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Heat transfer analyses of older versus modern youth football helmets: A preliminary study

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Abstract

Exertional heat injuries (EHIs) are common in American youth football players. Modifications to the polycarbonate shells of helmets and memory foam padding have focused on reducing traumatic brain injuries (TBIs), experienced by players during helmet-to-helmet collisions. No study has compared the effects of modification to helmets design on the external and internal shell temperatures, T_{es} and T_{is} (°C), respectively. We simultaneously tested two hypotheses. (1) Do older and modern youth football helmets show statistically significant ($p<0.05$) differences in T_{es} (°C) and T_{is} (°C) during exposure to hot and humid outdoor environmental conditions. Secondly, do variations in helmet color (and solar absorptance, α_1) have a statistically significant ($p<0.05$) effect on T_{es} (°C) and T_{is} (°C). To test these hypotheses, we obtained three older model Schutt® youth football helmets (black, red, and white in color) and three new Riddell® Victor youth helmets of the same colors. We used a combination of infrared field thermometers and micro-metrology equipment to test these hypotheses. There was no statistically significant ($p<0.05$) in T_{es} (°C) and T_{is} (°C) among pairs of helmets with the same color. At the end of the 35-min trials, T_{is} of red and black helmets were ~ 15 to 22 °C hotter than white helmets. Helmet color and α_1 may play a functionally significant role in EHIs.

Abbreviations

α_1	Absorptance of solar radiation (%)
α_2	Absorptance of near-Earth thermal radiation (%)
ε	Emissivity (%)
EHIs	Exertional heat injuries
λ	Wavelength (nm)
Q_a	Atmospheric radian environmental heat gain (W m^{-2})
R_a	Atmospheric near-Earth thermal radiation (W m^{-2})
S_n	Direct solar radiation normal to the helmet shell surface (W m^{-2})
s	Diffuse solar radiation scattered by clouds and atmospheric particles (W m^{-2})
T_b	Core body temperature (°C)
TBIs	Traumatic brain injuries
T_{es}	Temperature of the external helmet shell surface (°C)
T_{is}	Temperature of the internal helmet shell surface (°C)
T_{ty}	Tympanic temperature (°C)

Introduction

Youth athletes (between the ages of 7 and 14 years of age) make up ~ 70% of the total number of (> 5-million) American football players [1, 2]. They commonly experience helmet-to-helmet impacts that result in mild to potentially fatal traumatic brain injuries (TBIs) [3–5]. Unsurprisingly, considerable research has been directed towards modifications to the design of football helmets that reduce TBIs [6–8]. Similarly, youth football athletes also common experience mild to potentially fatal exertional heat injuries (EHIs) [9–11]. No published data are available comparing the thermal characteristics of older versus modern youth football helmets. In this pilot study, we quantified and compared the physical and spectral characteristics of older *versus* modern youth football helmets (Table 1). We then measured and recorded the effect of variations in the characteristics that influence external and internal helmet shell surface temperatures, T_{es} (°C; Fig. 1A–C) and T_{is} (°C; Fig. 2A–C), during

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Table 1 Physical and spectral characteristics of youth football helmets that may influence heat transfer and thermoregulation

Brand	Size	Older/modern	Color/finish	Mean (±SD) Solar absorptance, α_1 (%; $n=4$)	Emissivity (ε)	Mean (±SD) Shell thickness (~mm; $n=4$)	Ventilation (mm^2; $n=4$)
Schutt	L	Older	White/gloss	$0.43 \pm 0.02^{\dagger}$	0.95	5.2 ± 0.10	2331 ± 241
Schutt	L	Older	Red/gloss	$0.64 \pm 0.04^{\dagger}$	0.95	5.2 ± 0.10	2331 ± 241
Schutt	L	Older	Black/gloss	$0.89 \pm 0.02^{\dagger}$	0.95	5.2 ± 0.10	1567 ± 67
Riddell	L	Modern	White/matt	$0.44 \pm 0.03^{\dagger}$	0.95	4.8 ± 0.10	4787 ± 205*
Riddell	L	Modern	Red/ matt	$0.61 \pm 0.07^{\dagger}$	0.95	4.8 ± 0.10	4787 ± 205*
Riddell	L	Modern	Black/matt	$0.92 \pm 0.02^{\dagger}$	0.95	4.8 ± 0.10	4787 ± 205*

The asterisk (*) indicates statistically significant ($p < 0.05$) differences between older and modern football helmets of the same color. The dagger (†) indicates statistically significant ($p < 0.05$) differences in solar absorptance, α_1 (%) between helmets of different color

exposure to hot and humid outdoor environmental conditions (Table 2).

