Appendix A.1 - Methods - *Heat flux calculations*

Total heat exchange is the sum of radiative (Q_{rad}) and convective (Q_{conv}) heat transfer.

$$q_{tot} = q_{conv} + q_{rad} \quad [1]$$

Q_{rad} can be calculated for each bird at a given T_{air}, with the following equation from McCafferty et al., (2011):

$$q_{rad} = \varepsilon \sigma A(T_{s^4} - T_{a^4})$$

[2]

Where A is the body part surface area in m^2, σ is the Stefan-Boltzmann constant (5.67 $x10^{-8}$ Wm^{-2} $°K^{-1}$), ε is the emissivity (0.97), T_s is the body part's radiative surface temperature in °K and T_a is the air temperature in °K. Q_{onv} can be calculated for each bird at a given T_{air} with the following equation:

$$q_{conv} = Ah_c\left(T_s - T_a\right) \quad [3]$$

Where T_s is the body part surface temperature (°C), T_a is the air temperature (°C) and h_c is the forced convective heat transfer coefficient (W m^{-2} $°C^{-1}$) that is calculated as follows:

$$h_c = Nu\frac{k}{d} \quad [4]$$

k represents the thermal conductivity of air that calculated per °C of T_{air} (e.g., 0.026 W m^{-1} at 20°C, using the formula k = 0.0241 + $7.5907e^{-6}*T_a$), the characteristic dimension of each body part is given by d (m) and *Nu* is the dimensionless Nusselt number. The Nusselt number is a measure of the ratio of buoyant to viscous forces and is dependent on the shape of the characteristic body part. In air with low wind speeds (<1 ms^{-1}), heat transfer occurs by forced convection and thus *Nu* is a function of the Reynoldt's number (Re) such that:

$$Nu = cRe^n$$

[5]

Where c = 0.174 and n = 0.618 for the bill and c = 0.34 and n = 0.6 for facial skin (Mitchell 1976). The Reynoldt's number is calculated as follows:

$$R_e = (V * D)/v$$

[6]

Where V is the air velocity (ms^{-1} - measured with T_{air} for every thermal image), and v is the kinematic viscosity of air at each particular T_{air} (i.e., v = -1.088e^{-5} + 8.85e^{-8}*T_a). D is the vertical critical dimension for each body part (m, as per equation [4]). The relationship between Nusselt and Reynoldt's numbers for simple geometrical shapes has already been determined (see Mitchell 1976; Paris et al., 2013). In the instance of hornbill's beaks and facial skin, the ratio of flat plates and cylinders were used to calculate the Nusselt number, i.e., $Nu = 0.60*R_e^{0.5}$ and $Nu = 0.89*R_e^{0.33}$, respectively (Monteith and Unsworth, 2013).

Conductive heat loss is measured using the temperature difference between the bird and any object it touches, however, during this study, birds were only in contact with a wooden perch via the feet. Therefore, conductive heat loss was ignored due to the low conductivity of wood (0.12 W m^{-2} °K^{-1}) and the small surface contact of the feet on the perch.

Unpublished data for vultures (J. Wessels, R. Kemp, M. T. Freeman and A.E. McKechnie)

Data were collected from 98 Cape vultures (CV; *Gyps coprotheres*), 6 lappet-faced vultures (LFV; *Torgos tracheliotos*) and 54 African white-backed vultures (AWV; *Gyps africanus*) between September 2021 and August 2022 at VulPro conservation centre (2542'40.1" S

2757’12.6” E) in the North West province of South Africa. Vultures were housed in large flight aviaries (6 - 9 m high, 6 - 9 m wide and 18 - 30 m long) that contained artificial cliff ledges and/or perches and 90% shade netting which covered most of the enclosures. The target areas of this study were the beaks of all three vulture species and the areas of the heads and necks of Cape vultures and lappet-faced vultures that are not covered with feathers. White-backed vultures were excluded in this case as their heads and necks are mostly feathered. Any areas with sparse feathers were not considered unfeathered regions. Data were collected over daily values ranging from of 10 - 35°C in the same method as that of the hornbill dataset of the present study. Heat loss calculations were identical to those used in the present study.

