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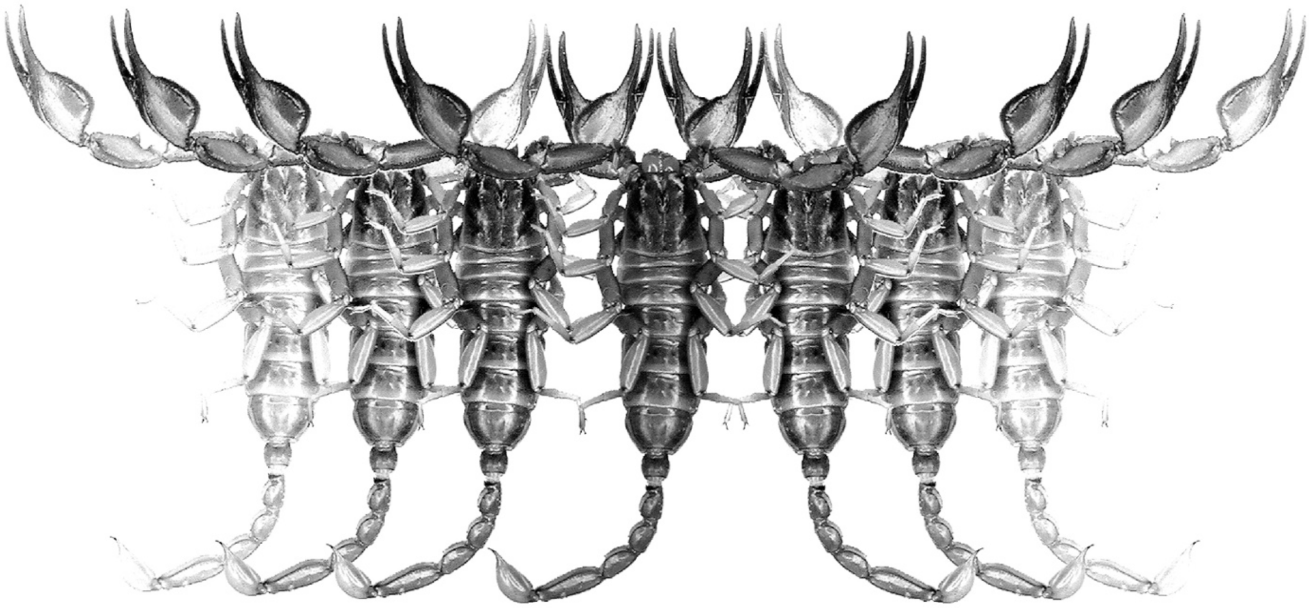

Albinism in *Olivierus martensii* (Karsch, 1879) (Scorpiones: Buthidae)

Victoria Tang & Zhenbang Liu

October 2024 — No. 396

Euscorpius

Occasional Publications in Scorpiology

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Publication date: 3 October 2024

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Euscorpius — Occasional Publications in Scorpiology. 2024, No. 396

Albinism in *Olivierus martensii* (Karsch, 1879) (Scorpiones: Buthidae)

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Summary

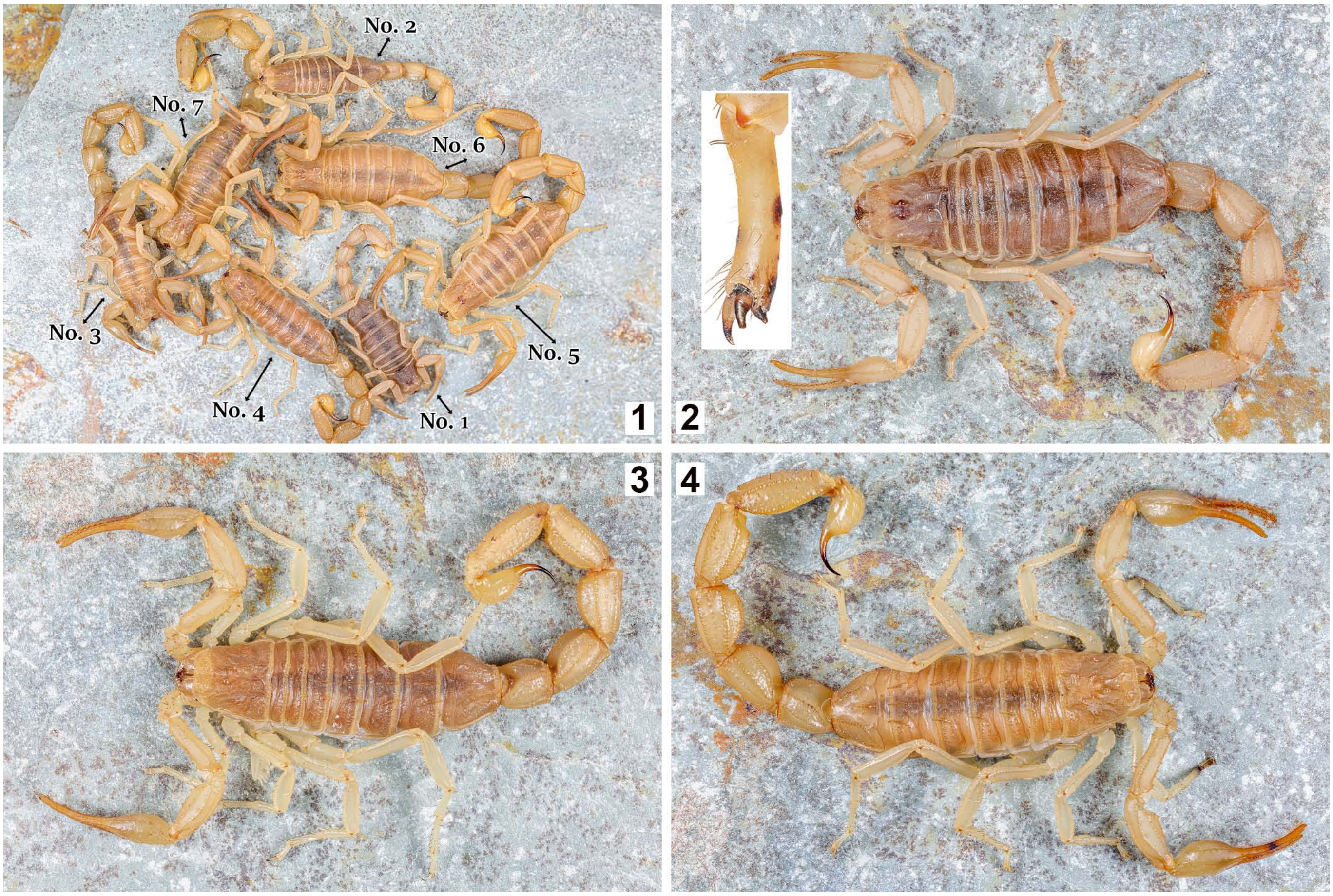
This is a formal case report for the albinism in *Olivierus martensii* (Karsch, 1879). Albino phenotype is compared with its normal counterpart in terms of their morphology and behavior by cursory experiments. The examined 7 albino individuals (5 of which were adults) were smaller and more slender than their normal counterparts. However, these quantitative differences were not statistically significant and should be treated with caution due to the low sample size. Their abilities to detect both white light and UV light or UV-excited fluorescence were not significantly undermined, although their tendency to ensure a clear vision through self-cleaning behavior appeared to be reduced. Their heightened visibility on dark, leafmould substrate and greater crypticity on yellowish gravels may play a significant role in their natural survival. Additional evidence is required to substantiate this hypothesis as the function of scorpion coloration has been hardly studied. Several theoretical assumptions were proposed following a literature review on scorpion coloration and fluorescence, and this paper also serves as a brief synopsis of those aspects. Other three rare phenotypes in this species are also reported, defined here as piebaldism, hypomelanism and leucism. Given their existence, it is suggested that the loss of melanin in the epidermis beneath the ocelli is diagnostic for albinism in scorpions.

Introduction

The term "albinism" (from Latin *albus* "white") holds a variety of inconsistent definitions by different authors owing to the categories of biological coloration taken into account, stemming from the various conditions among distinct organisms. Biological colorations are essentially induced by the selective absorption or physical interference of the introduced light, resulting in the partial reflection eventually perceived. Typically, the coloration is caused by the pigments contained in chromatophores that absorb specific wavelengths of light. In contrast, structural colors refer to hues resulting from the coherent scattering effect of the light that passes through multilayered structures that are inherently translucent and colorless; for instance, leucophores and iridophores comprised of plates of crystalline chemochromes made from purines (usually guanine). A generally accepted definition for "albinism" can be concluded as "a congenital condition in which the pigment melanin is absent in the eyes, skin, hair, scales, or feathers", irrespective of the structural colors and other pigments (Oetting & Adams, 2018). Such albinism is caused by the genetic mechanisms, involving mutations in genes responsible for the production of melanin or the enzymes involved in melanin synthesis (Landa-Jaime et al., 2018).

According to Locket (1986: 111–112), the process of melanin formation in scorpions aligns with that observed in humans. The enzyme, tyrosinase (or o-diphenol oxidase), is initially produced as an inactive precursor called "pro-tyrosinase", transported into premelanosomes (found in melanocytes, a developing stage of the melanosome) where via post-translational modifications (e.g., glycosylation and proteolytic cleavage) it is activated into tyrosinase which catalyzes the hydroxylation of tyrosine (a type of aromatic amino acid) into L-dopa (levodopa). Tyrosinase further catalyzes the oxidation of L-dopa into dopaquinone. The dopaquinones then undergo a series of chemical reactions within the premelanosomes, leading to the polymerization of melanin. As melanin granules mature within the melanosomes, they are eventually transported to the tips of melanocyte dendritic processes, where they are released and transferred to neighboring keratinocytes or other target cells, contributing to pigmentation.

As the first report of albinism in scorpions, in his exhaustive documentation, Locket (1986) meticulously elucidated the histological differences between an albino and a normal *Urodacus yaschenkoi* regarding their median ocelli. Despite the presence of basic components of eyes in the albino individual, melanin granules normally present in the epidermis and retina were replaced by the non-pigmented



Figures 1–**4**. Albino *Olivierus martensii* in vivo habitus. **Figure 1**. Size comparison. **Figure 2**. Immature female (No. 1) with regenerated tarsal ungues and dactyl; additional setae were developed at the distal end that are absent from the normal legs. **Figure 3**. Immature male (No. 2). **Figure 4**. Adult male (small sized; No. 3).

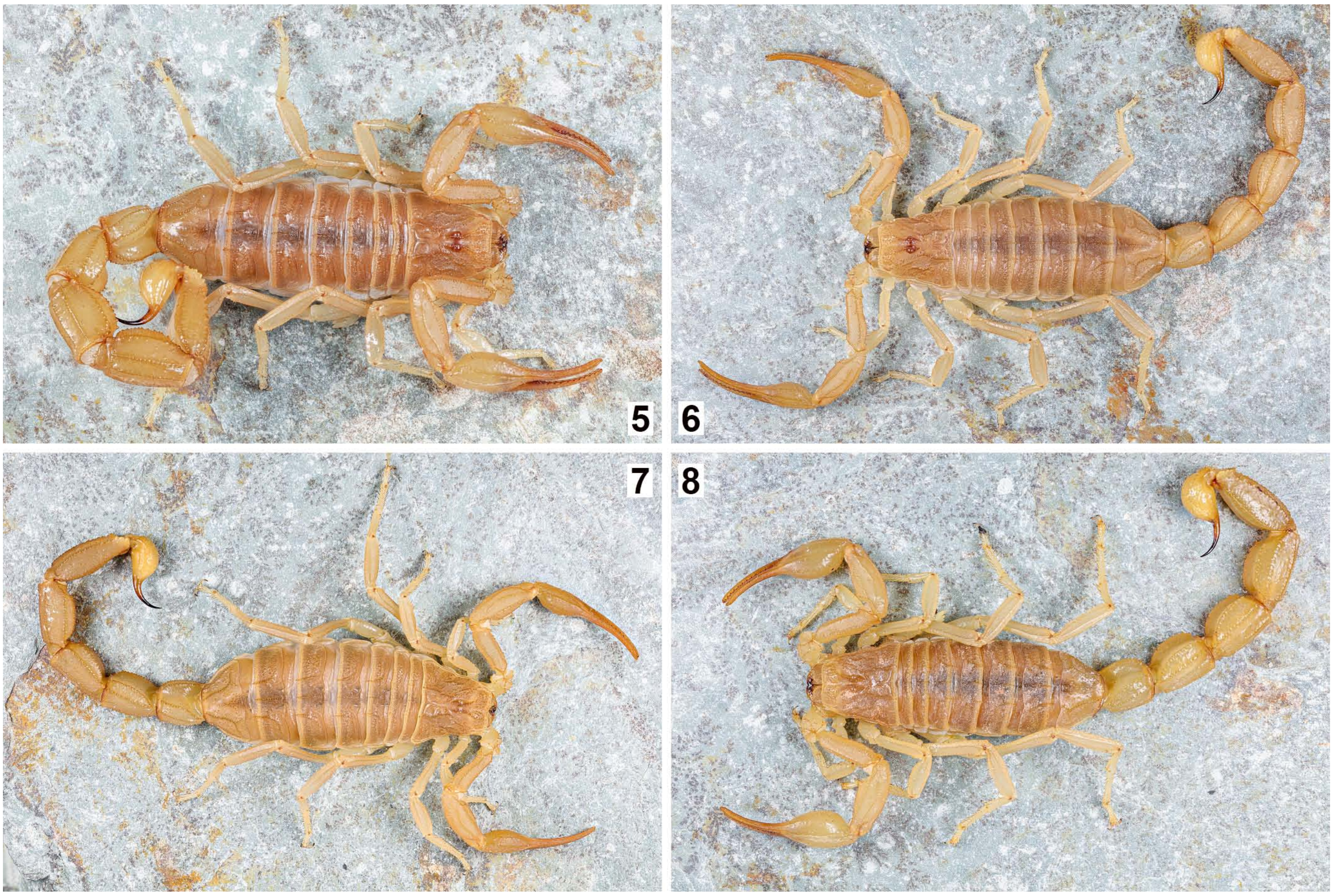
premelanosomes of greater size range and density. In addition, two ocular structures were abnormal while other organs resembled those of the normal specimen: (1) rhabdoms markedly degenerate, consisted of disorganized microvilli with extremely reduced length and density; (2) phaospheres were typically represented by smaller and irregular clumps of dense amorphous material lacking the normal granular substructure.

A subsequent report of albinism transpired 36 years later within the family Buthidae (C. L. Koch, 1837), which was documented for the species *Buthus castellano* Teruel & Turiel, 2022 in its original description (Teruel & Turiel, 2022: 20, figs. 23c–e). More recently, as an illustrative evidence substantiating the qualitative characters scored for *Olivierus martensii* (Karsch, 1879) in their table 5, Tang et al. (2024: figs. 157–162) provided a series of photographs showcasing various phenotypes in this species. Their figure 160 featured an albino adult female. However, given the paper to which that photo belonged primarily centered around the revision of its congeners in Xinjiang, no additional description for this phenotype was offered. Therefore, in this study, a formal documentation for the albinism in this species is supplemented. Here, the morphological and behavioral aspects were compared between the albino and normal phenotypes of *O. martensii*, alongside brief discussions for three other rare phenotypes observed in the same species. The objective of this paper is to serve as a source of potential research directions, and an updated synopsis on this phenomenon by introducing some new terminologies as well as reporting the new observations, rather than an exhaustive exploration of the ultrastructure, optical properties, or physiology in albino scorpions.