Football helmets influence thermoregulation. The additional weight of football helmets increases metabolic heat production, and the helmet shell and memory foam padding constrain heat loss from the head, and may contribute to EHIs [12]. Controlled lab studies (using artificial lighting) showed that variations in helmet design influenced atmospheric radiant environmental heat gain, Q_a (W m^{-2}) and differentially influenced heat storage in core body tissues, as evidenced by an increase in core body temperature, and tympanic temperature, T_b and T_{ty} (°C), respectively [13, 14]. However, lab experiments may not fully reflect heat transfers in outdoor environments. For example, artificial lighting often has an excess of near infrared wavelengths ($\lambda \sim 750$ to 3000 nm) and reduced amplitude of some solar wavelengths ($\lambda \sim 300$ to 750 nm) [15]. No peer-reviewed publish data are available describing the effect of the physical characteristics (such as helmet color) or spectral characteristics (such as solar absorptance, α_1; Table 1) on T_{es} and T_{is} (°C) during exposure to dangerously hot and humid environmental conditions (Table 2).

In an outdoor environment, Q_a results from two modes of electromagnetic radiation, each with a characteristic range of wavelengths, λ (nm). Firstly, global solar radiation, $S_n + s$ (W m^{-2}), the combined effect of direct solar radiation striking a surface, normal to the sun's rays, S_n, and diffuse solar radiation, s, scattered by clouds and atmospheric dust particles [15]. Secondly, the downward stream of atmospheric near-Earth terrestrial thermal radiation, R_a ($\lambda \sim 3000$ to 10^6 nm) [15]. Equation 1 from Gates (1980) provides an estimate of the rate Q_a from the sky is absorbed by the outer surface of biological and non-living materials when α_1 (%) is the absorptance of $S_n + s$ and α_2 (%) is the absorptance of R_a,

$$Q_a = \alpha_1 \left(S_n + s\right) + \alpha_2 \left(R_a\right). \tag{1}$$

At biologically relevant temperatures and over peak λ, the range of α_2 is narrow (from ~ 0.94 to 0.99) and can be approximated by 0.96 for most non-reflective surfaces. Therefore, variations in α_1 of different colored youth football helmets (Table 1) may differentially effect T_{es} and T_{is} (°C).

In this preliminary study, we simultaneously tested two hypotheses. Firstly, do older and modern youth football helmets show statistically significant ($p < 0.05$) differences in T_{es} (°C; Fig. 1A–C) and T_{is} (°C Fig. 2A–C) during exposure to dangerously hot environmental conditions (Table 2). Secondly, do variation in helmet color (and α_1; Table 1) have a statistically significant ($p < 0.05$) effect on T_{es} (°C; Fig. 1A–C) and T_{is} (°C Fig. 2A–C). To test these two hypotheses, we measure and record T_{es} (°C) and T_{is} (°C), in three (white, red, and black) older model Schutt® youth football helmets and three (white, red, and black) modern Riddell Victor® youth football helmets using infrared field thermometers. In conclusion, we discuss our results in relationship to future research to model the effect of differential internal helmet air temperature, T_{ai} (°C) on evaporative water loss (i.e., dehydration) from the head and heat storage in brain tissue.

Methods and materials

Helmets

Three used Schutt® youth football helmets were purchased online. Use of Schutt® helmets was based strictly on availability. Three new Riddell Victor® youth football helmets were purchased directly from the manufacturer.

