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Does sexual size dimorphism vary with temperature in forest millipedes *Centrobolus* Cook, 1897?

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Abstract
The objectives of this study were to determine what happened when Bergmann's Rule met Rensch's Rule if Sexual Size Dimorphism (SSD) and body size changed with an eco-geographical factor. The environmental temperature was correlated with body size and SSD in the forest millipede genus *Centrobolus*. There was a significant positive correlation between SSD and environmental temperature (r=0.34, Z score=1.49, n=22, $p< 0.07$). Eco-geographical variance in the polygynandrous reproductive systems occurs with larger females and higher SSD in warmer habitats.

Keywords: Dimorphic, eco-geography, gradient, size, species

1. Introduction
A forest genus of diplopods belonging to the Order Spirobolida found along the eastern coast of southern Africa was the subject of this study. The millipede genus *Centrobolus* is found in the temperate South African subregion, its northern limits on the east coast of southern Africa being about -17° latitude S. It occurs in all the forests of the coastal belt from the Cape Peninsula to Beira in Mocambique. While the coastal forests of the South-West and Eastern Cape are mist belt temperate forests, those of the Transkei, Natal, Zululand, and Mocambique are somewhat different, being better described as East Coast Bush, they are developed almost entirely in a narrow strip of the litoral on a dune sand substratum, and are more tropical in aspect and composition than those to the west of them. There is a summer rainfall of 762-1016 mm, a uniform environmental temperature, and an absence of frost; the component trees of the coastal bush with their abundant creepers and lianes, while not usually reaching a height of more than 11 meters, provide a dense covering with abundant shade and humidity at ground level. As essentially shade-loving Diplopoda, the members of the genus are especially well represented in these litoral forests of the eastern half of the subcontinent [1].
Sexual size dimorphism (SSD) is correlated with environmental temperature in the pachybolid millipede genus *Centrobolus* Cook, 1897 [1-3]. The null hypothesis is that there is no body size i. e. sexual size dimorphism correlated with temperature.

2. Materials and methods
39 valid species were identified as belonging to the genus *Centrobolus* Cook, 1897 [2]. Millipede-type localities were obtained from a checklist of southern African millipedes [3]. These were tabulated and known type localities also listed in Microsoft Word online (https://office.live.com/start/Word.aspx) (Table 1). Global Positioning System (GPS) coordinates were obtained from internet sources for known type localities using google (https://www.google.co.za/maps/place). Mean annual precipitation and environmental temperature values were obtained from https://en.climate-data.org/search/?q= and internet sources for known type localities using google (https://www.google.co.za). Body size was obtained by calculating the volumes (cylindrical) using the lengths and widths of species which were inputted into the formula for a cylinder's volume (https://byjus.com/volume-of-a-cylinder-calculator). SSD was calculated as the ratio of female volume to male volume. SSD and latitude, longitude, precipitation, and environmental temperature were checked for correlations using the Pearson Correlation Coefficient calculator (https://www.gigacalculator.com/calculators/correlation-coefficient-calculator.php).

3. Results

There was a significant positive correlation between SSD and environmental temperature (Fig. 1: r= 0.33842758, Z score=1.49161177, n=22, p=0.06790051). There was no difference between the correlation coefficients of SSD with precipitation and SSD with environmental temperature (z=-0.1782, p=0.8586), SSD with latitude and SSD with longitude (z=-0.2383, n=22, 22, p=0.8117), SSD with precipitation and SSD with latitude (z=0.7919, p=0.4284), SSD with precipitation and SSD with longitude (z=1.0302, p=0.3029), SSD with environmental temperature and SSD with latitude (z=0.3589, p=0.7197), or SSD with environmental temperature and SSD with longitude (z=0.1206, p=0.9040). Environmental temperature correlated with latitude (Fig. 2: r=0.36420866, Z score=1.66392111, n=22, p= 0.04806408) and longitude (Fig. 3: r=0.52217735, Z score= 2.52523527, n=22, p=0.00578106). Environmental temperature was normally distributed (D=0.24691, n=22, p=0.11466). SSD was normally distributed (D=0.15168, n=22, p=0.63788).