Appendix A.2: Figures and Tables

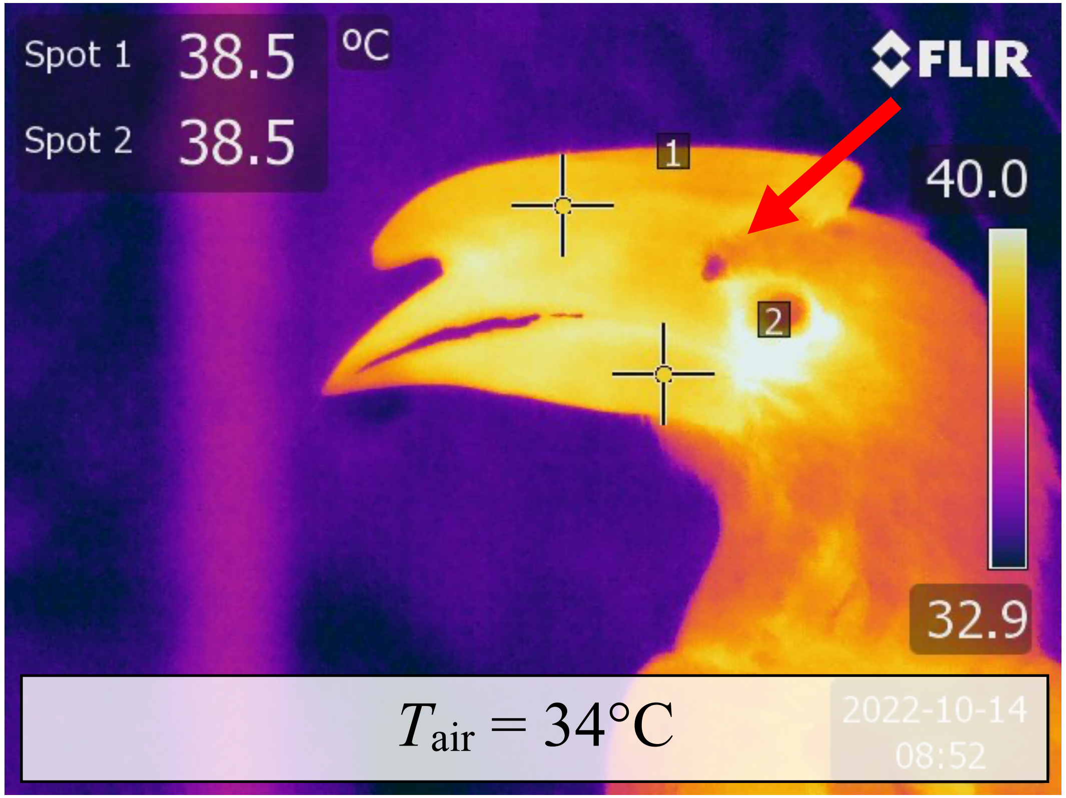

Fig. A1. An individual trumpeter hornbill (*Bycanistes bucinator)* at T_{air} = 34°C displaying signs of nasal secretions, indicated by the red arrow.

Table A.1. Tukey HSD post-hoc test comparing surface temperature values of the distal, proximal, upper, lower and casque sections of the beak for A) *Bycanistes bucinator*, B) *Bycanistes brevis* and C) *Ceratogymna atrata*. Significant difference is indicated by bold p-values ($p<0.05$). Upper and lower confidence limits (95%) of the honest significant difference (HSD) are provided.

	HSD	95% CI lower	95% CI upper	p-value
A				
Lower vs. casque	0.3357	-1.2768	1.9483	0.8765
Upper vs. casque	0.4176	-1.1949	2.0302	0.8156
Lower vs. upper	0.0819	-1.5307	1.6944	0.9921
Distal vs. Proximal	0.0524	-1.7823	1.9210	0.8987
B				
Lower vs. casque	0.2800	-2.0719	2.6320	0.9577
Upper vs. casque	0.2784	-2.0735	2.6304	0.9581
Lower vs. upper	-0.0016	-2.3535	2.3504	0.9999
Distal vs. Proximal	-0.1672	-2.1567	2.2321	0.8763
C				
Lower vs. casque	0.2815	-2.1855	2.7486	0.9607
Upper vs. casque	0.1584	-2.3086	2.6256	0.9873
Lower vs. upper	-0.1231	-2.5902	2.3440	0.9923
Distal vs. Proximal	-0.1584	-2.2097	1.8928	0.8788

Table A.2. The number of thermal images taken per species per 1°C in air temperature, with each data point representing one individual bird at a set point air temperature.