Instrumentation and experimental procedures

The physical characteristics of the helmets (Table 1), such as the area of the ventilation ports were determined mathematically. The spectral characteristics of the helmets (i.e., α_1; Table 1) were determined in the field using a Swissteco® micro-solarimeter (Hawthorn. Vic. 3123 Australia) and the techniques developed by Hutchinson et al. [16]. These

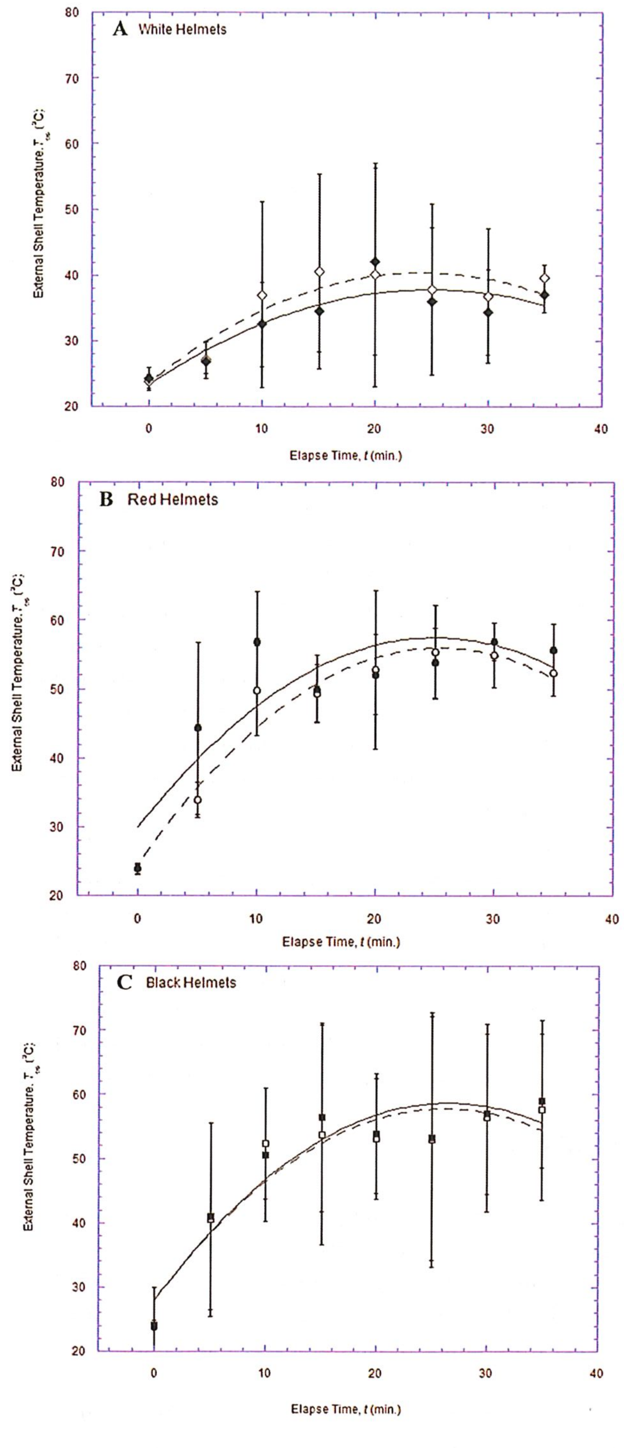

Fig. 1 The positive curvilinear relationship between mean (±SD) external helmet shell temperature, T_{es} (°C), and elapse time, t (min.), for **A** older white helmets (open diamonds [◊] and dashed line and for modern white helmets (solid diamonds [◆] and solid line; for **B** red (older helmets open circles [○] and dashed line and modern red helmets solid circles [●] and solid lines, and for **C** older black helmets open squares [□] and dashed line and modern black helmets solid squares [■] and solid lines. Second-order polynomial equations describing the positive increase in T_{es} (°C) with increasing t (min.) in older and modern youth football helmets are listed in Appendix 2