Table 1: Species in the millipede genus *Centrobolus* Cook, 1897, with SSD, type or collected localities GPS latitude and longitude points, temperature, and precipitation.

Species	SSD	Location	Latitude (°S)	Longitude (°E)	Temp. (°C)	Precipitation (mm)
C. albitarsis	2.89	Lochiel	-26.150174	30.786	15.9	919
C. angelicus		Makhanda	-33.318134			
C. anulatus	1.19	Umhlanga Rocks	-29.746190	31.084	20.4	893
C. atrophus		Signal Hill	-33.917273			
C. bifidus		Nkhandla	-28.728019			
C. coriaceus		caffraria	-	-		
C. decoratus	0.63	Ngome Forest	-27.840258	31.400	16.6	962
C. digrammus	1.01	Hout bay	-34.047685	18.357	16.4	498
C. dubius	1.35	Gans bay	-34.584895	19.350	16.9	408
C. formosus		caffraria	-	-		
C. fulgidus	1.65	Richards Bay	-28.778417	32.049	21.9	944
C. immaculuatus	2.72	Gorongosa	-18.686597	34.394	22.8	1266
C. inscriptus	1.21	Scottburgh	-30.280460	30.754	19.5	1015
C. inyanganus	1.44	Inyanga village	-29.707964	30.666	16.6	893
C. lawrencei	1.57	Pietermaritzburg	-29.630118	30.393	16.7	966
C. litoralis		Algoa Bay	-33.967135			
C. luctuosus		Inhambambane	-23.900071			
C. lugubris	2.18	Glenconnor	-33.932215	25.173	17.0	497
C. miniatomaculatus		Tsitsikamma	-32.220918			
C. pococki		Cape Peninsula	-34.244295			
C. promontorius	0.69	Little Lions Head	-34.016370	18.348	16.4	621
C. pusillus	2.08	Qolora River mouth	-32.571689	28.433	19.5	1050
C. richardii	0.95	Richards Bay	-28.778417	32.078	21.9	944
C. ruber	1.62	Port Shepstone	-30.715740	30.456	20.1	945
C. rubricollis		Karkloof waterfall	-29.399869			
C. rugulosus	1.97	Hluhluwe	-28.024622	31.952	22.0	837
C. sagatinus	1.27	Between Uitenhage and Addo	-33.636710	25.396	18.6	497
C. sanguineomarginatus		Bain's Kloof	-33.613179			
C. sanguinipes		Qolora River mouth	-32.571689			
C. saussurii		caffraria	-	-		
C. silvanus	1.13	Kentani	-32.506398	28.317	19.0	956
C. splendidus		Masiene near Chai Chai	-25.615527			
C. strigosus		caffraria	-	-		
C. striolatus		Port St Johns	-31.633372			
C. titanophilus	1.15	DeHoop vlei	-34.414179	20.383	17.0	401
C. transvaalicus	1.26	Mariepskop	-24.539147	30.867	17.0	1200
C. tricolor	1.10	Champaigne Castle	-29.093869	29.418	15.0	265
C. validus		Haroni River	-19.817644			
C. vastus	1.81	Port St Johns	-31.633371	30.451	19.7	1089