	Species (N)		
Air temperature (°C)	***Bycanistes bucinator***	***Bycanistes brevis***	***Ceratogymna atrata***
15	2	2	11
16	3	3	11
17	3	7	10
18	9	5	11
19	10	5	8
20	5	9	11
21	5	4	5
22	9	5	5
23	8	12	8
24	18	7	8
25	20	9	8
26	19	12	8
27	17	9	6
28	19	12	7
29	19	5	7
30	19	9	7
31	11	7	5
32	5	6	8
33	6	2	
34	2		
Total	**209**	**130**	**144**

Table A.3. Mean ± SD surface area (SA) measurements and body masses per sex for each species with number of individuals (n) in brackets.

Species	Beak SA (m^2)		Facial skin SA (m^2)		Average M_b (g)	
	M	F	M	F	M	F
Bycanistes bucinator	0.032 ± 0.004 (13)	0.016 ± 0.002 (10)	0.002 ± 0.001 (13)	0.001 ± 0.001 (10)	748 ± 103 (13)	580 ± 120 (10)
*Bycanistes brevis*ˣ	0.056 ± 0.005 (10)	0.026 ± 0.003 (8)	0.002 ± 0.001 (10)	0.002 ± 0.001 (8)	1265-1400	1050-1450
*Ceratogymna atrata**	0.057 ± 0.008 (4)	0.022 ± 0.005 (3)	0.004 ± 0.001 (4)	0.002 ± 0.001 (3)	1069-1600	907-1182

Note: Wattle SA measurements were not made available for *C. atrata* and as such, these values were not used to calculate heat loss. See Fig. 3 and Table A4. Body masses for *B. brevis and C. atrata* were not available for the individuals used in this study, masses were selected from Kemp & Kirwan (2020)* and Kemp & Boesman (2020)ˣ

Table A.4. Linear mixed effects model outputs for beak surface temperature for trumpeter hornbill (*Bycanistes bucinator,* TH), silvery-cheeked hornbill (*Bycanistes brevis*, SCH) and black-casqued hornbill (*Ceratogymna atrata,* BCH). Significant differences (p-value < 0.05) are indicated in bold.

Species	Variable	Slope	Std. Error	T-value	P-value
	Intercept	7.643	3.689	2.067	**0.040**
	T_{air}	2.201	0.555	3.965	**<0.001**
	Wind speed	-1.333	1.977	-0.674	0.501
TH	Humidity	-1.505	0.230	-6.555	**<0.001**
	Sex	-0.206	0.289	-0.713	0.477
	T_{air}:Humidity	-0.054	0.009	6.273	**<0.001**
	Intercept	-0.269	4.184	-0.064	0.949
	T_{air}	1.181	0.165	7.125	**<0.001**
SCH	Wind speed	-1.234	1.877	-0.873	0.977
	Humidity	-0.993	0.288	-3.439	**<0.001**
	Sex	0.055	0.360	0.154	0.878
	T_{air}:Humidity	0.037	0.011	3.395	**<0.001**
	Intercept	13.766	2.555	5.387	**<0.001**
	T_{air}	0.451	0.129	3.486	**<0.001**
BCH	Wind speed	-1.546	0.744	-0.911	0.855
	Humidity	-1.551	0.179	-8.671	**<0.001**
	Sex	0.515	0.252	2.049	0.061
	T_{air}:Humidity	0.067	0.007	9.004	**<0.001**

Table A.5. Linear mixed effects model outputs for facial skin temperature for trumpeter hornbill (*Bycanistes bucinator,* TH), silvery-cheeked hornbill (*Bycanistes brevis*, SCH) and black-casqued hornbill (*Ceratogymna atrata,* BCH). Significant differences (p-value < 0.05) are indicated in bold.