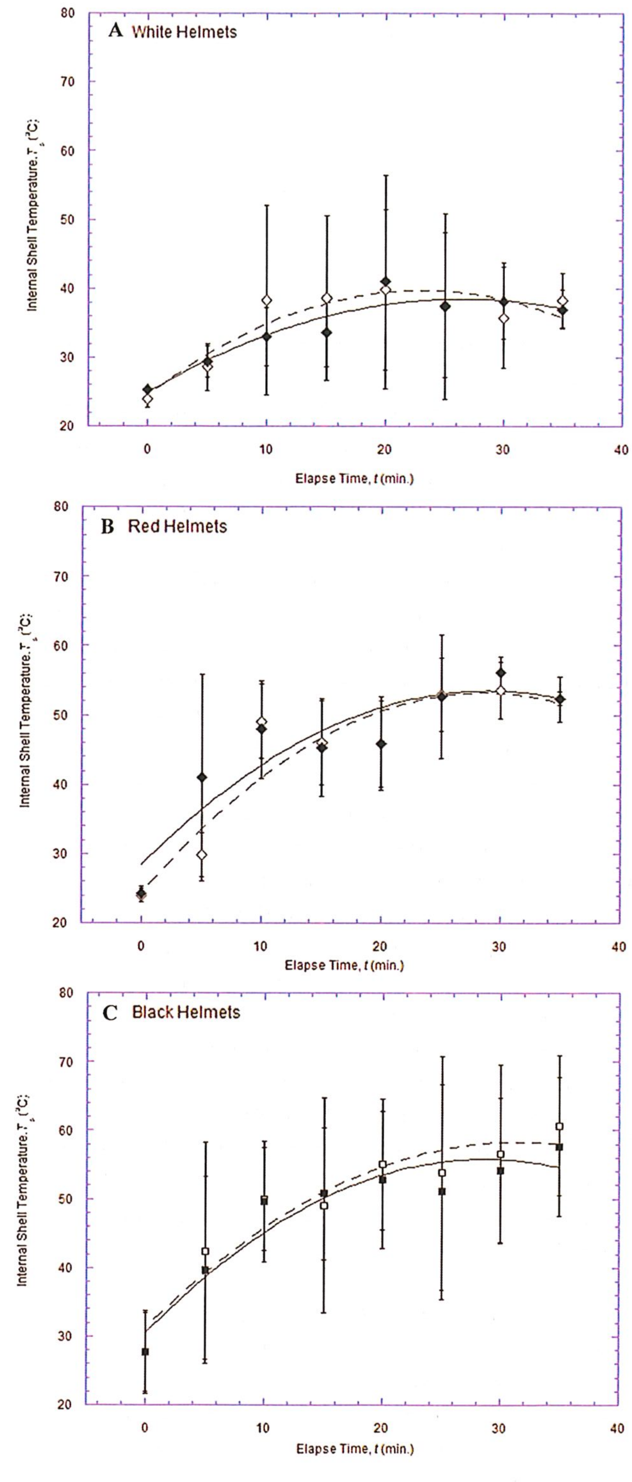

Fig. 2 The positive curvilinear relationship between mean (±SD) internal helmet shell temperature, T_{is} (°C), and elapse time, t (min.), for **A** older white helmets (open diamonds [◊] and dashed line and for modern white helmets (solid diamonds [◆] and solid line; for **B** red (older helmets open circles [○] and dashed line and modern red helmets solid circles [●] and solid lines, and for **C** older black helmets open squares [□] and dashed line and modern black helmets solid squares [■] and solid lines. Second-order polynomial equations describing the positive increase in T_{is} (°C) with increasing t (min.) in older and modern youth football helmets are listed in Appendix 2

Table 2 Mean (±SD) environmental conditions measured and recorded during a total of ($n=9$) experimental trials to quantify external and internal helmet shell temperatures, T_{es} (°C) and T_{is} (°C), respectively

Helmet color	Trials ($n=$)	Ambient air temp. (°C)	Relative humidity (%)	Wind speed (m s^{-1})	Globe temp. (°C)	WBGT (°C)	ACSM heat index
White	3	32.3±0.6	70.5±2.8	0.70±0.33	44.2±4.5	33.0±2.3	Black extreme danger STOP
Red	3	33.9±1.4	70.8±1.3	0.69±0.32	48.5±0.5	35.1±0.3	Black extreme danger STOP
Black	3	33.7±1.6	69.3±5.1	1.00±0.33	47.3±2.3	34.7±0.6	Black extreme danger STOP