Material & Abbreviations

Methods. Terminology and basic examination of the specimens followed Tang et al. (2024). The second author was responsible for matting the photos. Morphological analysis utilized only the adult specimens when involving ontogenetically variable features (e.g., total length and ratiometrics). Specific steps of each experiment were elucidated in the following content. Cursory behavior experiments were not calibrated against the circadian phase of the scorpions. All scorpions were housed individually in a dim environment when comparing their behaviors, except for light experiments. Statistical tests performed online with default settings: www.statskingdom.com/index.html.

Materials. Scorpions were procured online in China, without specific locality (see below for further explanation), deposited



Figures 5–8. Albino *Olivierus martensii* in vivo habitus. **Figure 5**. Adult male (small sized; No. 4). **Figure 6**. Adult female (small sized; No. 5), presumably; died prior to all experiments. **Figure 7**. Adult female (large sized; No. 6). **Figure 8**. Adult male (large sized; No. 7).

in the personal collection of the first author. Examined normal *O. martensii* were procured from Luoyang City, Henan Province, with two adults illustrated in Tang et al. (2024: figs. 157–158). A total of 7 albino *O. martensii* of different development stages were examined. One female specimen accidentally died prior to the experiments (preserved in 75% ethanol) and was donated to Charles University, Prague, Czech Republic, for potential histological study in the future. A pair of adult albinos were euthanized for exemplar photography subsequent to their fulfillment of experiments.

Abbreviations. TL, total length (in mm); PTC, pectinal tooth count (left/right, in ventral view); DSC, pedipalp finger denticle subrow count (left/right); L/W-IV, length to width ratio of metasoma IV; L/D-IV, length to depth ratio of metasoma IV; L/W-V, length to width ratio of metasoma V; L/D-V, length to depth ratio of metasoma V.

Pigmentation reduction in scorpions

Albinism remains a rare phenomenon in scorpions while reduced pigmentation is commonly observed. Extreme pigmentation reduction in scorpions eventually results in a hue that is almost identical with the cuticle (“exoskeleton”) itself, manifesting as a pale yellow tint, often occurring in psammophilous and hypogean taxa. Psammophilous taxa, adapted to arenaceous environments, have plausibly leveraged this pale coloration for facilitating optical camouflage (Lourenço & Cloudsley-Thompson, 1996). In such habitats, the reduced coloration aids these scorpions in blending seamlessly with their surroundings, rendering them less conspicuous to potential visual predators and prey. Conversely, troglobites, those dwelling in subterranean environments, also frequently display pale coloration. However, in their case, the significance of coloration may be diminished due to the absence of light in their habitat. Consequently, maintaining vibrant pigmentation might not confer any notable advantages. It is imperative to point out that scorpions may optically appear less pale due to the dark-colored viscera beneath the cuticle, which may also be influenced by the food consumed.

Epigean scorpions with relatively pale coloration are represented by the species that dwell in light-colored substrate (commonly psammophilous, occasionally lapidicolous and lithophilous), for example, some *Alayotityus* spp. (e.g., *A. pallidus* Teruel, 2002), some phenotypes of *Androctonus amoreuxi* (Audouin, 1826), *Apistobuthus pterygocercus* Finnegan, 1932, *Australobuthus xerolimniorum* Locket, 1990, *Birulatus* Vachon, 1974, most *Buthacus* Birula, 1908, *Buthiscus bicalcaratus* Birula, 1905, *Buthus pococki* Kovařík et al., 2020, *B. somalilandus* Kovařík et al., 2020, *B. zeylensis*

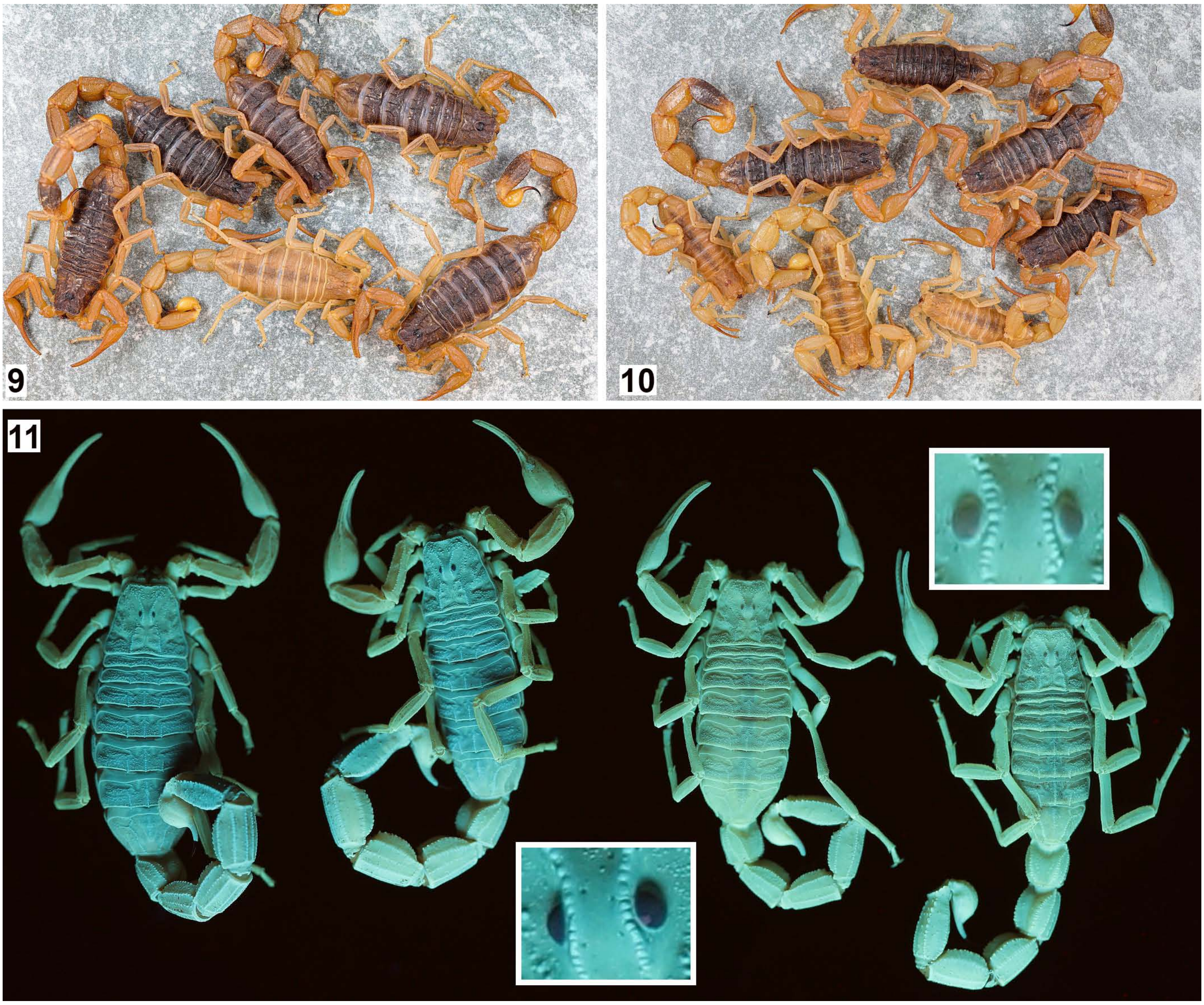
Specimen	TL (mm)	PTC	DSC	L/W-IV	L/D-IV	L/W-V	L/D-V
No. 1 ♀	-	20/20	13/12	-	-	-	-
No. 2 ♂	-	25/25	12/12	-	-	-	-
No. 3 ♂	43.37	26/27	12/12	1.72	1.84	2.2	2.45
No. 4 ♂	43.65	26/27	12/12	1.7	1.73	2.22	2.45
No. 5 ♀	48.7	20/19	13/13	1.73	1.88	2.18	2.63
No. 6 ♀	52.51	20/20	12/13	1.7	1.88	2.14	2.44
No. 7 ♂	52.02	23/26	13/13	1.71	1.78	2.18	2.32
Normal ♂	52.63–60.92	23–27	12–13	1.64±0.036	1.74±0.031	1.98±0.038	2.2±0.1
Normal ♀	51.99–60.37	19–21		1.65±0.033	1.8±0.032	2.05±0.032	2.3±0.041
DSC frequency	***f* (12)**	***f* (13)**	**PTC statistics**	**Albino (♂)**	**Albino (♀)**	**Normal (♂)**	**Normal (♀)**
Albino (♂)	0.75	0.25	Mean ± SD	25.63±1.3	19.83±0.41	25.13±1.46	20.41±0.67
Albino (♀)	0.3333	0.6667	Median	26	20	25	20.5
Normal (♂)	0.125	0.875					
Normal (♀)	0.3333	0.6667	**TL statistics**	**Albino (♂)**	**Albino (♀)**	**Normal (♂)**	**Normal (♀)**
Albino (all)	0.5714	0.4286	Mean ± SD	46.35±4.92	50.61±2.69	56.02±3.57	56.75±2.76
Normal (all)	0.25	0.75	Median	43.65	50.61	55.26	56.91

Table 1. Comparison of morphological value between examined albino and normal *O. martensii*. PTC of albinos corresponds to "left/right" values in ventral view. Some values for normal specimens are represented by mean ± SD (normal male *n* = 4; normal female *n* = 6, including the one depicted in Tang et al. (2024: fig. 157)). PTC and DSC included both sides. Frequencies are normalized relative frequencies. Abbreviations: TL, total length; PTC, pectinal tooth count; DSC, denticle subrow count; L/W, length to width ratio; L/D, length to depth ratio; IV, metasoma IV; V, metasoma V; SD, sample standard deviation.

Pocock, 1900, *Centruroides sculpturatus* Ewing, 1928, some *Compsobuthus* spp. (e.g. *C. arabicus* Levy et al., 1973), *Diplocentrus mitchelli* Francke, 1977, *Femtobuthus shutuae* Lowe, 2010, some *Gint* spp. (e.g., *G. maidensis* Kovařík et al., 2018), some phenotypes of *Hadogenes tityrus* (Simon, 1888), some *Hadrurus* spp. (e.g., *H. concolorous* Stahnke, 1969 and the pallid phenotype of *H. arizonensis* Ewing, 1928), some *Hemiscorpius* spp. (e.g., *H. enischnochela* Monod & Lourenço, 2005), *Hottentotta pellucidus* Lowe, 2010, *H. saxinatans* Lowe, 2010, *Iranobuthus krali* Kovařík, 1997, *Leiurus arabicus* Lowe et al., 2014, *L. macroctenus* Lowe et al., 2014, some *Olivierus* spp. (e.g., *O. elenae* Fet et al., 2018), *Orthochirus kryzhanovskyi* Kovařík et al., 2020, *Palaeocheloctonus pauliani* Lourenço, 1996, some *Parabuthus* spp. (e.g., *P. glabrimanus* Prendini & Esposito, 2010), some *Paravaejovis* spp. (e.g., *P. confusus* (Stahnke, 1940)), many *Paruroctonus* spp. (e.g., *P. arenicola* Haradon, 1984, *P. baergi* (Williams & Hadley, 1967), *P. luteolus* (Gertsch & Soleglad, 1966), and *P. xanthus* (Gertsch & Soleglad, 1966), etc.), *Smeringurus mesaensis* (Stahnke, 1957), *Trypanothacus* Lowe et al., 2018, some phenotypes of *Urodacus yaschenkoi* (Birula, 1903), some *Uroplectes* spp. (e.g., *U. pilosus* (Thorell, 1876)), etc.

On the other hand, hypogean taxa are often paler and more translucent. Representative taxa include *Aemngvantom* Prendini et al., 2021, *Alacran* Francke, 1982 (partially pale), *Aops oncodactylus* Volschenk & Prendini, 2008, *Chaerilus agnellivanniorum* Lourenço & Rossi, 2018, *C. chapmani* Vachon & Lourenço, 1985, *C. sabinae* Lourenço, 1995, *C. telnovi* Lourenço, 2009, *Diplocentrus actun* Armas & Palacios-Vargas, 2002, *D. anophthalmus* Francke, 1977, *Euscorpius studentium* Karaman, 2020, *Hormurus polisorum* (Volschenk et al., 2001) (partially pale), *Sardoscorpius troglophilus* Tropea & Onnis, 2020, *Sotanochactas elliotti* (Mitchell, 1971), *Stygochactas granulosus* Vignoli & Prendini, 2009, *Troglotityobuthus gracilis* (Fage, 1946), many *Typhlochactas* spp. (e.g., *T. rhodesi* Mitchell, 1968), *Uroctonus grahami* Gertsch & Soleglad, 1972, *Vietbocap canhi* Lourenço & Pham, 2010, etc.

