Cryptocentrus steinhardti (Actinopterygii; Gobiidae): a new species of shrimp-goby, and a new invasive to the Mediterranean Sea

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ABSTRACT

A new species of shrimp goby was collected at depths of 60-80 m, off the southern Israeli Mediterranean coast, revealed by a unique 'DNA barcoding' signature (mtDNA *COI* and *Cytb*) that differed from any other previously published goby species. This finding constitutes the third record of an invasive shrimp goby in the Mediterranean Sea, revealing an intriguing ecological consideration regarding possible formation of a fish-shrimp symbiosis in a newly invaded territory. Following a comprehensive morphological and anatomical examinations, this species is being described here as *Cryptocentrus steinhardti* n. sp., clustered phylogenetically with the silt shrimp-gobies group, in which *Cryptocentrus* is the most speciose genus. However, a present phylogenetic analysis demonstrates paraphyly of *Cryptocentrus* hence a generic name for the new species is provisional. ~~This finding constitutes the third record of an invasive shrimp goby in the Mediterranean Sea, revealing an intriguing ecological consideration regarding possible formation of a fish-shrimp symbiosis in a newly invaded territory.~~

Last, describing tropical species in the Mediterranean prior to their discovery in the native distribution is an unusual event, although not the first such case. Several similar examples are provided in the present article ~~below~~.

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INTRODUCTION

Since the opening of the Suez Canal in 1869 more than 400 multicellular nonnative species of Red Sea origin, including approx. 100 fish species, have been found along the Israeli Mediterranean coast (Galil et al., 2020). Out of this diverse invasive fauna, two species are the shrimp-gobies *Vanderhorstia mertensi* Klausewitz, 1974, (Goren, Stern and Galil, 2013) and *Cryptocentrus caeruleopunctatus* (Rüppell, 1830) (Rothman and Goren, 2015). These species are part of a group of near-reef fishes that inhabit sandy and silty habitats and display a remarkable mutualism with burrowing alpheid shrimps, exchanging tunnel construction capabilities and sentinel services (Karplus and Thompson, 2011). Common throughout the tropics, this unique fish-shrimp association is documented from over a 100 fish species that belong to eleven valid genera of gobies: *Amblyeleotris* Bleeker, 1874; *Cryptocentrus* Valenciennes (ex Ehrenberg) in Cuvier & Valenciennes, 1837; *Cryptocentroides* Popta, 1922, *Ctenogobiops* Smith, 1959, *Lotilia* Klausewitz, 1960; *Mahidolia* Smith, 1932; *Myersina* Herre, 1934; *Psilogobius* Baldwin, 1972; *Stonogobiops* Polunin & Lubbock, 1977; *Tomiyamichthys* Smith, 1956 and *Vanderhorstia* Smith, 1949 (Karplus, 2014; Ray, Mohapatra and Larson, 2018). An additional genus, *Flabelligobius* Smith, 1956 is considered a synonym of *Tomiyamichthys* (Hoese et al., 2016; Fricke and Eschmeyer, 2020).

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During cruises to sample the benthic biota off Ashdod (southern Israel, Mediterranean Sea), three specimens of an unknown shrimp-goby were collected at depths of 60 to 80 m by a bottom trawl net. Integrative examinations of molecular taxonomy and traditional practices indicated that these fish belong to an undescribed species of *Cryptocentrus* genus.

MATERIALS & METHODS

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Fish specimens were collected from the southern coast of the Israeli Mediterranean by the commercial 240 hp F/V bottom trawler, *Moty*, under captained by L. Ornoy. The fish were preserved in 70% alcohol and stored at the fish collection of The Steinhardt Museum of Natural History, Tel-Aviv University (SMNHTAU). Muscle tissue samples were taken from fresh specimens for genetic analyses and preserved in 96% alcohol.