Species	Variable	Slope	Std. Error	T-value	P-value
	Intercept	15.712	2.911	5.396	**<0.001**
	T_{air}	0.844	0.117	7.210	**<0.001**
	Wind speed	-0.618	1.557	-0.397	0.692
TH	Humidity	0.086	0.181	0.476	0.635
	Sex	0.112	0.227	0.494	0.622
	T_{air}:Humidity	-0.002	0.007	-0.345	0.731
	Intercept	26.961	4.641	5.810	**<0.001**
	T_{air}	0.324	0.183	1.764	0.080
SCH	Wind speed	0.987	1.256	-0.433	0.874
	Humidity	-1.212	0.320	-3.783	**<0.001**
	Sex	0.223	0.399	0.557	0.578
	T_{air}:Humidity	0.452	0.012	3.673	**<0.001**
	Intercept	4.868	3.883	1.254	0.212
	T_{air}	1.446	0.197	7.345	**<0.001**
BCH	Wind speed	1.244	0.365	1.267	0.995
(facial)	Humidity	0.776	0.272	2.857	**0.005**
	Sex	-0.323	0.383	-0.846	0.399
	T_{air}:Humidity	-0.037	0.011	-3.256	**0.001**
	Intercept	6.811	4.202	1.621	0.108
	T_{air}	1.161	0.205	5.654	**<0.001**
	Wind speed	-0.765	0.823	1.659	0.458
BCH	Humidity	-0.462	0.271	-1.694	0.093
(wattle)	Sex	0.209	0.382	0.546	0.586
	T_{air}:Humidity	0.010	0.011	0.870	0.387

Table A.6. Mean minimum and maximum heat dissipation (W) as well as heat loss capacity as a proportion of allometrically predicted resting metabolic rate for trumpeter hornbills (*Bycanistes bucinator*), silvery-cheeked hornbills (*Bycanistes brevis*) and black-casqued hornbills (*Ceratogymna atrata*) per region (i.e., beak and facial skin). Values are shown as mean ± SD (n).

Species	Min. Heat loss (W)	Max. Heat loss (W)	Maximum heat loss as a % of resting metabolic rate
B. bucinator			
Beak	0.213 ± 0.18 (3)	3.482 ± 1.12 (12)	83.30 ± 23.45 (12)
Facial Skin	0.015 ± 0.18 (3)	0.574 ± 0.09 (12)	5.660 ± 1.02 (12)
B. brevis			
Beak	0.124 ± 0.10 (8)	4.750 ± 2.04 (7)	38.46 ± 16.52 (7)
Facial Skin	0.200 ± 0.05 (8)	0.345 ± 0.02 (7)	2.79 ± 0.17 (7)
*C. atrata**			
Beak	0.100 ± 0.06 (5)	4.500 ± 2.36 (5)	31.03 ± 19.11(5)
Facial skin	0.184 ± 0.12 (5)	0.446 ± 0.04 (5)	3.08 ± 0.28 (5)

*Note: Wattle SA measurements were not made available for *C. atrata* and as such, these values were not used to calculate heat loss.

Table A.7. Slope of heat loss (W °C^{-1}) as a function of air temperature for trumpeter hornbills (*Bycanistes bucinator*), silvery-cheeked hornbills (*Bycanistes brevis*) and black-casqued hornbills (*Ceratogymna atrata*) per region (i.e., beak and facial skin).

Species	Slope (W °C^{-1})	SE	F-statistic	Lower 95% CI	Upper 95% CI	P-value
B. bucinator						
Beak	0.327	0.027	$F_{1,180} = 150.2$	0.274	0.379	**<0.001**
Facial skin	-0.005	0.002	$F_{1,223} = 26.24$	-0.007	-0.003	**<0.001**
B. brevis						
Beak	0.266	0.022	$F_{1, 119} = 143.6$	0.222	0.310	**<0.001**
Facial skin	-0.007	0.001	$F_{1,101} = 23.29$	-0.008	-0.003	**<0.001**
C. atrata						
Beak	0.260	0.025	$F_{1,102} = 112.2$	0.211	0.308	**<0.001**
Facial skin	-0.008	0.002	$F_{1,126} = 24.06$	-0.010	-0.004	**<0.001**

Note: There were no significant differences between the slopes of all species for heat loss across the beak ($F_{2,401} = 2.094$, $P = 0.125$) or eye skin ($F_{2,452} = 1.100$, $P = 0.334$).

Table A.8. Model outputs for between-species comparisons of heat loss across the beak and facial skin (eye skin and wattle) for trumpeter hornbill (*Bycanistes bucinator,* TH), silvery-cheeked hornbills (*Bycanistes brevis*, SCH) and black-casqued hornbill (*Ceratogymna atrata,* BCH).