While the paleness owing to the scant epidermal pigmentation in those species is either a distinctive trait inherent to the species itself or remains consistent for a particular color morph thereof, albinism occurs as an abnormal condition. In this regard, it is not an ecologically adapted color tonality and stands as a relatively infrequent

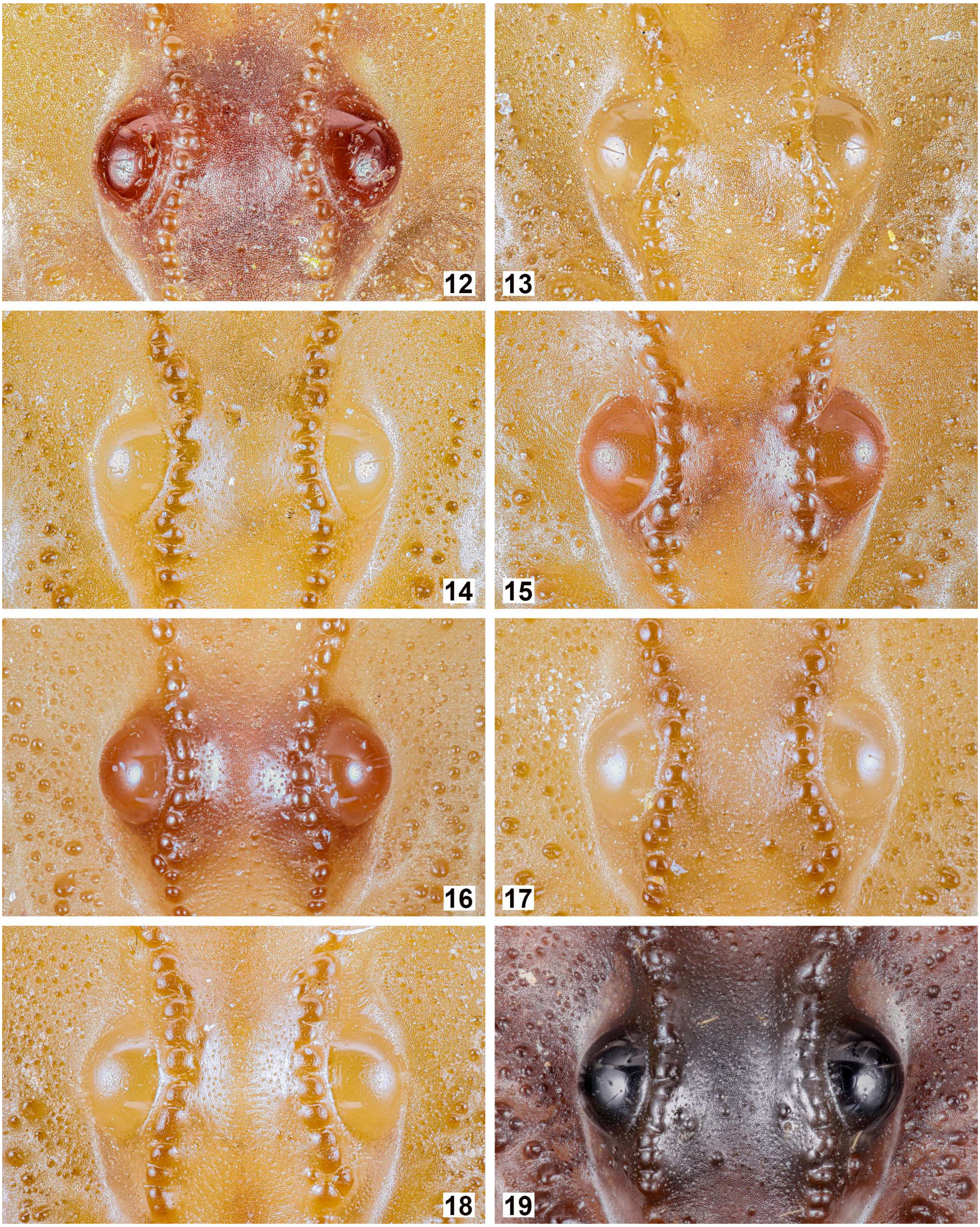


Figures 9–11. Comparison between adults of albino and normal *O. martensii* in vivo habitus. **Figures 9–10**. Size comparison between adult females (9) and males (10). **Figure 11**. UV fluorescence comparison between adults of normal (left two) and albino (right two) *O. martensii* under 395 nm UV light (those scorpions were used for subsequent photography of detailed structures). Following their submersion under water to cause temporary hypoxia, dried scorpions were placed on an elevated layer of non-fluorescent, non-reflective glass layer against a black light-absorbing fabric. A 450 nm long pass filter was assembled onto the camera lens. Camera settings (single shot): manual mode, white balance = AWB, shutter speed = 1/25, F5.6, ISO = 100. Raw file (CR2.) was converted into JPG. No further adjustment was applied to the photo.

incidence attributed to genetic mutations. If their normal, dark colored counterparts are cryptic upon the substrates within their habitat, it is then foreseeable that the albinism is maladaptive in making the animal more visible to predators. As opposed to some hypogean scorpions with pale coloration while simultaneously lacking ocular structures (or reduced, or partially, e.g., lacking merely the median ocelli), the median ocelli are retained but simply lacking melanin in the underlying structures in albino scorpions, thereby rendering those structures inconspicuous in their appearance. This apparently "bleaching" of the ocelli must therefore be considered as a key indicator for the identification of albinism.

Results

Olivierus martensii (Karsch, 1879), also known by its Chinese equivalent "马氏奥氏蝎", stands as the most prevalent scorpion species in China. An overview pertaining to its taxonomic history can be referenced in Qi et al. (2004). Remarkably, this species has a long history of its utilization in traditional Chinese medicine under the name "全蝎" (Tang, 2022; Tang et al., 2024: 33). Numerous "scorpion farms" dedicated to the cultivation of this species exist in China. Supported by an enormous number of the individuals captively bred, various phenotypes unreported from its natural habitat have been observed under those captive conditions,



Figures 12–19. Comparison of median ocelli of *O. martensii*. **Figures 12–18**. Albinos (same sequence as in Figs. 2–8). **Figure 19**. Normal adult male.

with photos disseminated via social media platforms. Among these observed anomalies, anatomical malformations (teratology) characterized by the duplication of metasoma were most frequently observed, albeit devoid of any formal documentations in this regard (Sherwood & Armas, 2023). On the other hand, chromatic mutations were particularly displayed as a reduction of infuscation, including albinism.

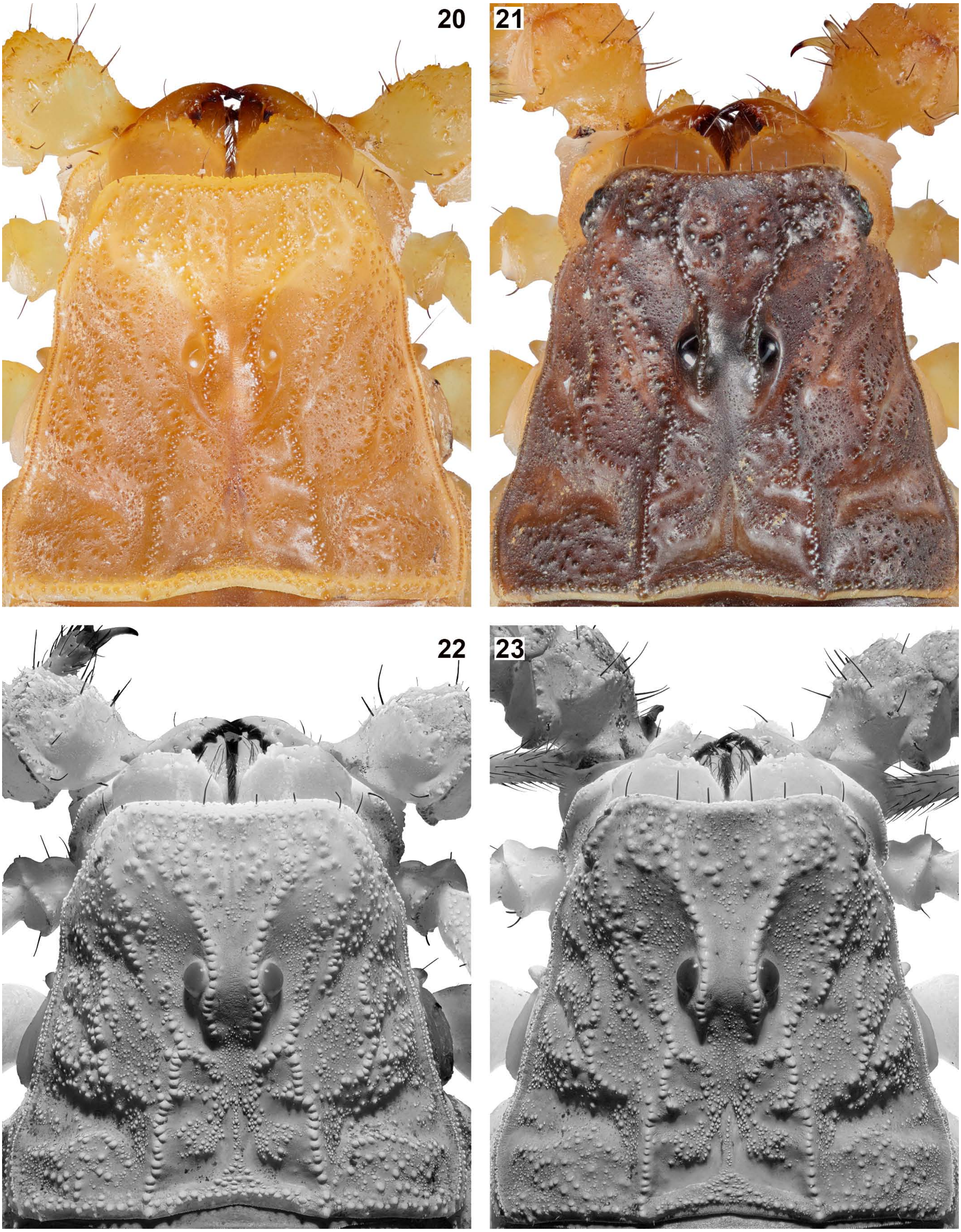
Morphological comparison between albino and normal phenotypes

Coloration: *O. martensii* typically exhibits a base color range that spans from pale brownish yellow to orangish/reddish yellow, with chelal fingers being pale reddish brown (cf. Tang et al., 2024: figs. 157–158, 163–164) and patellae of legs occasionally being greyish brown. The contrasting color pattern is manifested in two regions, dorsum (carapace + tergites) and metasoma V, which are often dark brownish. A crude inspection upon these two regions may yield a visual effect as being blackish (due to the underlying viscera) or greyish (due to dust accumulation). However, beneath these superficial appearances, the regions exhibit intricate color patterns (Figs. 36–37). The color pattern on the dorsum follows a symmetrical arrangement along the longitudinal axis, appearing as a dark, regularly hollowed mask on the tergites, but forming patches of dark areas on the carapace. On the other hand, the color pattern on metasoma V, especially on its ventral surface, is more distinguishable. Two layers of color constitute the overall infuscation: a brighter base layer and a darker, reticulated layer (cf. Tang et al., 2024: figs. 164, 167). The dark layer is essentially formed by two Y-shaped (with two heavy "branches") chromatic configurations flanking the ventromedian carina, with the "stalk" directing anteriorly and the "branches" extending posteriorly. The underneath along the ventromedian carina is also darkened.

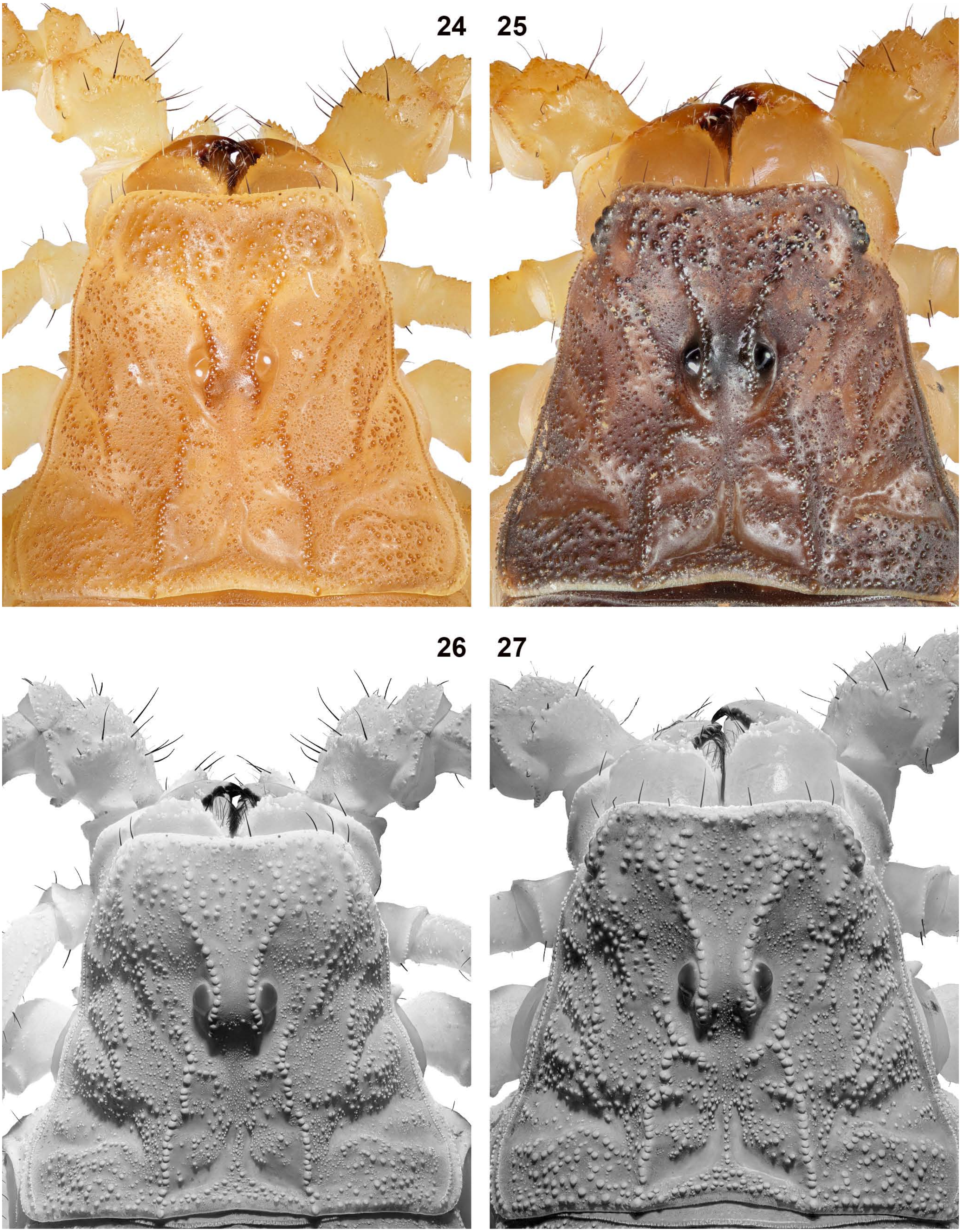
The overall coloration of the albino *O. martensii* is pale yellow, with the following contrasting areas: (1) pedipalp fingers somewhat reddish, akin to those of the normal specimens; (2) legs gradually lighten distally; (3) telson resembles that of the normal specimens, characterized by a bright yellow vesicle and a reddish aculeus that increasingly becomes black towards the extremity (Figs. 1–8). The color of the median ocelli varied among specimens, with some being pale reddish brown and others being undistinguishable from the surrounding cuticle (Figs. 12–19). It is worth noting that the median ocelli of the albinos were more greyish than their normal counterparts under UV light (Fig. 11), probably owing to the lack of melanin. Due to the absence of black epidermal pigmentation, the mesosoma took on a brownish tint and displayed a dark longitudinal band attributed to the underlying viscera. This brownish hue extended to the carapace, and terminated at an arcuate border, beyond which a pale yellow hue dominated. This semicircular region is associated with the oral concavity that accommodates the chelicerae of the scorpion. Posterior margins of the carapace and I–VI tergites were bright yellow, probably owing to the sclerotization and its separation from the coelom. All carinae and granules appeared pale reddish brown, nearly blended into the underlying cuticle.

