{br} (°C) with increasing elapse time, t (s) in white, red, and black football helmets (Fig. 2)

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Author contributions MFR. was the principal investigator who designed the study, oversaw data collection and analyses and was the lead authored the paper.
TLD. collected and analyzed data in the 2022 [9] and current study and cowrote a portion of discussion section.
DNOT. collected and analyzed data in the current study and cowrote a portion of results and discussion section.
DFD. oversaw data integrity and management and helped design and write the heat storage model.
BPJ. conducted laboratory measurements of evaporative water loss and wrote a portion of methods and materials, and discussion section.
AMC. conducted laboratory measurements of helmet and head model (Table 1) and wrote a portion of introduction and methods and materials.

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Data availability Data is available from the corresponding author upon request.

Declarations

Competing interests On behalf of all authors, the corresponding author states that there are no competing interests.

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