procedures have previously been used by the PI to determine α_1 in biological and non-biological materials [17–19]. Emissivity (ε) of plastics generally ranges from 0.90 to 0.97 (https://www.engineeringtoolbox.com/). However, colors and surface characteristics can influence ε. We used the modern matt black Riddell® helmet (with no dings or scuff marks) to test ε in laboratory conditions. Two fast-responding (type-K) thermocouples attached to a COMARK N9002 (COMARK, Hitchin, UK) thermocouple thermometer were used to measure T_{es} (°C). Prior to measurements the thermocouples were calibrated with mercury thermometer in ice water and boiling water. Differences between the thermocouples and mercury thermometer were ≤0.2 °C. The thermocouples (separated by a distance of ~ 10 cm) were secured to the anterior surface of the helmet with electrical tape. The T_{es} (°C) between the two thermocouples was measured and recorded using a Digi-Sense™ Precalibrated Professional infrared thermometer (Fisher Scientific; Walthman, MA, USA). Emissivity was systematically changed from $\varepsilon \sim 0.88$ to 1.0 until T_{es} and thermocouple temperature was equal. This procedure was repeated for all helmets. It should be noted that dings, scuff marks, and general wear and tear of the external shell of the older model Schutt® helmets may have influenced measurements of ε. For all helmets, varying ε between 0.94 and 0.96 produced differences between T_{es} and thermocouple temperature that were < 0.5 °C. Therefore, ε of 0.95 (Table 1) was used for all measurements with the Digi-Sense™ Precalibrated Professional infrared thermometer.

Measurements of T_{es} (°C; Fig. 1A–C) and *T*is (°C; Fig. 2A–C) were recorded (between ~ June 15 to July 20) on open grassy terrain on the front lawn of Dillard University, in New Orleans, Louisiana, USA. The experimental trials were conducted in full sun exposure ~ 30 to 50 m from any structures. This location provided adequate replication of environmental conditions experienced by youth football players on a natural grass playing field. Environmental conditions (Table 2) at approximate mid-head height (150 cm) were measured and recorded using a Kestrel 5400 Heat Stress Tracker Pro (Boothwyn, PA. USA) mounted on a tripod. The Kestrel 5400 was programmed to the American College of Sports Medicine (ACSM) Wet Bulb Glob Temperature Index Guidelines for practice and competition. ACSM WBGT Heat-Index thresholds are as follows: "Green" ≤22.2 °C, normal activity; "Yellow" 22.3–27.7 °C, monitor fluid intake; "Red" 27.8–30.1 °C, limit intense exercise; "Black" ≥ 32.2 °C, extreme danger stops exercise or competition.

As a control, helmets were housed in the lab inside insulated ice chests prior to the start of each experimental trial. Experimental trials consisted of concurrent measurements of T_{es} (°C; Fig. 1A–C) and *T*is (°C; Fig. 2A–C) using older versus modern helmets of the same color. At the start of each experimental trial, helmets were placed on a plastic shelf with the center point of the helmet at ~ 150 cm, approximate height of a 12-year-old boy. The posterior helmet surface was aligned with the solar azimuth angle using the online NOAA solar position calculator https://gml.noaa.gov/grad/solcalc/azel.html. T_{es} (°C; Fig. 1A–C) and *T*is (°C; Fig. 2A–C) of the helmets were measured and recorded using the previously described Digi-Sense™ Precalibrated Professional infrared thermometer. Measurements of T_{es} (°C) and T_{is} (°C) on the superior/anterior surface of the helmets were made an at distance of ~ 2.5 m. For improved access to the interior shell surface, memory foam padding was removed from the helmets prior to measurements of T_{is} (°C) (Fig. 2A–C).

Data and statistical analyses

Graphing and statistical analyses were carried out using KaleidaGraph 4.5 (Synergy Software, Reading, PA. USA). Data are available on request. One-Way ANOVA at the ($p < 0.05$) level was used to determine whether statistically significant differences in α_1 and area of ventilation ports (Table 1). Similarly, A paired student's *t* test at the ($p < 0.05$) level was used to determine whether statistically significant differences in T_{es} (°C) and T_{is} (°C) existed between pairs of similarly colored helmets (Figs. 1A–C. and 2A–C). A paired student's *t* test at the ($p < 0.05$) level was used to determine whether statistically significant differences in the thickness of the polycarbonate helmet shells existed between older and modern football helmets (Table 1). One-Way ANOVA was used to test for statistical significance differences in environmental variables between experimental trials (Table 2), and between helmets of different color (Figs. 1A–C. and 2A–C).