Ratiometrics and morphometrics: Locket (1986) found no morphological difference between the albino and normal *U. yaschenkoi*. However, crude inspection of our *O. martensii* revealed an obvious disparity in the ratiometrics, especially those concerning the metasomal segments. As shown in Table 1, metasoma IV–V are typically more slender in the albinos, although none of the ratiometrics displayed significant difference (Mann-Whitney U test, $p \in \{0.05714, 0.07143, 0.2286\}$, for all test results), probably owing to the extremely low sample size. Additionally, the albino *O. martensii* were also smaller than the normal ones (Figs. 9–10). Total length difference was not statistically significant when tested between phenotypes, while the opposite was true when tested between sexes (phenotypes pooled for each sex) (Table 2). Those results must be treated with caution, as the low sample size introduces bias related to potential intraspecific variations in those regards. Specifically, genes controlling the melanin production and morphology (size and ratiometrics) may be completely independent of each other, and a possible simultaneous inheritance of albinism and slenderness from the parents argues against the correlation between the two traits in albinism. Consequently, it remains ambiguous as to whether the defect in genes controlling the melanin production would negatively impact other genes (i.e., whether slenderness and small size are inevitable by-products in albino *O. martensii*).

Meristics regarding PTC and DSC exhibited no mutation, falling into the variation range of normal *O. martensii*. However, mean DSC appeared to be somewhat lower in the albinos, with 12 rows being more frequently observed (Table 1). Nevertheless, no significant difference was detected (Mann-Whitney U test, $p = 0.1205$). The lower mean DSC might be correlated with the smaller size in albinos. To testify the assumption, the total length of each scorpion (for both phenotypes) was paired with its mean DSC value (continuous vs. discrete variables). The result from a simple linear regression analysis confirmed a strong positive correlation between males, but a weak to moderate one between females (Table 2). However, sexual dimorphism in total length could result in a misleading result. Still, within-phenotype comparison detected no significant difference in this regard, nor did between-phenotype (sexes pooled for each phenotype) comparison (Table 2); again, cautions are warranted when interpreting those results due to the low sample size. Similarly, regression tests were also performed for the correlation between total length and the four metasoma ratiometrics in Table 1, with albino and normal specimens pooled together. The results showed a moderate to strong inverse relationship between the body size and metasoma ratiometrics for both sexes, except for the L/W of metasoma IV in females (Table 2).



Figures 20–23. Comparison of carapacial carination and granulation between male albino (20, 22; No. 7) and normal (21, 23) *O. martensii*. **Figures 20–21**. Under white light. **Figures 22–23**. Under UV light.



Figures 24–27. Comparison of carapacial carination and granulation between adult female albino (24, 26; No. 6) and normal (25, 27) *O. martensii*. **Figures 24–25**. Under white light. **Figures 26–27**. Under UV light.

Morphosculptures: Examination of morphosculpture focused on the carinae and granulations on the carapace and tergites (Figs. 20–31). No conspicuous distinction regarding the development and density was discovered between the albino and normal specimens, except that the tergal morphosculpture was slightly coarser in the normal female *O. martensii* examined (Figs. 30–31), but could nonetheless be ascribed to the intraspecific variation. On the contrary, tergal granules were slightly denser in the albino male (Figs. 28–29). It thus appears that the mutation in melanin formation did not significantly lead to the decline of morphosculptural coarseness or density. A more objective methodology for analyzing the statistical significance of the difference in carapacial granulation can be found in Tang et al. (2023: 15).

Hemispermatophores: A pair of hemispermatophores from one adult male albino *O. martensii* and one adult male normal counterpart were retrieved (Figs. 41–44). No discernable difference was observed, except that the hemispermatophore length (from the tip of capsule to the junction between mid-axial rib and pedicel) of the albino male is shorter than that of the normal male by a fraction of 9%. We inclined to ignore the difference in absolute length since this aspect is intraspecifically variable (smaller males do not necessarily possess smaller hemispermatophores; Tang, pers. obs.).

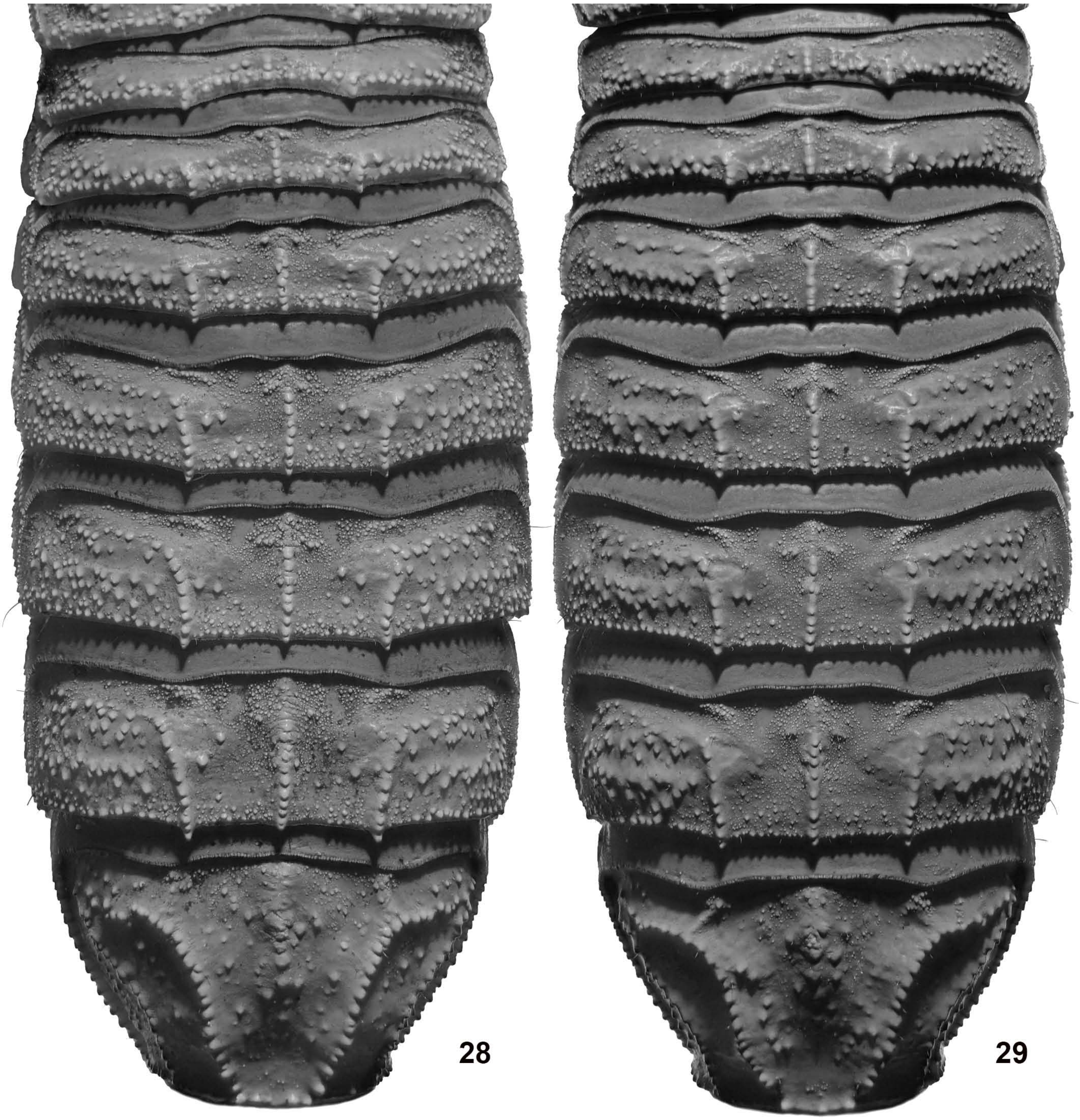
Behavioral comparison between albino and normal phenotypes

Predatory & anti-predatory responses: No discernable difference was discovered between the albino and normal phenotypes regarding their predatory behavior towards the crickets introduced. This result was foreseeable since scorpions do not heavily rely on their visual ability but trichobothria to detect the potential prey; no obvious difference was found in the chelal setation between the two phenotypes (cf. Figs. 32–35 vs. Tang et al. (2024: figs. 163, 166)). On the contrary, in his study with *Leiurus quinquestriatus* (Ehrenberg, 1828), Abushama (1964: 151) discovered that blind scorpions did not prey upon the prey, albeit their positive responses towards the movement of cockroaches. However, the predatory desire is intraspecifically variable even within a group of normal scorpions (Tang, pers. obs.). Yet notably, Gaffin et al. (2012) mentioned that the median ocelli are possibly capable of image formation. During our investigation, albino individuals appeared to be more aggressive when confronting predatory stimulus, simulated by using tweezers to pinch or touch the specimens: while the normal specimens may remain rigid, motionless and display cataleptic response, the albinos often reacted violently by wielding their metasoma, in an attempt to evict the "predator". The albino *O. martensii* also appeared to be more sensitive to the vibrations. This stark behavioral disparity could be associated with the potential physiological difference between the normal and abnormal scorpions. Although eyes do not play an important role as in many other visual animals, they are nonetheless responsible for light detection, aiding scorpions in finding shelters. The presence of a potential predator could be accompanied by a sudden obstruction of light path which can be perceived by the scorpion, thereby triggering them withdrawing to their burrows. With presumably reduced light detection ability, albino scorpions have to, theoretically, rely more on their other sensorial functions. This may progressively lead to a heightened vigilance during their post-embryonic development, towards their adulthood. Additionally, it is still uncertain whether the lack of melanin could affect the hormonal regulation level related with physiological stress in scorpions, co-impacting the behavior in albino individuals.

White light perception & self-cleaning behavior: Black absorbs most of the visible lights that strike it, rather than reflecting them, a nature that may explain why all "eyed" scorpions exhibit a black appearance in their median and lateral ocelli. Within eumelanin and pheomelanin molecules, there are specific chromophores that have conjugated double bonds and aromatic ring structures. These chromophores allow melanin to absorb light effectively. In the first report of albino scorpions, Locket (1986: 112–113) also discussed the potential disadvantages induced by the lack of melanin in the median ocelli. The efferents of the optic nerves in the retina mediate the migration of pigment granules which follows a circadian pattern – concentrated at the vitread part of the retina diurnally and retreat to the basal part nightly, thereby regulating the light absorption. The lack of melanin in the retina would undoubtedly contribute to the functional deficit. In the albino *U. yaschenkoi*, the rhabdoms were disorganized, presumably arising from the absence of melanin granule that normally protect the integrity of rhabdoms from excessive illumination.

It is also interesting to note that the black pigment is not restricted within the radius of the ocellus itself in many scorpions. This is particularly observable in light-colored species. For instance, in *Olivierus longichelus* (Sun & Zhu, 2010), a black interocular band connects the two median ocelli (cf. Tang et al., 2024: figs. 5–6). This dark epidermis is likely linked with that of the median ocelli, increasing the surface area for light absorption. Alternatively, it may also assist in shielding the median ocelli from the glare of direct sunlight shining down from above. Notably, a teardrop-shaped area presents anterior to each of the median ocelli. This area shares the same hue as the base color (pale yellow), is delineated by a peripheral brownish color band that gradually transitions into pale yellow externally. The function of this teardrop-shaped area is unclear, but it might serve to enhance light reflection anterior to the dark median ocelli.

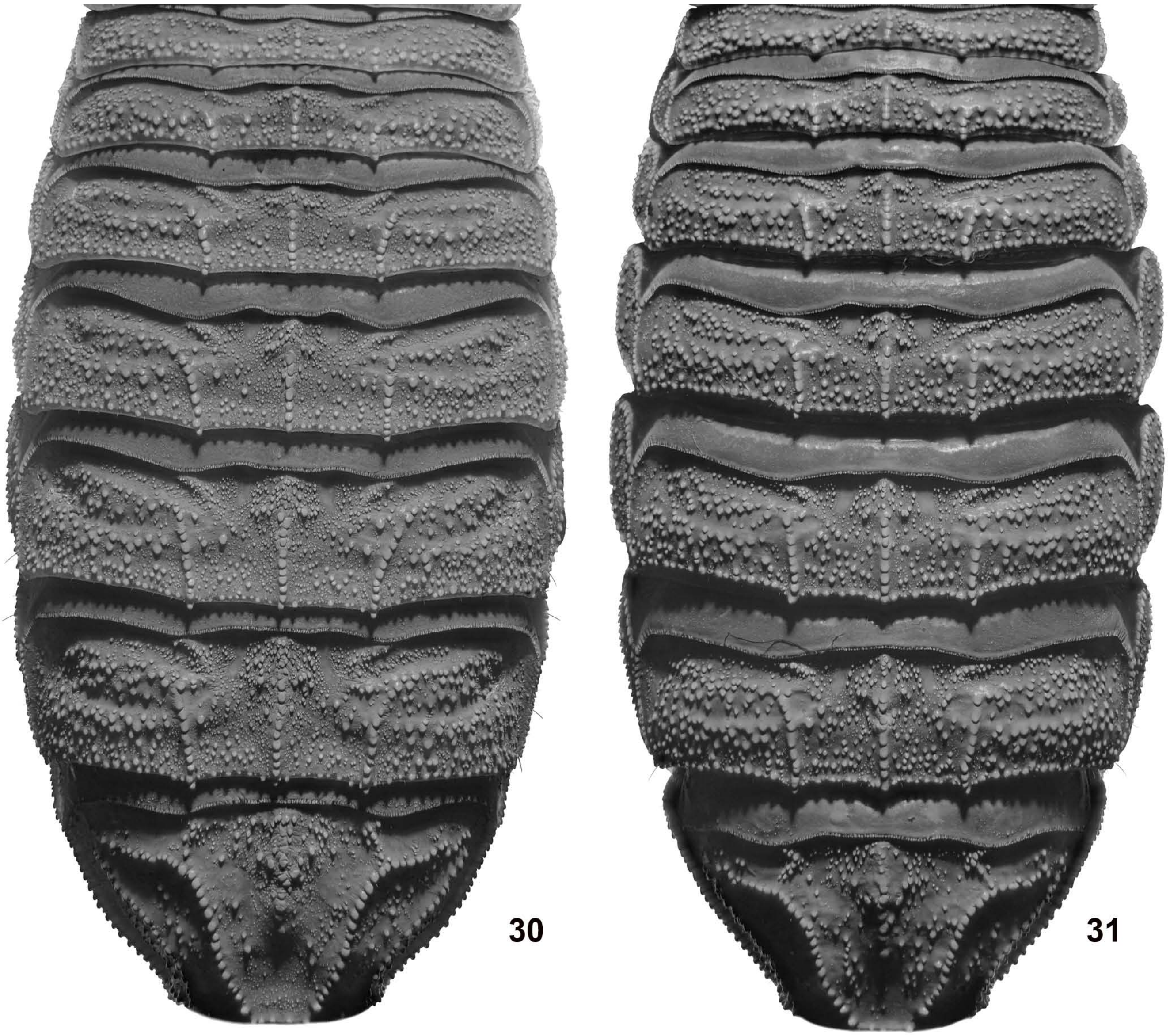
Under captive condition, several scorpions have displayed intriguing behaviors. When their cuticle was covered by sand dust, *Androctonus australis* (Linnaeus, 1758), *A.* aff. *crassicauda* (Olivier, 1807) and *Leiurus jordanensis* Lourenço et al., 2002 were observed engaging in self-cleaning behavior (Tang, pers. obs.). The self-cleaning behavior typically entailed the manipulation of pedipalps, metasoma and telson,



Figures 28–29. Comparison of tergal carination and granulation between adult male albino (28; No. 7) and normal (29) *O. martensii* under UV light (for white light of normal adult male *O. martensii*, see Tang et al., 2024: fig. 158).

and occasionally the first two pairs of legs. Scorpions appeared to secrete a type of liquid, potentially with similar components to their digestive juice, which they applied to the surfaces of the chela and telson by inserting these structures between their chelicerae. Their cleaning areas consistently involved the area surrounding the median ocelli (this was conveyed by the "dust pattern" on their carapace), notwithstanding the rest area remained dusty (cf. Tang, 2023: fig. 8f; the lateral ocelli appeared to be of less concern). This result putatively demonstrated that scorpions are aware of the importance of their median ocelli, supposedly only if when their visual function remains intact. The anatomical structures involved during the cleaning procedure were subsequently extensively investigated in (Lowe & Tang, 2024).

