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Does sexual size dimorphism vary with time in red millipedes *Centrobolus* Cook, 1897?

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Abstract
Sexual Size Dimorphism (SSD) variation with time was studied in red millipedes. Time (1964.7±29.4 years) was correlated with SSD in volumes in the red millipede genus *Centrobolus*. There was an marginal absolute difference (T=1.271239, n=2, 5, p=0.071465) but not a relative difference (T=0.914933, d.f.=5, p=0.201098) between mean log SSD_{1+2} (0.065050 mm^3) and mean log SSD_3 (0.156442 mm^3). This converted back into an absolute difference of 8.35 μm^3 in mean volume. Neither an inverse Rensch's rule nor Rensch's rule pattern could be confirmed from log SSD with body size (r=0.25608594, Z score=0.69296229, n=10, p=0.24416654). Systematic variation of SSD with time was shown in two examples in *Centrobolus* with higher SSD in more recent times being faster in the smaller *C. digrammus* (58% more female-biased after 32 years) and slower in the larger *C. ruber* (25% more female-biased after 60 years). There was a relative difference in size between *C. digrammus* and *C. ruber* compared to recent measurements of four species (T-score=6.242725, d.f.=4, p=0.002). *C. digrammus* and *C. ruber* were relatively larger sizes after the time (T-score=3.858367, d.f.=2, p=0.030541).

Keywords: Dimorphic, female, male, length, morphology, time, width

1. Introduction
Numerous studies are finding animal taxa have female-biased SSD and mostly disobey Rensch's rule including corvids and pinnipeds [1, 2, 5-11, 13-17, 19-26, 28-33, 35-38, 40-42]. The finding of converse or inverse Rensch rule implies SSD increases with body size when females are larger [1, 2, 5-11, 13-17, 19-26, 28-33, 35-38, 40-42]. This has implications in the genus *Centrobolus* because females are larger than males and SSD increases hypoallometrically with body size [5-10].

The forest genus *Centrobolus* of diplopods belonging to the Order Spirobolida found along the eastern coast of southern Africa was the subject of this study. Its northern limits are on the east coast of southern Africa being -17° latitude South (S) and its southern limits -35° S; from the Cape Peninsula to Beira in Mocambique in all the forests of the coastal belt [4]. As essentially shade-loving Diplopoda, the members of the genus are represented by 39 species in these litoral forests of the eastern half of the subcontinent [4]. Sexual size dimorphism (SSD) in volumes is compared across time [3, 4, 14, 18]. The hypothesis that there is no SSD correlation with time was tested.

2. Materials and Methods
Four valid species were identified as belonging to the genus *Centrobolus* Cook, 1897 (Table 1). Millipede localities were obtained from the Mating dynamics of South African forest millipedes *Centrobolus* (Diplopoda: Pachybolidae) [4]. SSD was calculated from the publication of collected material over three dates [4, 34, 39]. SSD was calculated as the ratio of female volume to male volume. SSD and differences in time were checked for correlations with female body size using the Pearson Correlation Coefficient calculator (https://www.gigacalculator.com/calculators/correlation-coefficient-calculator.php). Male and female collection dates were at the same time except for *C. ruber* where only male data is given [39]. Tests for normality were conducted (https://www.socscistatistics.com/tests/kolmogorov/default.aspx). A Lilliefors test was used to test for normality of time data at http://www.statskingdom.com/kolmogorov-smirnov-test-calculator.html. Six potential measurements for the time were 1928, 1934, 1966, 1967, 1995, and 1998. To test between divergent and convergent series a series integral test calculator was used (http://www.symbolab.com/solver/series-integral-test-calculator). Body sizes were tested for differences over time with a P-value Calculator (https://www.gigacalculator.com/calculators/p-value-significance-calculator.php).