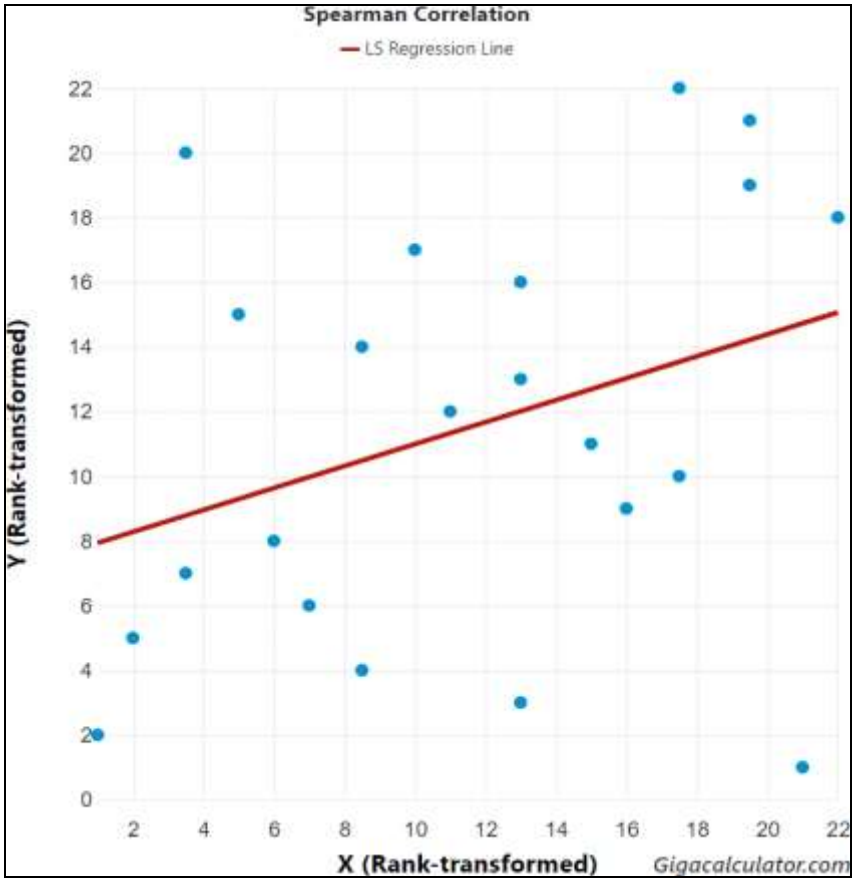

Fig 1: Relationship between Sexual Size Dimorphism (y-axis) and environmental temperature (x-axis: °C) in *Centrobolus* Cook, 1897 [2].