In order to test whether the albino *O. martensii* retains such a behavior, loess dust (contrasting better with the cuticle) was covered upon the normal and albino *O. martensii* with the former as the control. The dust-coating procedure was



Figures 30–31. Comparison of tergal carination and granulation between adult female albino (30; No. 6) and normal (31) *O. martensii* under UV light (for white light of normal adult female *O. martensii*, see Tang et al., 2024: fig. 157).

repeated multiple times to ensure consistent results. Scorpions were housed individually in small containers with moistened sand. Observations of the first author have revealed that a wet substrate stimulates the self-cleaning behavior of scorpions. This hygrokinetic response is likely due to the presence of adequate humidity in the environment, which assures scorpions that using their own liquid will not result in dehydration. Since those albino specimens were observed with self-cleaning behavior prior to this trial, it was expected that the resulting "dust pattern" would be irregular and not targeted at the median ocelli. Footages of their self-cleaning behavior can be found at: www.youtube.com/watch?v=nTv-MTBp7zQ; www.youtube.com/watch?v=Fj77GQKKO2M. Those videos were taken casually with mobile phone in dim environment for fear that the scorpion may be disturbed, thus not optimal for inspecting their sophisticated behavior.

Following several rounds of "dust-coating" procedures, a dissimilar outcome was observed. As anticipated, normal *O. martensii* engaged in the expected self-cleaning behavior by cleaning the lateral surfaces flanking their median ocelli. However, not all albino *O. martensii* performed this self-cleaning behavior. It seems that the importance of maintaining a clean carapace is somewhat diminished in albino individuals. The "dust pattern" on the carapace was relatively uniform among different normal individuals (Figs. 45–52): approximately symmetrical with the median axis, with at least four regions being cleaned; some individuals performed a more thorough cleaning. In contrast, the "dust pattern" varied among different albino individuals and appeared irregular (Figs. 53–58). Occasionally, only one side flanking the median ocelli was cleaned. Particularly, even if the lateral surfaces were cleaned, the same can often not be said for the areas

Figures 32–35. Right pedipalp chelae of adult albino *O. martensii* under white light. **Figures 32–33**. Pedipalp chela in external view (32) and movable finger in dorsal view (33), male (No. 7). **Figures 34–35**. Pedipalp chela in external view (34) and movable finger in dorsal view (35), female (No. 6).

proximal to the median ocelli. It hence appears that the albinos did not owe their cleaning behavior to the purpose of ensuring a clear vision. Instead, we surmise that those scorpions did so only as a response to the excessive dust accumulation on their bodies.

Response to UV light:

Fluorescence and UV detection in scorpions: As commonly being nocturnal, scorpions exhibit negative phototaxis (Abushama, 1964; Gaffin & Barker, 2014). The photosensitivity in scorpions was initially associated with their median and lateral ocelli. Belmonte & Stensaas (1975) suggested that it was characterized by a graded depolarization and a generation of nerve impulses from the axons, forming the optic nerve originated directly from the photoreceptors caused by the exposure to light. However, Fleissner (1985) later clarified that the photoreceptors are non-spiking retinular cells that only generate graded receptor potentials. On the contrary, arhabdomeric cells within the retina are responsible for the action potentials superimposed on a similar graduated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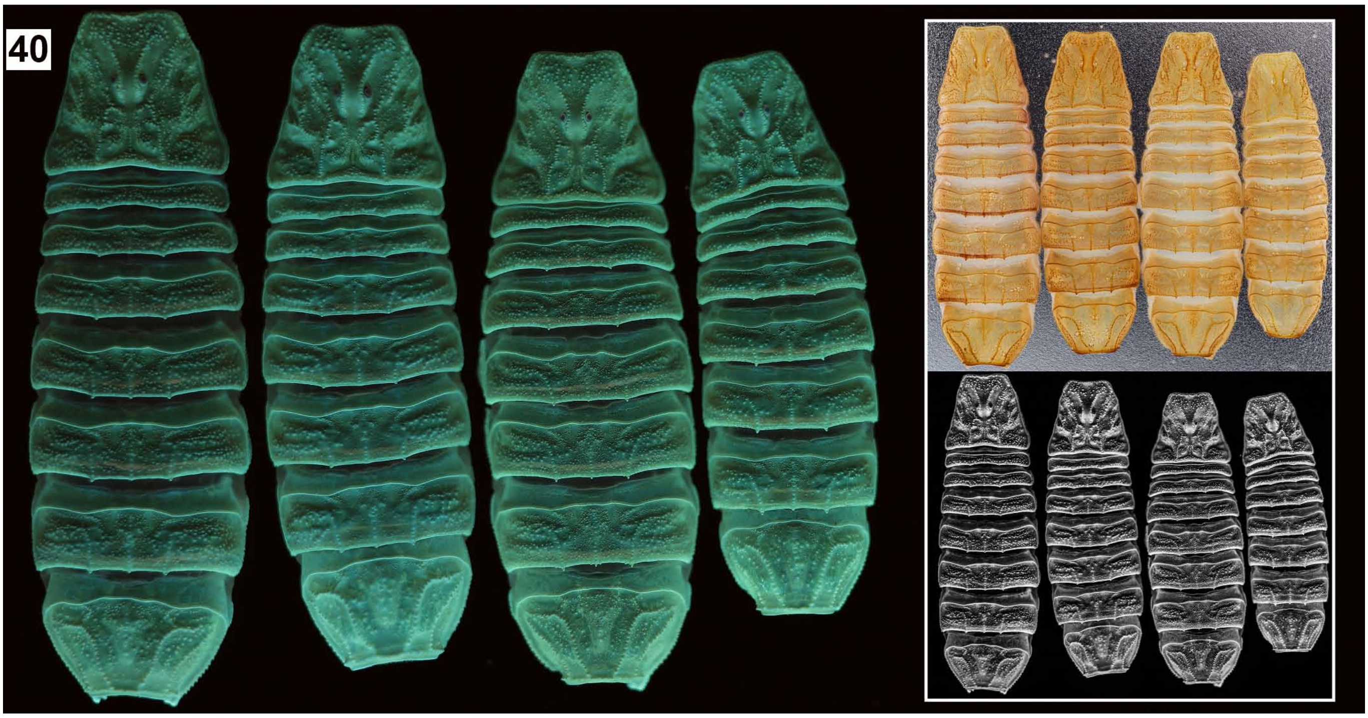
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Figures 36–40. Comparison of carapace and tergites between adult normal and albino *O. martensii* after removal **Figures 36–39**. Comparison of coloration between adult normal (36–37) and albino (38–39) specimens, placed against a white A4 paper background under water, with normal specimens showing intricate color pattern: adult female normal (36) and albino (38; No. 6) specimens; adult male normal (37) and albino (39; No. 7) specimens. **Figure 40**. Comparison of UV fluorescence between adult albino and normal specimens (same sequence and settings as in Fig. 11, no further adjustment, but an achromatic counterpart with enhanced details is provided as additional information). Inner surface of cuticle was further cleansed by sonication and fine tweezers in trypsin solution (dissolved in 37 ˚C water), and subsequently air-dried.

potential. Abushama (1964: 150) studied the photosensitivity of *L. quinquestriatus* by coating their carapace with red-brown nail varnish paint covered with Indian red ink, concluding that this species relies solely on its ocelli for light detection. However, it appears that not all scorpions are confined by their eyes for photosensitivity, a fact which Zwicky (1968, 1970) first pointed out when he discovered the existence of extraocular photoreceptors in the metasoma of *Urodacus* sp. and suggested these might also occur in other light-colored body parts. His figure 1 (Zwicky, 1968: 259) indicated that the photoreceptors may be located in the fifth metasoma and unrelated to the ganglia presented in preceding segments. Subsequently, Geethabali & Pampapathi Rao (1973) found similar neural photoreceptors in two species of Heterometrinae, *Srilankametrus gravimanus* (Pocock, 1894) and *Chersonesometrus madraspatensis* (Pocock, 1900) (misidentified as *C. fulvipes* (C.L. Koch, 1837); Prendini & Loria, 2020: 86), with latency in response negatively correlated with light intensity. They also noted that those receptors can adapt to the prolonged exposure of light. On the contrary, their findings demonstrated that the location of the photoreceptors varied between the two species (located in telson in *S. gravimanus* but in ganglia in *C. madraspatensis*), and the photosensitivity was not affected by the separation of the telsonic nerves, as opposed to Zwicky (1968)'s results. This implies that a diversity of metasomal photoreceptor types may yet to be found across different taxonomic groups. Interestingly, observations of the first author also revealed that the curling of metasoma typically preceded the overall locomotion after a resting scorpion was illuminated by the UV light. Using the cuticle covering the entire body as a broad photon-collector is theoretically more efficient than using merely the ocelli restricted to the carapace directed at a limited visual field. However, it remains unknown as to the total coverage of those extraocular photoreceptors.

All known scorpions exhibit varying degrees of fluorescence when exposed to UV light, emitting a green to blue glow under the long-wave UV excitation range of 320–400 nm, as a result of the fluorophores presented in their cuticle. Krishnan's (1953) study on the cuticle of *Gigantometrus swammerdami* (Simon, 1872) revealed that the exoskeleton was comprised of three main layers, viz., epicuticle, exocuticle and endocuticle (EC). Subsequent research further discovered several sublayers within the former two (e.g., inner exocuticle (IX); Filshie & Hadley, 1979; Hjelle, 1990), including the outer sublayer, hyaline exocuticle (HX; Kennaugh, 1959), containing beta-carboline and 7-hydroxy-4-methylcoumarin, giving rise to the main fluorescence under UV light (Frost et al., 2001; Rubin et al., 2017). In fact, the "epicuticle" termed by Krishnan (1953) was the HX, and his "exocuticle" was the tanned IX (Kennaugh, 1959; Malek, 1964). Another intermediate layer between the exo- and endocuticle, termed "mesocuticle", was found in structures requiring higher mechanical tolerance (Lowe & Fet, 2024: 79). Recent study shows that the fluorescence may not be always restricted to the HX, and weak fluorescence can be observed in the EC (as a secondary barrier against UV penetration) as well as the lenses of ocelli (Lowe & Fet, 2024: 88). If the fluorescence in the EC is perfectly uniform across its depth, it may then imply an intrinsic property rather than an artifact resulting from the diffusely scattered light from the strongly fluorescent HX (Lowe & Fet, 2024: figs. 871, 873). Intriguingly, in some species, the EC may emit stronger fluorescence than the exocuticle in some regions of the body (Lowe & Fet, 2024: fig. 880). Yoshimoto et al. (2020) discovered another fluorescent compound from the exuviae of the scorpion *Liocheles australasiae* (Fabricius, 1775), macrocyclic diphthalate ester, albeit its presumably negligible contribution to the ultimate fluorescence. Recent studies conducted by (Liu et al., 2024) suggest that there may be other compounds responsible for the fluorescence.

Major studies revolving the light detection in scorpions pertain to whether scorpions react more actively to the original UV light, or the UV-excited green light emitted from their cuticle. It was observed that scorpions are most active and emit green light most strongly when elicited by 395 nm UV light. Their median eyes are most sensitive to green light of longer wavelength (~500 nm) and secondarily to UV (350–400 nm), while their lateral eyes show negligible response to green light but being particularly responsive to UV light (Machan, 1968: 104; Gaffin et al., 2012: 434; Gaffin & Barker, 2014: 111). As already proposed by previous authors, this suggests a hypothesis that fluorescence may assist in light detection by converting UV light into increased light intensity within the range of their visual system's peak sensitivity at higher wavelength (Gaffin & Barker, 2014). Compared to unimpaired individuals, fluorescence-reduced scorpions exhibited lesser preferential disparity between UV-exposed and unexposed zones, indicating weaker sensitivity to the UV light (Kloock et al., 2010). Gaffin et al. (2012) compared the behavior of *Paruroctonus utahensis* (Williams, 1968) with their median and lateral ocelli of covered with aluminum foil pieces (but the foil pieces actually covered a broader area on the carapace; Gaffin et al., 2012: fig. 4b) when treated under four light conditions (395 nm UV light, 505 nm cyan-green light, 565 nm yellow light, no light). Despite significant differences between 395 nm vs. 565 nm and 505 nm vs 565 nm, all groups of scorpions reacted to the illumination. They also found that the locomotion of the scorpions exposed to 505 nm was strongly reduced, whereas under 395 nm, such activity was less affected (Gaffin et al., 2012: fig. 4c). Based on these results and interpretations, it is plausible that the ecological significance of fluorescence in scorpions lies in their contributions to detect shelters, with their cuticles effectively serving as whole-body UV photon collectors which may contain additional extraocular photoreceptors. Kloock et al. (2010) postulated that the fluorescence of scorpions might influence their decision to avoid foraging on brightly moonlit nights. However, a subsequent study by Gaffin & Barker (2014) found no behavioral differences between conditions where UV light levels matched those of full moon nights and no-light conditions, indicating that UV component of moonlight does not act as a deterrent to scorpions' nocturnal activities.

Figures 41–44. Comparison of paired hemispermatophores between albino and normal *O. martensii*. **Figures 41–42**. Albino male (No. 7). **Figures 43–44**. Normal male (the pedicel of one hemispermatophore accidentally detached during manual dissection).