3. Results

There was a marginal absolute difference between mean log SSD_{1+2} (0.065050 mm^3) and mean log SSD_3 (0.156442 mm^3) (Figure 1: T=1.271239, n=2, 5, p=0.071465) but not a relative difference of mean log SSD_{1+2} (0.065050 mm^3) and mean log SSD_3 (0.156442 mm^3) (T=0.914933, d.f.=5, p=0.201098) (Table 1). There was also a marginal absolute difference (0.135919 mm^3) between the past (0.065050 mm^3) and present (0.200969 mm^3) SSD for pooled *C. digrammus* + *C. ruber* (T=1.994615, n=2, 2, p=0.092119). SSD was normally distributed (D=0.15168, n=22, p=0.63788). Time was normally distributed (D=0.2067, n=6, p=0.91609). Mean time was 1964.66667 Anno Domini (A. D.). and median time was 1966.5 A. D. Standard deviation in time was 29.405215 years. An integral test showed both the SSD_{1+2} and SSD_3 series (Table 2) diverged. Neither a Rensch nor an inverse Rensch's rule pattern was confirmed here (r=0.35728793, Z score= 0.74754699, n=7 pairs, p=0.22736665) (Table 3). *C. digrammus* male length was normal (D=0.30113, n=5, p=0.65956); male width was normal (D=0.3, n=7, p=0.664); female length was normal (D=0.24906, n=7, p=0.69292); and female width was normal (D=0.27926, n=7, p=0.55343). The mean SSD of *C. digrammus* was 1.28 (S.D.=0.41012, n=2) and *C. ruber* was 1.45 (S.D.=0.21213, n=2). There was no difference in SSD between *C. digrammus* and *C. ruber* (t=-0.521, n=2,2, p=0.6545). Mean SSD were not absolutely different (T-score=-0.630358, d.f.=2, p=0.296440) and not relatively different (T=score=-0.622882, d.f.=2, p=0.298460). The mean size of *C. ruber* was 1704.575 (S.D.=164.22555, n=2) and *C. digrammus* was 751.465 (S.D.=331.97956, n=2). Mean size differences between *C. digrammus* and *C. ruber* were marginally significant (t=3.643, d.f.=2, p=0.0678). There was no absolute difference in size between *C. digrammus* and *C. ruber* compared to recent measurements of four species (T-score=1.144381, d.f.=1.5154, p=0.102870). There was a relative difference in size between *C. digrammus* and *C. ruber* compared to recent measurements and four species (Figure 2: T-score=6.242725, d.f.=4, p=0.001678). *C. digrammus* and *C. ruber* were relatively different in time (Figure 3: T-score=3.858367, d.f.=2, p=0.030541). The two *C. inscriptus* SSD means were not significantly different (t=0.308, d.f.=133, p=0.7585). *C. fulgidus* SSD was not different to *C. inscriptus* mean SSD (t=0.047, d.f.=11, p=0.9634). *C. ruber* SSD was not different to *C. inscriptus* mean SSD (t=0.055, d.f.=18, p=0.9566). *C. fulgidus* SSD did not differ from *C. ruber* SSD (t=0.032, d.f.=27, p=0.9744). *C fulgidus* SSD did not differ from *C. digrammus* mean SSD (t=-0.035, d.f.=11, p=0.9730). *C. inscriptus* SSD did not differ from *C. digrammus* SSD (t=0.040, d.f.=2, p=0.9719).

Table 1: Species in the millipede genus *Centrobolus* Cook, 1897, with SSD recorded at three different times ($_{1-3}$). Two mean measurements are included for *C. inscriptus.*

Species	SSD_3	SSD_2	SSD_1
C. fulgidus	1.48947444		
C. inscriptus	1.20538504 1.33693499		
C. ruber	1.60428011		1.35849057
C. digrammus	1.57274594	0.993214801	-

Table 2: Four species in the millipede genus *Centrobolus* Cook, 1897, with *log* SSD recorded at three different times ($_{1-3}$). Two mean measurements are included for *C. inscriptus.*

Species	*log* SSD_3	*log* SSD_2	*Log* SSD_1
C. fulgidus	0.173033055		
C. inscriptus	0.0811257971 0.12611029		
C. ruber	0.205280199		0.133056628
C. digrammus	0.196658573	-0.00295681716	

Table 3: Four species in the millipede genus *Centrobolus* Cook, 1897, with *log* SSD and female body size recorded at four different times ($_{1-4}$). Two mean measurements are included for *C. inscriptus.*

Species	*log* SSD_3	Female $size_3$	*log* SSD_2	Female $size_2$	*Log* SSD_1	Male $size_1$
C. fulgidus	0.173033055	1917.11		1888.47		
C. inscriptus	0.0811257971 0.12611029	2221.16		2221.16		
C. ruber	0.205280199	1820.70		1811.93	0.133056628	1588.45
C. digrammus	0.196658573	986.21	-0.00295681716	516.72		