Variable	Mean diff.	SE	n1	n2	Q	df	p-value
Beak							
TH ~ SCH	1.611	0.837	220	125	2,723	34	0,133
TH ~ BCH	5.709	0.830	220	128	9,726	34	**<0,001**
SCH ~ BCH	4.099	0.939	125	128	6,172	34	**<0,001**
Facial Skin							
TH ~ SCH	4.337	0.445	220	125	13,78	34	**<0,001**
TH ~ BCH eye	0.518	0.564	220	64	1,297	34	0,796
TH ~ BCH wattle	5.744	0.571	220	62	14,22	34	**<0,001**
SCH ~ BCH eye	-3.820	0.611	125	64	8,845	34	**<0,001**
SCH ~ BCH wattle	1.407	0.617	125	62	3,223	34	0,104
BCH eye ~ BCH wattle	5.226	0.708	64	62	10,44	21	**<0,001**

Table A.9. Species comparison table detailing the differences in inflection air temperature (T_{air} - °C), slope after inflection (W T_{air}^{-1} °C) and surface area specific heat loss (W m^{-2}) between sexes for *Bycanistes bucinator* (TH), *Bycanistes brevis* (SCH) and *Ceratogymna atrata* (BCH). Values are shown as mean ± SD (or SE for slopes) and 95 % confidence intervals for inflection T_{air}.

Species	**Sex (n)**	**Inflection T_{air} (°C) ± SD [95% CI]**	**Slope above inflection (W °C^{-1}) ± SE**	**Surface area specific heat loss @ 31°C* (W m^{-2}) ± SD (n)**
TH	M (14)	24.94 ± 0.47 [23.75: 26.31]	0.583 ± 0.07	161.42 ± 23.18 (8)
	F (10)	24.65 ± 0.19 [22.96:26.34]	0.312 ± 0.04	194.68 ± 12.40 (4)
SCH	M (5)	26.80 ± 0.40 [26.54:27.06]	0.932 ± 0.25	122.40 ± 25.24 (3)
	F (7)	24.30 ± 0.50 [23.39:25.19]	0.473 ± 0.06	121.96 ± 29.53 (4)
BCH	M (5)	22.46 ± 0.10 [20.72:24.20]	0.669 ± 0.10	129.65 ± 13.17 (3)
	F (7)	24.71 ± 0.01 [23.75:25.67]	0.355 ± 0.06	121.04 (2)

*31°C was selected as it was the highest common T_{air} where there was more than one individual per sex per species

Table A.10 Tukey HSD post-hoc test comparing surface area specific heat loss (W m^{-2}) across the beak at 31°C for *Bycanistes bucinator* (TH), *Bycanistes brevis* (SCH) and *Ceratogymna atrata* (BCH). Significant differences are indicated by bold p-values ($p < 0.05$). Upper and lower confidence limits (95%) of the honest significant difference (HSD) are provided.

	HSD	95% CI lower	95% CI upper	p-value
Surface area specific heat loss @ 31°C				
TH: M ~ F	2.662	-20.469	15.146	0.768
SCH: M ~ F	0.439	-54.327	55.206	0.984
BCH: M ~ F	8.612	-22.681	39.905	0.446

Table A.11. Species comparison table detailing average body mass (kg), threshold air temperature (°C), from this and other thermal imaging studies.

Species	Average body mass (kg)	Threshold air temperature (°C)	Study
Southern yellow-billed hornbill (*Tockus leucomelas)*	0.2	30.5	van de Ven et al. (2016)
Toco toucan (*Ramphastos toco*)	0.7	20.0	Tattersall et al. (2009)
Trumpeter hornbill (*Bycanistes bucinator)*	0.74	24.2	This study
Silvery-cheeked hornbill (*Bycanistes brevis)*	1.27	24.5	This study
Black-casqued hornbill (*Ceratogymna atrata)*	1.33	25.2	This study
Southern ground hornbill (*Bucorvus leadbeateri*)	3.8	22.0	Janse van Vuuren et al. (2020)
White-backed vulture (*Gyps africanus*)	5.5	15.1	J. Wessels et al. unpubl. Data
Lappet-faced vulture (*Torgos tracheliotos*)	6.5	14.9	J. Wessels et al. unpubl. Data
Cape vulture (*Gyps coprotheres*)	8.5	14.4	J. Wessels et al. unpubl. Data