López-Cabrera et al. (2020) confirmed the positive correlation between the intensity of fluorescence and the color tonality in scorpions, a conclusion also supported by the previous observations of the first author. While the UV light serves as a powerful tool to cancel out the optical artefacts induced by the coloration of different species, hereby facilitating the examination of the cuticle surface reliefs, basic color patterns are occasionally retained even under the UV illumination. These patterns are manifested by the intensity disparity in fluorescence, associated with the color tonality under white light. The color tonality under the white light is primarily determined by the concentration of melanin and other epidermal pigments underneath the cuticle. The intensity of fluorescence is positively linked to the thickness of cuticle and the brightness of color, resulting in stronger emission in condensed structures with thicker HX (e.g., carinae and granules; Lowe & Fet, 2024: 77–78) and regions with brighter colors. López-Cabrera et al. (2020) concluded that association between the fluorescence intensity and the color tonality, and that between the color tonality and the specific substrate on which the scorpions inhabit, indicate a direct relationship between the fluorescence and the ecomorphological adaptation in scorpions. However, the heterogeneous fluorescence intensity is simply a side effect of epidermal pigments absorbing some of the emitted fluorescence. Therefore, the fluorescence may not necessarily contribute to the adaptation in this regard. Certain pigments within and/or under the cuticle may absorb a fraction of the emitted fluorescence, yielding the reduced amount of fluorescence back-scattered by tissues that can be observed externally, and therefore the overall heterogeneity. To this end, a comparative photo of normal and albino *O. martensii* under UV light was taken, which showed a heterogeneity of fluorescence in the normal specimens (Fig. 11). In addition, another photo was taken for carapace and tergites following their removal from the scorpions (Fig. 40). It is evident and foreseeable that the sub-cuticular pigment plays an important role in affecting the emitted fluorescence, as the intensity was alike among the removed cuticles. Recently, it has been emphasized that such optical disparity may also be due to the cuticle geometry heterogeneity where convex areas would enhance the fluorescence trapping as opposed to the concave areas (Lowe & Fet, 2024: 80). The diameter of the cross-section curvature (of carinae and granules) and the thickness of the HX together enhance the fluorescence intensity as one decreases and the other increases.

In many vertebrates, melanin in the skin absorbs UV rays, acting as a protective shield by preventing deep penetration of UV radiation and damage to DNA and other cellular components. It is uncertain whether the melanin in scorpions also serve the same function. Frost et. al. (2001: 367) tangentially proposed that the fluorescent compounds in their cuticle could be effective in shielding against DNA damage caused by solar UV radiation: "*We would like to propose an additional hypothesis: that fluorescent compounds in scorpion hyaline exocuticle are a relict feature, which could have served as a sunblock, shielding scorpions from the UV component in sunlight... protection from cell- and DNA-damaging UV light would be an extremely highly valuable selective trait*". High level of fluorophore concentration is found in the HX of most scorpion species (except for some chaerilids; Lowe & Fet, 2024: 94–95), which may be responsible for the major UV absorption. However, the weaker fluorescence intensity in other layers of cuticle does not necessarily indicate the absence of UV absorbing molecules, which may simply be weak or non-fluorescent (e.g., melanin). The combination of HX, IX and EC was found to be highly effective during UV transmission reduction, attenuating the UV passage by ~91–99% (Lowe & Fet, 2024: 88, 101). Taking all these previous findings and hypotheses into account, we speculate that the color tonality, microhabitat substrate, fluorescence intensity and the fluorescence function, are interrelated. To be specific, scorpions with bright color are often found on arid substrates where desiccation poses a threat, while those with darker colors tend to dwell in more humid and dim forest environments; it must be noted, however, dark species (e.g., some *Androctonus*) also occur in arid environments, and vice versa for light species dwelling in the humid ones. If the ocelli of the scorpions were to perceive the green light converted from the UV light and emitted from their cuticle, scorpions in open, arid environments may be more dependent on this ability to accurately gauge the level of UV radiation outside their burrows. However, the correlation between the color tonality and the fluorescence intensity may suggest that the latter could be a byproduct of the cryptic coloration, i.e., the bright coloration serves a dual purpose: blending into the substrate while rendering high fluorescence intensity.

UV response of *O. martensii*: In light of all the above considerations, we assume that albino scorpions may not display a significant functional deficit regarding basic light-intensity detection provided that there are other photosensitive regions available, but will be less proficient compared to their normal counterparts. Additionally, albino scorpions may emit stronger fluorescence due to the absence of epidermal pigments. This will increase the available fluorescence to extraocular (or ocular) receptors for a hypothetical UV-to-green light detection mechanism, thereby counteracting with the compromised visual ability (but only in terms of its fluorescence detection). Finally, if the melanin pigments are indeed responsible for DNA protection in scorpions, then a lack thereof will likely affect the well-being of the albino individuals. A preliminary assessment of their sensitivity to UV illumination at a wavelength of 365 nm was conducted. Since the fluorescence is a byproduct that can be perceived by the scorpion as well, this test does not distinguish their reactions to the UV light and their own green light. The objective of this experiment was to determine if the albino scorpion could still utilize their eyes as a means to locate shelters, whether by UV or fluorescence perception.

Figures 45–52. Comparison of the "dust pattern" on carapace after self-cleaning in normal *O. martensii*. **Figures 45**, **49–52**. Adult females. **Figures 46–48**. Adult males.

Scorpions were tested individually on an expanded polyethylene foam board aimed to amplify UV reflectance, surrounded by four UV lamps. This allows scorpions to be able to grip on a substrate, thereby reducing their anxiety. Scorpions were covered by a black light-absorbing fabric and constrained by an inverted glass beaker, left undisturbed for about 5–10 minutes (depending on the current behavior of the individual) to allow acclimation until they became motionless. First, it was ensured that all normal individuals (untreated) exhibited a response to UV light by confirming their ability to detect and evade UV illumination through their observable locomotion (Phase 1). The evasion from UV light was recognized by a sudden sprint rather than any movement which may simply represent a familiarization towards the environment by the scorpion, especially when the speed is low or gradual. Next, their carapace, tergites and metasoma (including the telson) were coated with black modeling clay. This approach was adopted as the scorpion's cuticle proved resistant to ordinary light-blocking tapes, while stronger adhesives or paint could pose a potential harm to the scorpions. The objective was aimed to determine if the scorpion would still react to UV illumination under such condition, considering


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Figures 53–58. Comparison of the “dust pattern” on carapace after self-cleaning in albino *O. martensii*. **Figure 53**. No. 1. **Figure 54**. No. 2. **Figure 55**. No. 3. **Figure 56**. No. 4. **Figure 57**. No. 6. **Figure 58**. No. 7.

Figures 59–62. Comparison of albino and normal *O. martensii* on two types of substrates under white light. **Figures 59–60**. Albino (59; No. 6) and normal (60) adult females on heterogeneous leafmould. **Figures 61–62**. Albino (61; No. 7) and normal (62) adult male on gravels.

the potential existence of other photosensitive areas. Covering the appendages of the scorpion with clay would cause several problems, including the potential for a struggle response that might bias the assessment of their reaction to UV light, as well as potential interference with the scorpions' locomotion and adhesion between adjacent appendages induced by the clay. If it were confirmed that there were no photosensitive receptors in the scorpions' appendages, the assessment of their eye response to UV light could therefore be conducted without the need to cover those areas. However, such method does not take into account the microsetae that might potentially be used for UV detection arrayed on those appendages. This procedure was carried out for all tested normal individuals (Phase 2). Then, both normal and albino groups had their tergites and metasoma (including the telson) covered with clay to restrict the test area to their carapace (Phase 3). Finally, only the carapace of albino individuals was covered with clay, so as to see if they would still react to the UV illumination (Phase 4). On account of the possibility that thermal energy generated from the conversion of light energy when the UV light struck the scorpions' cuticle could potentially incite an escape response, leading to an artefact of their reaction to UV light, all individuals were initially exposed to white light for 10 minutes to equalize thermal conditions hence minimize this potential artefact. However, no available data were known to us as to the threshold temperature to be detected by *O. martensii* that would evoke their negative response (likely dependent on their cuticle). Thus, our equalization was based on arbitrary speculation. The response latency of both the normal ($n = 7$) and albino ($n = 5$) groups was recorded and compared to assess their response to UV light. Only a single trial was conducted for each individual, as we suspect that multiple stimulations by the UV light may cause accumulative effects in scorpion behavior that may bias the result, while if one were to increase the time interval between trials, the prolonged time of clay coverage might also affect the physiological state of the scorpion.

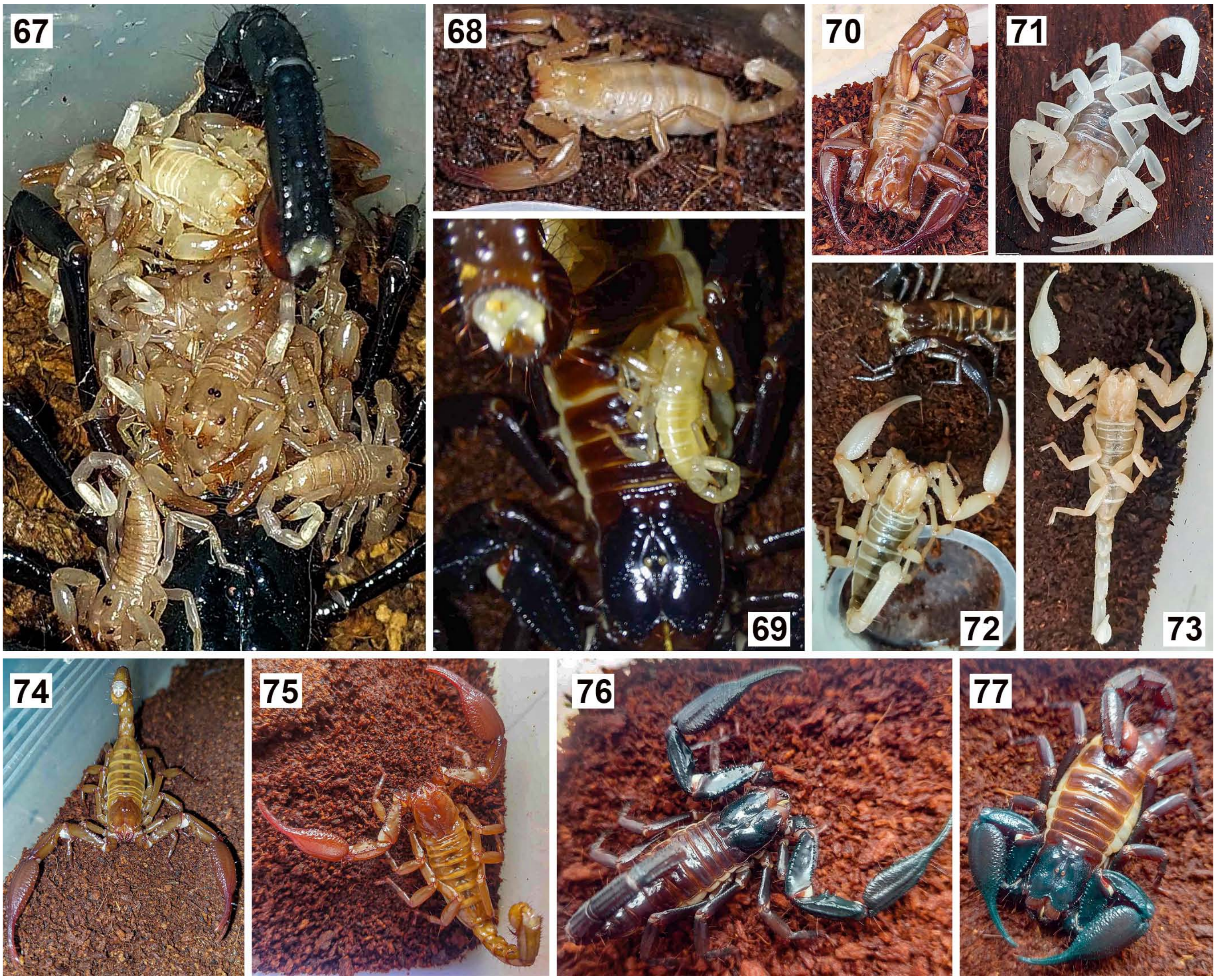
It was observed that all normal individuals immediately react to the UV light under the untreated condition (Phase 1) in an attempt to evade the illuminated area, while such rapid response greatly diminished or vanished during Phase 2 in 5/7 individuals (remained motionless even after two minutes), presumably suggesting the absence of photosensitive receptors in their appendages, or at least the insignificance of those receptors should any exist. An alternative explanation is interpreted by the fluorescent microsetae on those regions. The remaining two individuals exhibited the same response as that of the condition in which they were completely exposed under the UV light. Those two individuals were more agitated after being covered with the clay, which might result in their

Figures 63–66. Comparison of albino and normal *O. martensii* on two types of substrates under diffusely reflected white light. **Figures 63–64**. Albino (63; No. 6) and normal (64) adult females on heterogeneous leafmould. **Figures 65–66**. Albino (65; No. 7) and normal (66) adult male on gravels.

stronger sensitivity towards, e.g., thermal accumulation induced by the UV illumination. Likewise, disparity in response time across individuals under the same condition could be attributed to their different physiological states (more vigilant/calmed). Such disparity was also observed among untreated normal individuals during Phase 1; however, they all reacted within approximately at most one minute after illumination. During Phase 3, the response latency difference between normal and albino groups was featured as the latter group showing a relatively more immediate reaction (Table 2) In Phase 4, albino individuals responded even sooner (Table 2) than the previous condition where their carapace was exposed, potentially suggesting the presence of photoreceptors in their meso- and/or metasoma. However, those two differences in response time of the albinos were not statistically significant (Table 2; normal vs. albino in Phase 3; Phase 3 vs. Phase 4 of albino). While it was observed that, in comparison to the untreated condition in which they moved towards a specific direction, some albino individuals with their carapace covered exhibited a more “aimless” behavior, constantly circling within a small area, this did not occur frequently. It is also worth noting that, agitated behavior manifested as continuously seeking shaded area was observed in all albino individuals even when they were illuminated by the white light. All these results suggest that the need for locating shaded shelters is not obstructed in albino individuals, and the lack of melanin in their ocelli does not lead to their incapability of light detection. The ability to perceive light primarily depends on the functioning of the eye’s photoreceptor cells. Melanin in the eye can help reduce glare and enhance contrast. The reduced response latency observed in the albino individuals could be attributed to their increased sensitivity to optical stimuli by a similar mechanism as observed in their anti-predatory response. Conclusively, the survivorship of albino scorpions in this aspect is not likely to be undermined by a lack of melanin in their eyes. However, given the scarcity of the albino specimen being tested here, the results should be treated with caution.

Coloration as a camouflage

Crypsis: **hypothetical function and analysis**: Scorpions typically display distinctive color patterns that serve specific ecological purposes, primarily associated with their cryptic significance, occasionally being aposematic (contrasting color patterns; e.g., infuscate metasoma V). Although in other organisms, color may also serve signaling functions (e.g., sexual, territorial, and species recognition), scorpions appear only sensitive to blue-green light. The color patterns of scorpions



Figures 67–**77**. Photographic evidences of albino *Heterometrus longimanus* (photo courtesy of Ang Wei Ayang). **Figures 67**–**68**. Parent (F_0) brood (67) of one albino offspring (68). **Figure 69**. New born albino offspring of F_1 brood between albino parents. **Figures 70**–**71**. Juvenile albino *H. longimanus* before (70) and after (71) ecdysis. **Figures 72**–**73**. Freshly molted adult pair of *H. longimanus* (male: 72; female: 73). **Figures 74**–**75**. Adult pair of *H. longimanus* showing light brownish yellow color (74: male; 75: female). **Figures 76**–**77**. Regain of melanin (76: male; 77: female).

are primarily observable from above, a perspective that the scorpion itself cannot readily target. Thus, their own color patterns may not constitute inter- or intraspecific recognition. However, the latter function might theoretically exist if they could perceive the fluorescence intensity difference owing to the underlying color pattern exhibited by different species, despite that mechanoreception and pheromone detection are more likely their predominant discrimination methods (Kloock, 2008; Jordan, 2010). Nevertheless, the UV intensity is often too weak in the wild to incite their blue-green light to the same degree as induced by an artificial UV light. Two common color patterns have been observed in taxa dwelling in humid, dim forest, one featured by variegation and the other displaying a uniform black. On the contrary, translucence or pale yellow are often presented in taxa associated with sandy or rocky environment. The optical effect induced by those color patterns mainly functions in two ways, allowing the animal to avoid detection from either the predator or prey: (1) background matching: using colors and patterns resembling those of the surroundings; (2) disruptive coloration: adopting high-contrasting patterns that obscure the contours of their bodies (Rodríguez-Morales et al., 2018; Price et al., 2019). To our knowledge, there has been no formal study on the color pattern of scorpions. Previous information involving the ecological function of colors in scorpions was often inferred as intuitive interpretations towards the association between the colors of scorpions and their substrates (Mc Cormick & Polis, 1990: 154; Lourenço & Cloudsley-Thompson, 1996).