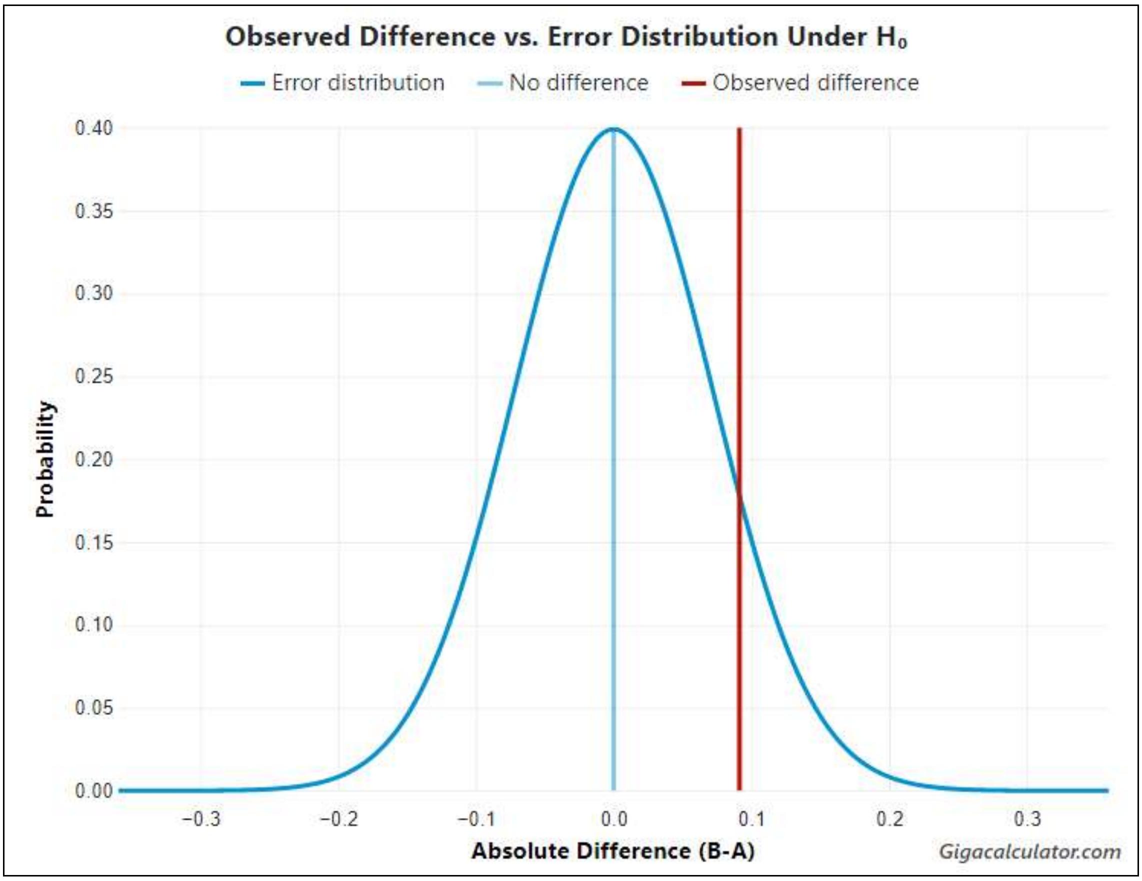

Fig 1: P-value showing marginal absolute difference (0.091392 mm^3) in *log* Sexual Size Dimorphism (x-axis) over time in *Centrobolus* Cook, 1897.