Results

Characteristics of football helmets

Helmet color had a statistically significant (One-Way ANOVA; DF = 5; $p < 0.001$) effect on α_1 of the outer shell. The external shell of black helmets absorbed ≥ 89% incident solar radiation (Table 1), a fraction ~ 1.4- to 2.0-time greater than the α_1 of red (~ 61% to 64%) and white helmets (~ 43.5%), respectively. There was no statistically significant (One-Way ANOVA; DF = 5; $p < 0.002$) difference in α_1 between older and modern helmets of the same color (Table 1).

There was no statistically significant (paired students t test; DF = 6; $p = 0.53$) difference in polycarbonate shell thickness between older and modern youth football helmets (Table 1). However, the area of the ventilation ports in modern helmets were statistically significantly (student's t-test; DF = 5; $p < 0.001$), ~ 2.1 to 3.1 times greater than the area of the ports of older helmets (Table 1).

Environmental conditions

There were no statistically significant (One-way ANOVA; DF = 2; $p > 0.05$) differences in any environmental variables that influence heat transfers in helmets of different colors (Table 2). Those environmental variables include, ambient air temperature, T_a (°C), relative humidity, RH (%), globe temperature, T_g (°C), wind speed, v_f, (m s^{-1}), and wet-bulb globe temperature, WBGT (°C). All experimental trials were conducted during environmental conditions characterized by the ACSM WBGT Heat Index as extremely dangerous (Table 2).

Temperature of the external helmet shells

Measurements of mean (± SD) T_{es} (°C) recorded in the controlled laboratory conditions varied by < 0.5 °C among helmets of the same color and between different colored helmets (Fig. 1A–C). Differences in mean T_{es} (°C) among similarly colored helmets and between different colored helmets were not statistically significant (One-Way ANOVA; DF = 5; $p = 0.99$).

Following exposure to hot outdoor Q_a (Eq. 1; Table 2), mean T_{es} (°C) of similarly colored helmets increased in a comparable fashion (Fig. 1A–C). At the end of the experimental trials (lasting 35-min in duration) mean T_{es} (°C) of similarly colored helmets differed by < 3.5 °C (Fig. 1A–C). The small differences in T_{es} (°C) between similarly colored older and modern helmets may have been influenced by the glossy finish, scuff marks, and general wear of the external shell surface of older helmets. On the contrary, mean T_{es} (°C) of pairs of white helmets increased at a slower rate than pairs of red and black helmets (Fig. 1A–C). At the end of experimental trials, mean T_{es} (°C) of pairs of white helmets (~ 38.4 ± 2.2 °C) were ~ 16 to 20 °C cooler than T_{es} (°C) red (~ 54.0 ± 3.3 °C) and black helmets (~ 58.3 ± 10.2 °C), respectively (Fig. 1A–C).

Temperature of the internal helmet shell

Measurements of mean (± SD) T_{is} (°C) recorded in controlled laboratory conditions varied by < 1.2 °C among helmets of the same color and < 1.3 °C between different colored helmets (Fig. 2A–C). Differences in mean T_{is} (°C) recorded in the laboratory among helmets of the same color were not statistically significant (student's t test; DF = 2; $p > 0.20$). Differences in mean T_{is} (°C) between helmets of different color were not statistically significant (One-Way ANOVA; DF = 5; $p = 0.67$).

Following exposure to hot outdoor Q_a (Eq. 1; Table 2), mean T_{is} (°C) of similarly colored helmets increased in a comparable fashion (Fig. 2A–C). At the end of the experimental trials mean T_{is} (°C) among red, and white helmets differed by 0.13 and 1.3 °C, respectively (Fig. 2A–C). There was no statistically significant (student's t test; DF = 2; $p > 0.35$) difference in mean T_{is} (°C) among pairs of older and modern white and red helmets (Fig. 2A, B). However, the 3.2 °C difference between the mean T_{is} (°C) of older and modernblack helmets was statistically significant (student's t-test; DF = 2; $p < 0.008$).