To comprehend how these color patterns serve the specific cryptic needs of a scorpion, whether as a means of evading predators or capturing prey relying on their visual acuity, it is essential to deconstruct them through the prism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Figures 78–85. Photographic evidences of chromatically abnormal *Leiurus quinquestriatus* offspring at 2nd instar (photo courtesy of Richard McJimsey). **Figure 78**. Normal phenotype. **Figures 79–83**. Leucistic phenotypes. **Figure 84**. “Intermediate” state where the melanin is only partially lost in the median ocelli. **Figure 85**. “Semi-albino” phenotype.

of the three fundamental facets of color (Clark et al., 2011: 1239). Two prevalent representations of the RGB color model are known as HSL (hue, saturation, lightness) and HSV (hue, saturation, value), with the latter also sometimes referred to as HSB (where "B" represents "brightness"). Hue represents the dominant wavelength of the color, essentially defining the color itself as perceived by an observer. Within their specialized visual systems, animals selectively absorb specific wavelengths. Saturation (or chroma) denotes the intensity or purity of the color. Higher saturation values give rise to more vibrant, striking colors, while diminished values result in muted or pastel-like shades. Lightness mirrors the luminance of a color, with greater lightness lending a brighter aspect and lower lightness casting a darker hue. Value (= brightness) is similar to lightness in its function, and shares its achromatic nature with lightness. However, while minimal lightness and value both yield black, maximal lightness imparts white, irrespective of other color attributes. Conversely, maximal value contributes to a brighter color, depending on the interplay of hue and saturation. These properties can be quantified by performing spectrophotometry, a process that captures surface reflectance data (Clark et al., 2011). In the obtained spectral distribution of the reflected light, the peak wavelength or the shape of the spectral curve corresponds to the hue, with the value pertaining to its height. On the other hand, saturation is identified by the relative width of the spectral curve which is inversely related to the intensity. Lightness can be determined by the overall reflectance across the visible spectrum, as to whether the surface reflects a significant amount of light across all wavelengths (rendering it whitish). Color (chromatic) and luminance (achromatic) contrast was often measured for the color patches on an animal, and between an animal and its background, as a main approach to examine the perception of visual signals by animals (Van den Berg et al., 2019: 2).

While some researchers perceive this as an objective measure, allowing absolute spectral comparisons for animals and backgrounds in controlled laboratory settings, extrapolating from such data could introduce errors. As suggested by Stuart-Fox et al. (2004), the visual system of the perceiver, which varies significantly across different species, represents a crucial parameter when evaluating an animal's cryptic coloration against a specific background. Those visual systems are dependent on eye shape and size, visual pigment number and maximal absorbance, photoreceptor type and number, and retinal and post-retinal processing (Van den Berg et al., 2019: 2). Vorobyev & Osorio (1998) and Vorobyev et al. (1998) developed a visual model ("Receptor Noise Limited Model") facilitating the prediction of color discrimination ability of any given animals with minimal additional assumptions, provided that information regarding their spectral sensitivities and the relative number of photoreceptors in the retina are available. This model was employed in conjunction with spectral reflectance data to estimate how well the target animal, such as a predator, perceives its cryptic prey. Unfortunately, information regarding the natural predator of *O. martensii* is non-existent to our knowledge, despite an exhaustive review of all major papers related to this species (e.g., Wu, 1936; Qi et al., 2004; Shi et al., 2007; Wang et al., 2019). Nevertheless, Li et al. (2019) did reveal the resistance of *Pyxicephalus adspersus* Tschudi, 1838 to the toxin of this species, implying that similar amphibians could potentially prey on *O. martensii* in its native habitat. Likewise, the mere interspecific interaction was limited to the parasitoidism by *Sarcophaga dux* (Thompson, 1869), documented by Shi et al. (2015). It is worth noting, however, that this particular case was deliberately conducted under laboratory conditions using deceased scorpion specimens, rather than observed in their natural habitat. Under the captive condition of scorpion farms, Meng et al. (2000: 40) particularly reported the predation of geckos, ants and rats towards *O. martensii*, further suggesting birds, frogs, snakes, cats and yellow weasels being other potential threats. The natural dietary habit of *O. martensii* is as well shrouded in obscurity, lacking detailed information. Consequently, it remains uncertain whether the scorpion's potential prey rely on their visual acuity to detect the presence of this arachnid.

Withal, it is crucial to underscore that spectrometers employing fiber optic probes can only collect data from the specific regions of interest on the target surface where the probe's tip is positioned over, making such spectral comparisons unable to account for the unique color patterns (e.g., shape and relative coverage/percentage) exhibited by the animal, which is also subject to/confined by the morphology of the animal. Likewise, the proportion of diverse elements within the heterogenous environment surrounding the target animal also engages in a dynamic interaction with the animal's color pattern. A mere gathering of their reflectance data restricts the analysis to a comparison between the color of a particular region on the animal's body and a specific element within the substrate. This limitation may render the assessment of animal's cryptic abilities prone to biases. It is also imperative to acknowledge that, in natural conditions, both light level and spectral characteristics fluctuate spatially and temporally (variables in the ambient light environment), conceivably impacting the animal's cryptic capabilities. Furthermore, spatial acuity and viewing distance also play a crucial role in determining the dynamic conspicuousness of the cryptic animal to its predator (Van den Berg et al., 2019: 2). A novel framework was presented by Van den Berg et al. (2019), called Quantitative Colour Pattern Analysis (QCPA), integrated into a previous plugin designed by Troscianko & Stevens (2015) for ImageJ, the Multispectral Image Calibration and Analysis (MICA) toolbox (www.empiricalimaging.com/download/micatoolbox/). We hereby bring it to light for any scorpiologists who may be interested in a more rigorous study on scorpion coloration.

Potential cryptic function in *O. martensii*: As above described, *O. martensii* displays a generally simple color pattern, with only two regions being almost uniformly black. This species appears to be occupying a variety of substrate, from gravelly terrain, to heterogeneous leafmould, occasionally associated with the rock surface.

Figure 86. Maternal parent *Leiurus quinquestriatus* carrying offspring at 2nd instar (photo courtesy of Richard McJimsey). **Figure 87**. Discoloration in ethanol-preserved specimens of *Scorpiops lowei* Tang, 2022.

In order to compare the different visual effect of normal and albino *O. martensii* on those backgrounds, following the photographs uploaded on iNaturalist (www.inaturalist.org/taxa/1324848-Olivierus-martensii/browse_photos), two different types of substrates were prepared: (1) a dark leafmould background (following obs. IDs = 173378526, 180265509); (2) a bright gravel background (following obs. IDs = 31980163, 135089982, 143925476). Normal and albino *O. martensii* were placed on both of the two substrates. We also sought to determine whether the two color patterns would function differently on these two substrates under moonlight, given that scorpions typically emerge from their burrows after nightfall. Recognizing that various urban lightings could interfere with moonlight, the moonlight was simulated with diffusely reflected white light emitted from a single flashlight (albeit their disparities in the spectrum), as an alternative to testing outdoors. The scorpions were photographed in an environment cloaked by black, light-absorbing fabric. Since our photographs were not processed under any animal vision model, those figures only serve as an intuitive visual reference as to how the two phenotypes may look like to human eyes on two different substrates for the convenience of the readers (Figs. 59–66). The result was explicit and predictable: normal phenotypes were not perfectly cryptic on either of the substrates, while the albino phenotypes were more cryptic on the bright gravels but conspicuous on dark leafmould. This holds true for both white light and dark conditions, although under the dark condition, the normal phenotype became somewhat less conspicuous on both substrates. A single analysis of crypsis is logically problematic, since numerous factors could influence the visual effect of a phenotype of an animal to its prey or predator. A comprehensive study would need to take into account all scenarios. However, those theoretical results may only suggest whether a color pattern is conspicuous to its prey or predator, but do not directly prove that they serve significant advantages to the survival of an animal against its visual prey or predator, albeit such hypothesis is logically sound given the premise that the prey and predator heavily rely on their visual ability to detect the animal. A rigorous confirmation of the ecological role of those color pattern would nonetheless find its basis on the long-term real-animal experiments.

The coloration of *O. martensii* is relatively unique among its congeners, although somewhat resembles that of *O. caucasicus* (Nordmann, 1840) (but darker) and less dark than *O. fuscus* (Birula, 1897). Most species of this genus inhabit arid environment and are pale yellowish in color, which reasonably supports a phenotype-environment association hypothesis. The color pattern observed in normal *O. martensii* might represent a "generalist camouflage" (Hancock & Troscianko, 2022: 878) which neither fully accord with the leafmould or gravel substrates. A bolder assumption is that this color pattern might not even constitute a cryptic function at all. *O. martensii* primarily distributes in the northeastern region of China consisting steppes and plains surrounded by several mountain ranges, which is predominantly characterized by a relatively cold, dry climate. The dark epidermis might therefore act as a heat-absorbing substance.

Comparison with three other rare phenotypes

Anomalous pigmentations have been given a diverse range of terms owing to the different phenotypic conditions exhibited in various organisms. Following the terminology used in Tang et al. (2024: 51), three other rare phenotypes regarding the abnormal color tonality variation in *O. martensii* were identified: piebaldism (from English pie "magpie" + bald "having white patches or blazes"), hypomelanism (from Greek ὑπο- (hupo-) "below" and μέλας (mélas) "black") and leucism (from Greek λευκός (leukós) "white"). These three phenotypes are all characterized by a lesser degree of infuscation reduction compared to albinism. While the albinism in scorpions is hereby defined as the complete absence of melanin (equating with the sense of "amelanism"), resulting in the "bleaching" of ocelli, all these additional anomalies retain a certain degree of melanism. In common, none of them entail the "bleaching" of ocelli. The ultimate selection of those terms was actually inspired by an exhaustive review of chromatic anomalies in bats (Mammalia: Chiroptera) undertaken by Lucati & López-Baucells (2016). In their table 1 (Lucati & López-Baucells, 2016: 9), explicit definitions have been given for each aberration, detailing the underlying causes and phenotypic manifestations. Standardizing terminology is crucial for ensuring coherent and unequivocal identification in the future. Here, those terms were employed for *O. martensii* with the corresponding phenotypic characteristics defined below. In cases where the anomaly is not fully exhibited, we suggest adding "partial" before those proposed terms to describe the phenotype

Piebaldism: DEFINITION BY PHENOTYPE: partial absence of black pigmentation in regions that are typically uniformly black, resulting in a variegated color pattern with the degree of those irregular dark areas undiminished (partial loss of original color pattern); eyes always black.
OBSERVATION IN *O. martensii*: This phenotype appears to be even rarer than albino and leucistic phenotypes observed in *O. martensii* thus far. The first author has hitherto observed a total of 9 albino and 6 leucistic *O. martensii*, while piebaldism is represented by only two immature specimens. The overall coloration is reminiscent of *Hottentotta rugiscutis* (Pocock, 1897) or *H. tamulus* (Fabricius, 1798), if one were to discard the infuscate metasoma V (cf. Tang et al., 2024: fig. 160). The two individuals bore a more orangish base hue, particularly on the dorsum, contrasting with the yellowish appendages. While the dark pigment on metasoma V was retained as normal, those on the carapace and tergites shattered into variegated but symmetrical patterns. The darkened areas were mainly confined to the granules and carinae. One individual preserved more melanistic pigments than the other, forming a confluent broad band longitudinally across the tergites. While being immature, these two specimens appeared to accord with the normal ratiometrics of *O. martensii*. Notably, they were also rather aggressive when displaying anti-predatory response.

Hypomelanism: DEFINITION BY PHENOTYPE: uniform reduction of infuscation in regions that are typically black, resulting in a pale brownish hue but retaining the original color pattern; eyes always black. This is sometimes referred to as "dilution" (Landa-Jaime et al., 2018: 1).

Albino vs. normal *O. martensii* (morphological comparison)					
TL (albino vs. normal)	Mann-Whitney U (*p*-value)		TL-MR Correlation	Pearson's *r*	*p*-value
Between-phenotype	0.05714 (♂)	0.1429 (♀)	Between-male	-0.7696 (L/W-IV)	0.04302 (L/W-IV)
Between-sex	0.002664			-0.5003 (L/D-IV)	0.2529 (L/D-IV)
TL-DSC Correlation	Spearman's *ρ*	*p*-value		-0.8252 (L/W-V)	0.02228 (L/W-V)
Between-male	0.7968	0.03193		-0.7136 (L/D-V)	0.07174 (L/D-V)
Between-female	0.4949	0.2125	Between-female	-0.3902 (L/W-IV)	0.3392 (L/W-IV)
TL (sexual dimorphism)	Mann-Whitney U (*p*-value)			-0.5155 (L/D-IV)	0.1911 (L/D-IV)
Within-phenotype	0.4 (albino)	0.6095 (normal)		-0.5357 (L/W-V)	0.1712 (L/W-V)
Between-phenotype	0.3357			-0.7832 (L/D-V)	0.02152 (L/D-V)
Albino vs. normal *O. martensii* (behavioral comparison)					**Sample size**
Response latency (in s)	Mean ± SD	Latency difference	Mann-Whitney U (*p*-value)		4 albino ♂ (1 juv.)
Phase 3 (normal)	19.59±4.9	Between (Phase 3)	0.202		3 albino ♀ (1 juv.)
Phase 3 (albino)	23.66±3.57	Latency difference	Wilcoxon signed-rank (*p*-value)		4 normal ♂
Phase 4 (albino)	14.2±3.34	Within (albino)	0.1875		6 normal ♀

Table 2. Statistical comparison of morphological and behavioral differences between examined albino and normal *O. martensii*. Non-significant results are reddened. Abbreviation: MR, metasomal ratiometrics; s, seconds; other abbreviations follow Table 1.