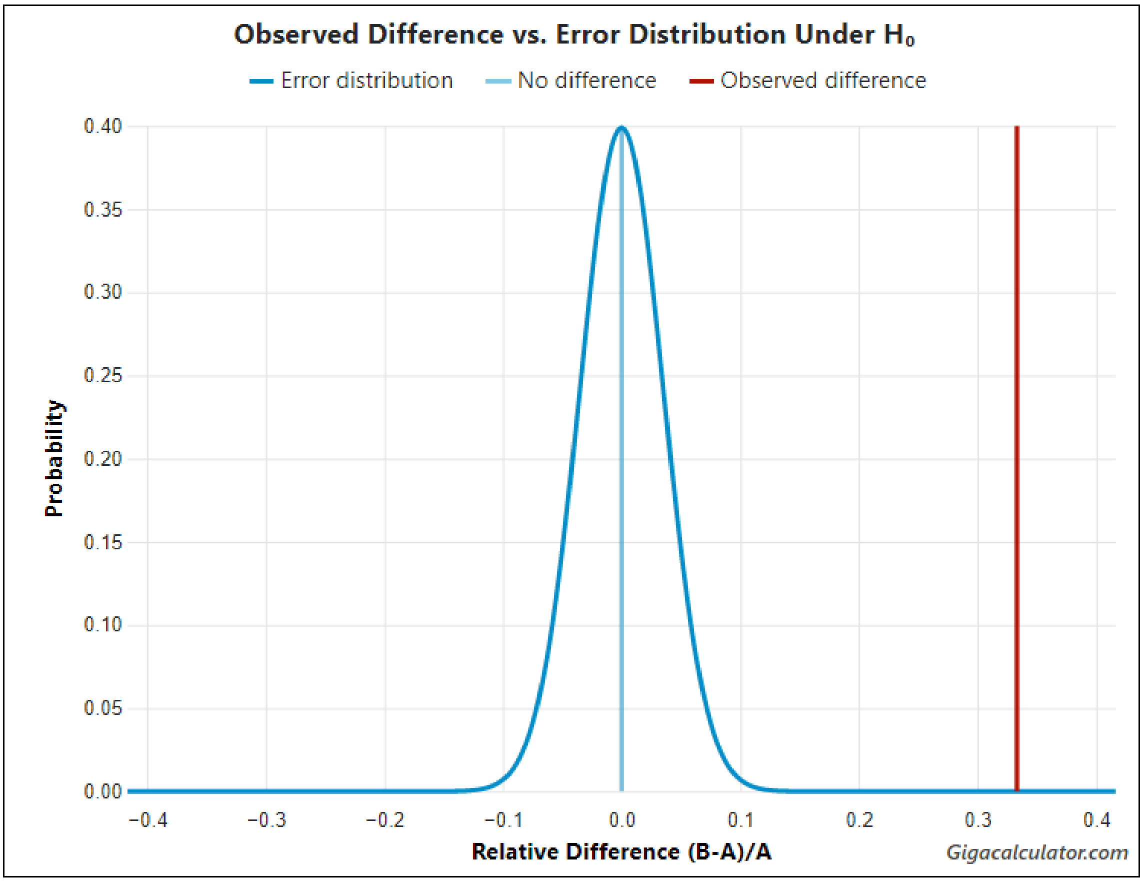

Fig 2: P-value showing relative size differences (0.333341 mm^3) between *C. digrammus* and *C. ruber* pooled over time (1052.5850 mm^3 to 1403.4550 mm^3).