On the contrary, mean T_{is} (°C) of pairs of white helmets increased at a slower rate than pairs of red and black helmets (Fig. 2A–C). At the end of experimental trials, mean T_{is} (°C) of white helmets (~ 37.6 ± 3.1 °C) were ~ 15 to 22 °C cooler than mean T_{is} of red (~ 52.4 ± 2.0 °C) and black helmets (~ 59.1 ± 10 °C), respectively (Fig. 2A–C). At the end of the experimental trials, the mean T_{is} (°C) between different colored helmets were statistically significant (One-Way ANOVA; DF = 5; $p < 0.03$).

Discussion

The shells of similarly colored older and modern football helmets showed similar T_{es} (Fig. 1A–C) and T_{is} (Fig. 2A–C). It is unlikely that modifications to polycarbonate plastics shells of football helmets to reduce TBIs have not affected EHIs in youth football athletes.

This is the first study to conclusively demonstrate that helmet color and the associated differences in α_1 (Table 1) have had a statistically and functionally significant effect on T_{es} (Fig. 1A–C) and T_{is} (Fig. 2A–C). Further studies are required to quantify and describe the effects of variations in α_1 on T_{is} (°C) on radiant heat transfers between the scalp surface and the interior of football helmets. For example, assuming a scalp temperature of ~ 35 °C, the temperature differentials between the scalp and T_{is} (°C) of white, red, and black helmets would be ~ 2.6, 17.4, and 24 °C, respectively. These variations are likely to influence radiant heat gain in the heads of youth football athletes.

The majority of EHI mortalities in football players occurs in the southeastern USA [11]. In the southeastern USA, $S_n + s$ is often ≈ 2.1 times greater than R_a during midday [19]. Although speculative, helmet color and α_1 may play a role in EHIs in youth football players. In addition, high (absolute) humidity (~ 16.5 g m^{-3}) reduces the effectiveness of evaporative heat loss [11, 15]. However, absolute humidity (https://www.omnicalculator.com/) recorded during the present study (~ 25.5 g m^{-3}) was ~ 1.5 times greater than environmental conditions known to cause EHIs. The combination of increased radiant heat gain in black and red helmets, and reduced ability to dissipate heat from the head via evaporative heat loss may influence EHIs. Most EHIs occur in the first weeks of preseason training. The use of white helmets may reduce Q_a and heating of the interior helmet air temperature, T_{ai} (°C).

In the fall of 2022, we will begin a study to quantify and describe the effect of helmet color and α_1 on T_{ai}. In this study, we will model the potential effect of differential T_{ai} on evaporative water loss from the scalp and heat storage in brain tissues. Through this research, we ultimately hope to improve helmet design and reduce or eliminate EHIs in youth football athletes.

Appendix 1

See Abbreviations.

Appendix 2

Second-order polynomial equations describing the increase in T_{es} (°C; Fig. 1A–C) and T_{is} (°C; Fig. 2A–C) with increasing elapse time, *t* (min.).

Variable	Vintage	Helmet color	Second-order polynomial equations	R^2
T_{es} (°C)	Older	White	$y = -0.029x^2 + 1.39x + 23.6$	0.86
	Modern	White	$y = -0.023x^2 + 1.17x + 23.3$	0.82
	Older	Red	$y = -0.049x^2 + 2.49x + 24.5$	0.96
	Modern	Red	$y = -0.044x^2 + 2.20x + 30.0$	0.79
	Older	Black	$y = -0.043x^2 + 2.27x + 28.1$	0.94
	Modern	Black	$y = -0.044x^2 + 2.31x + 28.0$	0.95
T_{is} (°C)	Older	White	$y = -0.028x^2 + 1.31x + 24.6$	0.92
	Modern	White	$y = -0.019x^2 + 1.03x + 24.9$	0.95
	Older	Red	$y = -0.035x^2 + 2.01x + 24.4$	0.94
	Modern	Red	$y = -0.030x^2 + 1.72x + 28.5$	0.92
	Older	Black	$y = -0.027x^2 + 1.72x + 31.3$	0.95
	Modern	Black	$y = -0.031x^2 + 1.76x + 30.5$	0.95

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there are no conflicts of interest.

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