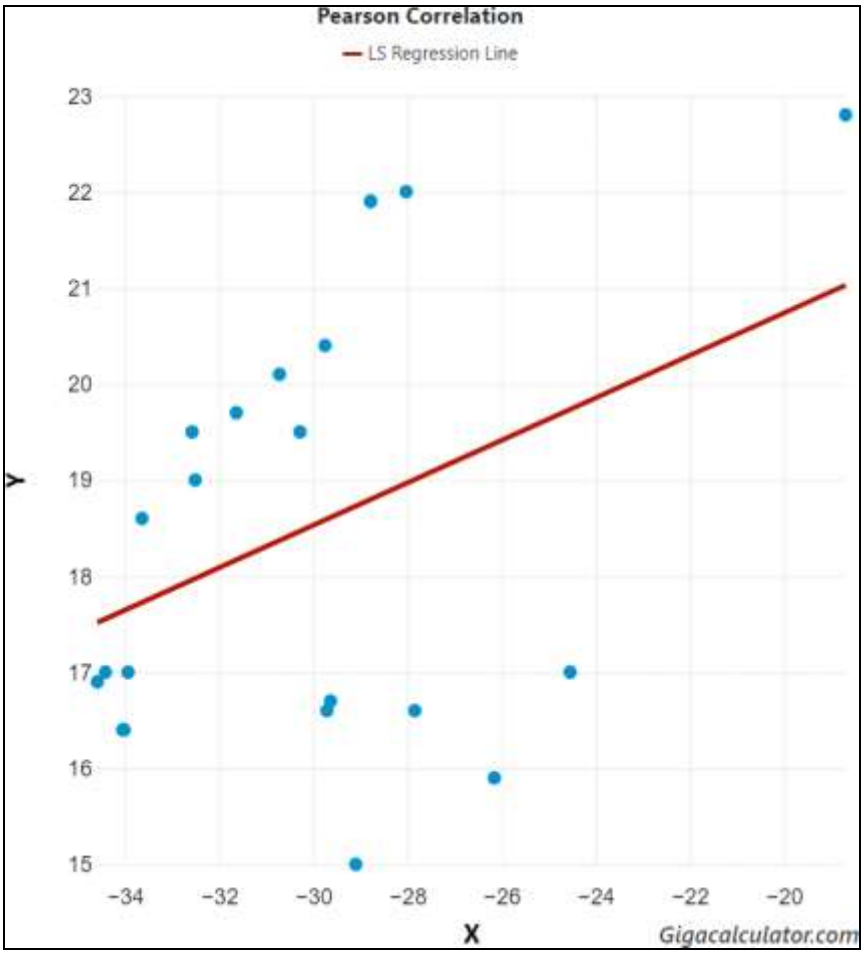

Fig 2: Relationship between environmental temperature (y: °C) and latitude (x: °South) in *Centrobolus* Cook, 1897 [2].

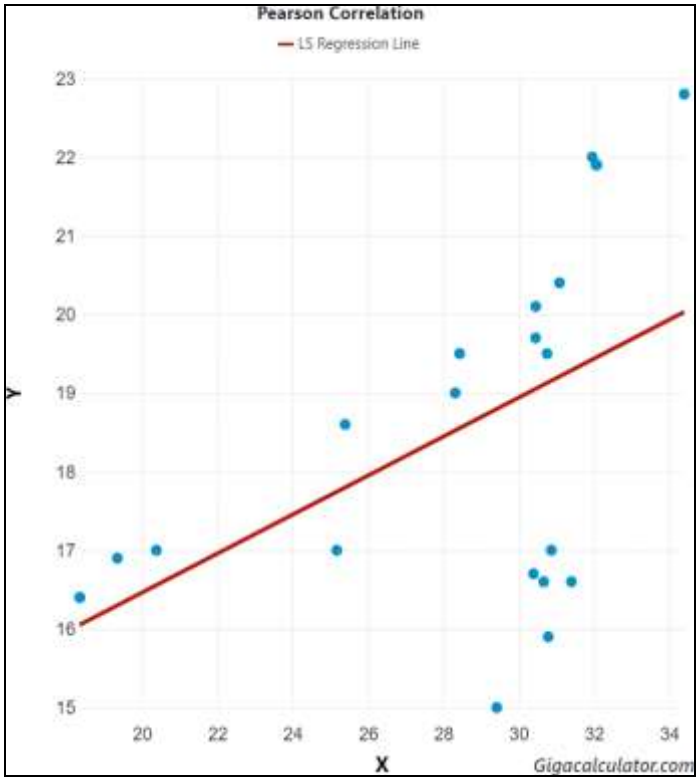

Fig 3: Relationship between environmental temperature (y: °C) and longitude (x: °East) in *Centrobolus* Cook, 1897 [2].

4. Discussion

Most relationships between body size and environmental temperature were significant with strong positive correlations between female, male, and species body sizes and temperature, there was also an important significant positive relationship between SSD and environmental temperature. *C. immaculatus* has the highest SSD (2.72) and occurred at the highest environmental temperature (22.8 °C). SSD was less apparent in *C. promontorius* (0.69) which occurred at 16.4 °C and *C. decoratus* (0.63) which occurred at 16.6 °C. This study supports environmental temperature as a predictor of SSD in *Centrobolus*. Size-assortative mating based on width and length also determines the variance in polygynandrous mating systems across an environmental temperature gradient with higher SSD occurring at higher environmental temperatures possibly due to sexual bimaturism [4]. Examples of sexually dimorphic traits varying with temperature in the literature have been documented in the lion *Panthera leo* [5], ambush bug *Phymata americana* [6], green turtle *Chelonia mydas* [7], zebrafish *Danio rerio* [8], and frogs *Limnodynastes tasmaniensis* and *L. peronii* [9]. Temperature may be an explanation for skewed sex ratios in species showing sexual size dimorphism, such as millipedes and mosquitofish [10].

5. Conclusion

SSD increased systematically with environmental temperature in *Centrobolus*. SSD increased with body size in this genus. Eco-geographical variance in the polygynandrous reproductive systems occurs if larger females and higher SSD occur in warmer habitats.

Competing interests

The author has declared that no competing interests exist.

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