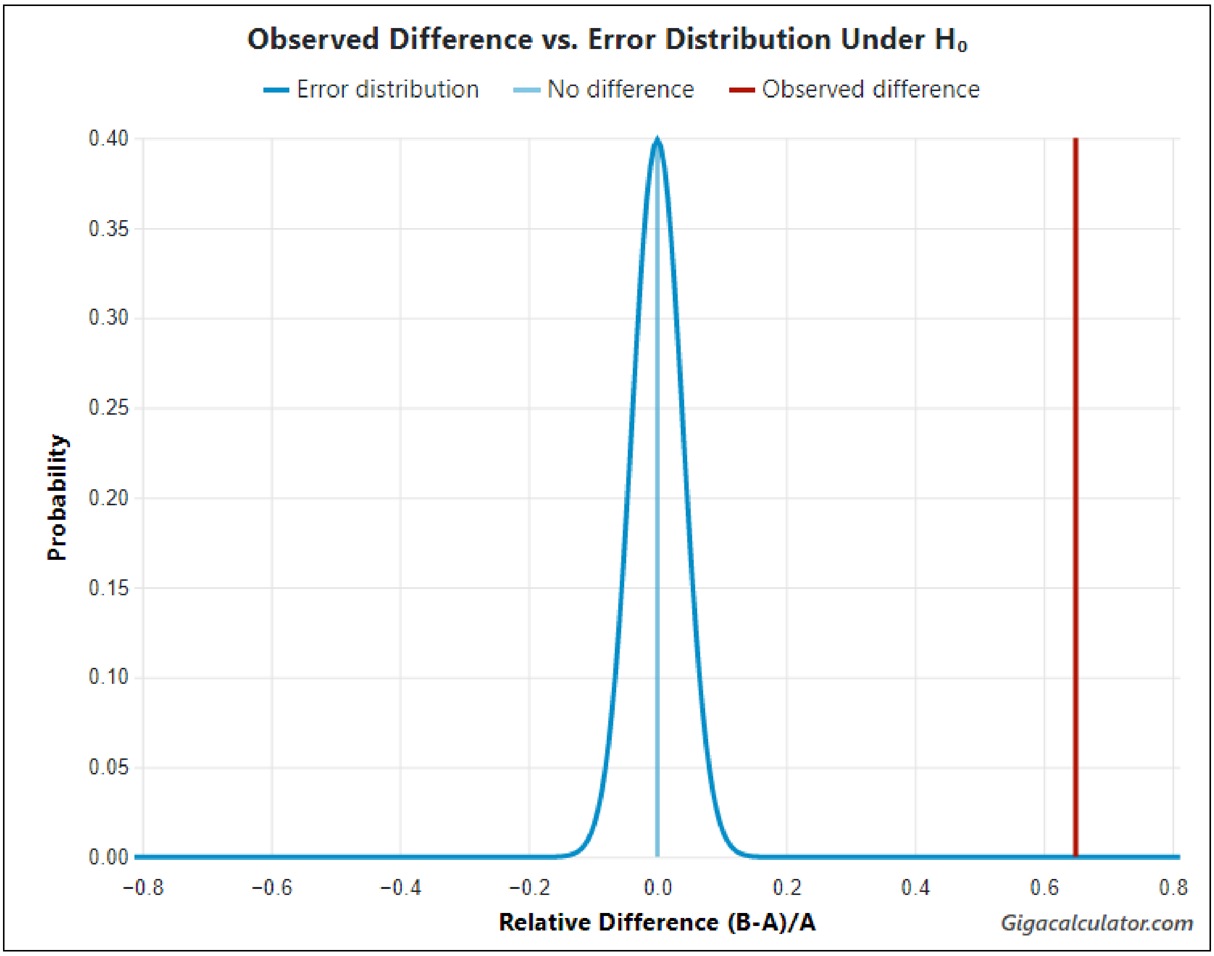

Fig 3: P-value showing a significant relative difference (0.649553 mm^3) between past size (1052.5850 mm^3) and present size (1736.2950 mm^3) in *Centrobolus* Cook, 1897.

4. Discussion

The null hypothesis that SSD did not change over time was falsified. A marginal absolute difference in SSD and a relative difference (increase) in size values with time (1928-1998) were found. The species were relatively smaller in the past. This study supports time as a reference character and as a predictor of SSD and size in *Centrobolus*. SSD and size increase over time and tends towards female-biased dimorphism in *C. digrammus* and *C. ruber*. SSD increase with time is only directly comparable in these two species and is explained as a positive relationship between past and present SSD. *C. digrammus* had female-biased SSD (1.57) and this was lower in the past (0.99). *C. ruber* also had female-biased SSD (1.60) and was lower in the past (1.36). This does not concur with the shifts in SSD found in ostracods across mass extinctions [27].

In this study, neither a Rensch nor an inverse Rensch rule was confirmed [31-32]. This is possibly due to the small sample size or the likelihood that an (inverse) Rensch rule is not evident over the time frame. Rensch's rule and Inverse Rensch's rules are both generalizations that fail to consider true variation across time [31-32]. This study successfully illustrates SSD variation across time in two species where females have become large due to a fecundity advantage [43]. Furthermore, this study supports the finding that both niche and fitness differences increase with size differences [12].

The finding of a temporal change in SSD is consistent with r/K selection theory because it was faster in the smaller *C. digrammus* (58% more female-biased after 32 years) and slower in the larger *C. ruber* (25% more female-biased after 60 years). These two exemplar species are not extremes and represent moderate SSD within the genus *Centrobolus*. A range of similar long-term SSD variations with time probably occurred in the past with the majority of the SSD being evolution towards female-biased SSD [43]. The finding of a temporal change towards female-biased SSD is also consistent with hypoallometry which is already established in this genus [5-10]. *C. digrammus* and *C. ruber* were relatively larger sizes after the time intervals (32 and 60 years) and are consistent with a hypoallometric function. The finding of a marginal absolute difference in SSD and a relative difference (increase) in size values with time is consistent with hypoallometric increases in SSD with size.

5. Conclusion

SSD increased systematically faster in smaller *C. digrammus* and slower in larger *C. ruber*. This is consistent with the r/K selection theory. Neither a Rensch nor an inverse Rensch rule was confirmed in this study.

6. Acknowledgements

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