Provinces & Cities	**Observation ID (www.inaturalist.org/observations/)**
Anhui	108678732
Gansu	134379588, 174169862, 178469048
Liaoning	169510900
Shaanxi	191462234, 196118433
Shandong	104525443, 111900438, 156414421, 162461211, 176389198, 18705869
Beijing	27425075, 50138268, 51776742, 91698131, 120796573, 126488957, 130901097, 163971513, 170130721, 173007703, 176899727, 178463002, 183020589, 183856006, 186838964, 187092525
Tianjin	173378526
Hebei	31980163, 60410070, 70622586, 7230955, 7242795, 129836215, 135089982, 143925476
Henan	173727260, 180265509, 182579363
Shanxi	133994921, 187115314

Table 3. Observation records of wild *O. martensii* in China cited from iNaturalist in this study. Numbers are to be placed behind the final slash of the website address. Part of the records has been incorporated into Global Biodiversity Information Facility (GBIF): https://www.gbif.org/species/10704725.

Observation in *O. martensii*: Among the 11 examined specimens from Luoyang, Henan, China, only one adult male was recognized as this phenotype. The typically darkened areas in this specimen were discernably brighter than the remaining conspecifics, especially the dorsum (cf. Tang et al., 2024: fig. 159). However, it is noteworthy that Qi et al. (2004: 142) have textually documented the color variation of *O. martensii* from different localities in China. According to their information, *O. martensii* displays a gradient reduction of infuscation from Hebei ("very dark brown"), to Henan ("dark mahogany color"), and to other regions ("yellowish to pale yellow"). Description for the color could be subjectively biased. Since the "other regions" was not specified, the records on iNaturalist were referred to (Table 2). We found that populations from provinces of Anhui, Gansu, Liaoning, Shaanxi, Shandong, and cities of Beijing and Tianjin, do not conspicuously differ from those from Hebei and Henan, and not being pale yellow. However, one record from Shanxi Province (obs. ID = 133994921) illustrated an adult female with relatively paler coloration. On the contrary, another observation from the same province depicted a typical juvenile (obs. ID = 187115314). While it remains to be verified whether the coloration is locality-dependent, the hypomelanistic male identified in this study belonged to the same population where the remaining individuals were all infuscate. In Tang (2022: fig 1), a presumably hypomelanistic phenotype also occurred (in the center of the figure). That adult male also appeared to be smaller than normal males (compare with the normal adult male on the left), according with the new specimen examined herein.

The colloquially defined "dark morph/form" and "bright/light morph/form" are common in many other scorpions (e.g., *Androctonus baluchicus* (Pocock, 1900)). However, those morphs represent neither hypermelanism nor hypomelanism as they are equally normal within the color variation range of a particular species and appear frequently. Identification of hypomelanism is hence reliant upon the knowledge of the normal coloration of a species. Empirical observation of the coloration mode in *O. martensii* indicates that pale brown represents an infrequently occurred condition, hence suggesting the presence of hypomelanism.

Leucism: Definition by phenotype: extreme reduction of overall infuscation, resulting in a pale yellow to whitish hue and the complete loss of original color pattern; eyes always black. Comparing with albinism: in albino phenotypes, eyes are also "bleached".

Observation in *O. martensii*: This phenotype has been previously depicted in Tang (2022: fig. 2c), but was termed as a "pallid" individual. Among the currently examined specimen series, only one immature individual fell into this category (cf. Tang et al., 2024: fig. 161). However, other observations of the first author have reported 4 additional specimens (www.inaturalist.org/observations/124981779); note: this specimen series also included two albino phenotypes. The sole consistent distinction between the leucistic and albino phenotypes lies in the presence of melanin in both median and lateral ocelli of the former. Intriguingly, both phenotypes are smaller and more slender than the normal *O. martensii*. One may postulate that the cessation of melanin production for epidermis and retina of eyes trails behind those of other body structures in scorpions. We have not encountered any specimens that exhibit normal pigmentation in other body regions while lacking it in the eyes. Likewise, in all previously described troglobitic taxa, despite their overall absence of pigmentation, the "bleaching" of ocelli consistently occurs, albeit its apparent ecomorphological cause. It appears that the presence of melanin in the eyes is of utmost significance in scorpions and remains unaffected barring the cases of troglomorphism and albinism. This norm and correlation justifies the "bleaching" of ocelli and the significantly low statistical frequency of being utterly pallid (except for the metallic regions) for a species in combination as a necessary and sufficient condition for the morphological recognition of albinism in scorpions.

Remarks on other observations: During our online research, we chanced upon a previous report of anomalous pigmentation in the scorpion species *Tityus pusillus* Pocock, 1893 by Lira et al. (2016). To our knowledge, this is the mere documentation of color anomalies in scorpions apart from the two albino cases. The authors described the condition as "leucism", with a frequency of 0.06%. Notably, the mere leucistic female gave birth to a litter of normal phenotypes, apparently suggesting the inheritability of "leucism". Upon examining their illustrations (Lira et al., 2016: fig. 1A), it was found that the original sub-cuticular color pattern was still retained, albeit rather faint. Since we have currently identified four anomalous pigmentations in *O. martensii*, it is suggested that, in accordance with our definitions given above, the case in *T. pusillus* should be reckoned as a scenario of hypomelanism.

Another case of "partial albinism" was reported by Armas & Cubas-Rodriguez (2023) in a female *Centruroides limbatus* (Pocock, 1898). According to the authors, the chromatic anomaly was observed prior to its death ("*…recolectaron durante un recorrido nocturno un pequeño lote del escorpión* Centruroides limbatus *(Pocock, 1898) en áreas del Jardín Botánico Lancetilla…*detectada mientras caminaba sobre la arena, la cual presenta una aberración cromática que consideramos corresponde a un caso de albinismo parcial…"). Their figures 1C–E illustrated the depigmentation on the carapace (including the median ocelli), tergites and sternites. The case was sufficiently unusual that it defies unambiguous classification into any category of chromatic anomalies defined for scorpions in this paper. But if one allows the definition of albinism to be entirely predicated upon the loss of melanin in the eyes, it can indeed be considered as a partial albinism. However, it is worth noting that similar façade can be observed in ethanol preserved specimens (Fig. 87). This could be a consequence of post-mortem gas accumulation due to microbial activities, leading to the inflation of the specimen and the subsequent detachment of epidermis underneath from the cuticle, causing regional discoloration. We include this caution to prevent misidentification of chromatic anomalies in preserved specimens, emphasizing that such cases should be assessed in live specimens to avoid erroneous conclusions.

Apart from the records in literatures, observations of anomalous pigmentation in scorpions have been supplemented by various amateurs and breeders online. In his personal website, the scorpiologist, Kawai Kazusa, provided a list of "albino" scorpions with photos in vivo (scorpiones6.webnode.jp/albino/). In addition, the Facebook user "Ang Wei Ayang" has shared several photos of his albino specimens of *Heterometrus longimanus* (Herbst, 1800) (www.facebook.com/ayang.ayang.3194). Mr. Giorgio Molisani has also depicted a brood of *Leiurus jordanensis* and a brood of *Hottentotta zagrosensis* Kovařík, 1997, each with several albino individuals (www.buthidae.ch/stocklist-download/). Furthermore, another scorpiologist, Prakrit Jain, has uploaded an observation of a wild albino *H. arizonensis* on iNaturalist (www.inaturalist.org/observations/116791674).

Conclusively, based on the classification defined in this study, the following records are recognized, in addition to *U. yaschenkoi*, *B. castellano*, *O. martensii* and *T. pusillus*: (1) albinism: *Hadrurus arizonensis*, *H. longimanus*, *H. silenus* (Simon, 1884), *Hottentotta zagrosensis*, *L. jordanensis*, *L. quinquestriatus*; (2) hypomelanism: *Liocheles australasiae* (Fabricius, 1775), *Opisthacanthus asper* (Peters, 1861); (3) piebaldism: *Leiurus haenggii* Lowe et al., 2014. However, issues may occur if a scorpion already lacks distinct color pattern in its normal state when allocating its abnormal phenotype to either hypomelanism or leucism. Therefore, we recommend to consider leucism as a subset of hypomelanism since, by definition, it is characterized by a greater extent of color reduction. In other words, scorpions, already lacking dark patterns, exhibiting color reduction can be simply classified as being hypomelanic.

Here, the case of *H. longimanus* warrants special attention. The six albino individuals owned by Mr. Ayang were from two broods of two pairs of wild caught *H. longimanus* showing the normal phenotype (five from one brood and one from the other), which suggests that the parents must possess a recessive allele of albinism acquired in the nature. These albino offspring were healthily raised under captive condition. It was observed that the albino *H. longimanus* exhibited a reddish yellow coloration (more reddish on carapace and chelae, yellowish on other parts) with a pair of highly whitened median ocelli during the immature stage. However, after they reached 7th instar as adults, their cuticle gradually darkened after this final ecdysis. The darkened adults showed dark cyan coloration on their carapace and chelae similar to the normal counterparts, but the remaining of their body was much brighter and appear brownish. Their median ocelli still lacked melanin but appeared less whitened due to the darkening of their carapace. According to the personal communication with the first author, Mr. Ayang successfully bred a pair of albino *H. longimanus*, and the sole offspring already showed the lack of melanin in its ocelli. Both the "pigment reversal" (postnatal regain of melanin) and the inherited genetic defect add another layer of mystery to the albinism in scorpions. After acquiring the copyright, we included some photos of albino *H. longimanus* reared by Mr. Ayang in this paper to secure those visual evidences (Figs. 67–77).

Recently, a friend of the first author's, Mr. Richard McJimsey, documented a clutch of *L. quinquestriatus* showcasing abnormal color combinations (74 individuals in total). While the majority of offspring (79.7%) exhibited normal pigmentation (i.e., orangish hue with a black metasoma V; cf. Fig. 78), some individuals exhibited significant pigment loss. Notably, the paternal parent was mated with three adult females, and only one of them, which was raised to adult under captivity from 5th instar and displayed typical coloration, gave birth to abnormal offspring. Among these individuals, some (17.6%) could be categorized as leucistic under the current classification framework (Figs. 79–83). Nonetheless, they retained faint traces of black and orange pigments on their cuticles. Curiously, one specimen (Fig. 84) evinced a what could be aptly called as "intermediate" state: the melanin is only partially lost in the epidermis under its median ocelli, rendering a variegated, reddish to brownish hue. Additionally, there was one individual that may represent another aberrant case of albinism (Fig. 85). This individual displayed more extensive pigment loss and retained fewer residual pigments. However, sprinkles of the melanin appeared to be more concentrated near its median ocelli. Consequently, we tentatively opt to portray it as a "semi-albino" phenotype. The two observations (2.7%; Figs. 84–85) might suggest a gradient of pigment loss between the superficial leucism and albinism, and more studies are required, preferably from a genetic level, to unravel the hidden nexus between the two phenotypes.

There is also one observation serving as an example of non-recognition for color reduction. In Mr. Jan Ove Rein's renowned website, *The Scorpion Files*, a photo illustrated two adult male *Opistophthalmus* taken by Mr. John Visser, with the right one identified as *O. carinatus* (Peters, 1861) (www.ntnu.no/ub/scorpion-files/visser/o_carinatus_namibia.jpg). The left species is most likely *O. cavimanus* Lawrence, 1928 (as suggested by Mr. Paul Bester). Intriguingly, both individuals exhibited whitish median ocelli, yet this might be an artefact arising from the viewing angle. The median ocellus of scorpions is inherently translucent by its lens, a thickened cuticle, appearing blackish only when viewed from an angle that directs toward the underlying epidermis. When observed from specific angles, particularly those aligned with the surface of prosoma, the median ocellus may display a whitish or yellowish hue. Additionally, the lateral ocelli of both specimens appeared blackish. Up to this point, there is no known instance in which a scorpion exclusively exhibits a reduction in coloration in its median ocelli without a corresponding effect on the lateral ocelli (note that the above mentioned case of *H. longimanus* does not fall into this category as well). Two observations of this species on iNaturalist depicted a similar condition in which the median ocelli appeared whitish (obs. IDs = 120865859, 152499198). Nevertheless, we reckon that those could be simply caused by the camera flash light without correcting the redeye error. Another intriguing case would be an observation of an unidentified *Chactas* species on iNaturalist (obs. ID = 206486764), where only the right median ocellus appeared to be lacking melanin.

Discussion

The appearance of darkness in specific areas, such as the aculeus tip, cheliceral and chelal denticles, and tarsal ungues, is partially a consequence of post-ecdysial metal deposition, containing metal ions like zinc, manganese and iron (Schofield et al., 2003). Recent study discovered that in some small-sized taxa, the basal parts of those regions could be weakly fluorescent, and the non-fluorescence in some sensory setae may also be owing to the metal incorporation (Lowe & Fet, 2024: 96). Conversely, the hardening of cuticle (sclerotization), the process by which cuticles are stabilized by the oxidative incorporation of phenolic compounds into the cuticular matrix (chitin-protein matrix), forming crosslinks between the proteins as well as forming polymers filling the intermolecular spaces, is correlated with darkening of coloration (Krishnan, 1953: 20). The sclerotization involves the tanning of cuticular proteins by quinones, with quinoid, in the oxidized state, being dark (Andersen, 1980; Locket, 1986: 111). However, the enzymes responsible for the tanning of cuticle are possibly different from those for the melanin formation (Locket, 1986: 112). This phenomenon is observable in 1st instar newborns and freshly molted individuals, whose cuticle is yet fragile and often appears whitish, or at least paler than the older or sclerotized individuals, which also fluoresces weakly under UV light. The cumulative intensity of fluorescence during different stages after ecdysis has also been studied (Li et al., 2022). The degree of sclerotization varies across the cuticle of the scorpion, typically being higher in regions that may form into granules and carinae. The overall amber color of the cuticle primarily arises from the exo- and endocuticle. It is essential to emphasize that these darker regions should not be regarded as evidence against albinism, as they are independent of the melanin production. The mere melanin-related coloration is associated with the epidermal pigmentation, and a complete absence thereof suggests the occurrence of albinism.

Albinism in *O. martensii* (as well as other scorpions) remains shrouded in mystery, with several questions (in addition to the unsolved ones mentioned earlier) pending answers, including but not limited to: (1) Can albinism also be inheritable in *O. martensii*?; (2) Is albinism also controlled by a recessive allele in *O. martensii*?; (3) Will two albino *O. martensii* produce exclusively albino offspring?; (4) What will happen after an albino *O. martensii* mates with a normal phenotype?; (5) Are albino *O. martensii* consistently smaller than the normal conspecific?; (6) Can albino *O. martensii* be found in the wild?; (7) Is leucism associated with albinism in *O. martensii*, given that the only difference lies in the coloration of ocelli?; (8) What other disadvantages do albino scorpions face in the wild?; (9) Is the cuticle of albino individuals structurally different from that of the normal ones?...Part of these conundrums are interrelated and part of them can be addressed by captive breeding. Questions 1–2 appear to be the case for *H. longimanus*.

Acknowledgements

We would like to extend our appreciation to Dr. Graeme Lowe for providing valuable comments on the text, as well as Mr. Ang Wei Ayang and Mr. Richard McJimsey for their provision of photos of albino scorpions. Our gratitude also goes to two anonymous reviewers.

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