Genetic analysis

Total genomic DNA was extracted from the three individuals using a micro tissue genomic DNA isolation kit following the manufacturer's protocol (AMBRD Laboratories, Turkey). Next, approx. 50 ng of template DNA was used to amplify a 651 bp fragment of the mitochondrial cytochrome c oxidase subunit I gene (*COI*) and 467 bp of the mitochondrial Cytochrome b (*Cytb*). Primers and PCR reactions are detailed in supplementary table S1. The contiguous sequences of both genes, including measurements, photos and its trace files, were uploaded to BOLD system at www.v4.boldsystems.org under the BIM project (Biota of the Israeli Mediterranean) with BOLD Sample IDs: BIM769-20 for the holotype and BIM534-17 and BIM770-20 for the two paratypes. In order to investigate the total genetic divergence of shrimp-associated gobies complex, 101 previously published sequences belonging to ten putative genera were mined from BOLD and NCBI to comprise an aligned dataset, with a single sequence of *Gobius niger* as an outgroup (Supplementary Table S2). The genetic vouchers were included in the dataset only if they indicated a precise information on the sampling localities and an unambiguous association with a Barcode Index Number (BIN) of their corresponding taxonomic identifications. In this regard, sequences of *Cryptocentrus yatsui* for example, were excluded from the analyses since they shared a BIN with the gobies *Oligolepis formosanus* and *Redigobius bikolanus* (BIN:BOLD:ADB4723). The best model test for nucleotide substitution was checked for the aligned dataset using Mega X

(Kumar et al., 2018) prior to further analyses. Last, phylogenetic reconstruction and genetic distances between species were computed for the dataset using the model HKY+G+I with 5,000 replicates.

Nomenclatural acts

The electronic version of this article in Portable Document Format (PDF) will represent a published work according to the International Commission on Zoological Nomenclature (ICZN), and hence the new name contained in the electronic version is effectively published under that Code from the electronic edition alone. This published work and the nomenclatural acts it contains have been registered in ZooBank, the online registration system for the ICZN. The ZooBank LSIDs (Life Science Identifiers) can be resolved and the associated information viewed through any standard web browser by appending the LSID to the prefix http://zoobank.org/. The LSID for this publication is: urn:lsid:zoobank.org:pub:B5279F4D-F5BC-454D-9ED8-3E2A13C69EAE. The online version of this work is archived and available from the following digital repositories: PeerJ, PubMed Central, and CLOCKSS.

RESULTS

***Cryptocentrus steinhardti* n. sp.**

Figures 1,2

Holotype: SMNH P-16037, Ashdod, Israel (31°44.835 N, 34°24.787 E), depth 80 m, January 8, 2018, 19:45, Col. N. Stern, Total length (TL) 81.9 mm, BOLD voucher BIM769-20.

Paratypes: SMNH P-14556, Ashdod, Israel (31°45.202 N, 34°27.036 E), depth 60 m, February 12, 2012, night, Col. N. Stern, TL 71.5, BOLD voucher BIM534-17; SMNH P-16038, Ashdod, Israel (31°45.589 N, 34°27.282 E), depth 60 m, December 11, 2016, 19:45, Col. N. Stern, TL 72.8 mm, BOLD voucher BIM770-20.

Diagnosis

A *Cryptocentrus* species with 59~~8~~-61 rows of cycloid scales along the body, 20-21 pre~~-~~dorsal scales, reaching ca. 3/4 of the distance to eye (Figure 2) and 19~~20~~-21 transverse rows. Scales cover abdomen and pre-pelvic region. First dorsal fin with six spines; second dorsal fin with a single spine and ten segmented rays (last one branched). Anal fin with one spine and nine segmented rays (last one branched). Pectoral fins with 14-15 rays. Pelvic fins completely united, with a well-developed fraenum. Caudal fin with 17 segmented rays, 13 of them branched. Gill rakers: 7-8 on outer gill arch, two on upper ~~arch~~limb, one at the angle, and 4-5 on lower ~~arch~~limb. Head sensory papillae in transverse pattern.

Description

Body elongate and compressed. Upper profile of head convex. Mouth oblique. Maxilla reaching to below a vertical ~~from~~ at posterior margin of eye. Upper jaw with outer row of 16 caniniform teeth (eight on each side of the jaw) curved backward. Internal teeth in 1-2 rows small, pointed, curved backward. Lower jaw with outer 2-3 rows of small caniniform teeth, curved backward. Internal teeth in a single row of six large canines (three on each side of the jaw). No teeth on vomer. Tongue rounded.

Gill opening moderate, extending forward to below posterior margin of pre~~-~~opercle~~culum~~, restricted by a membrane at lower part. Lower margins of opercle~~ula~~ intersect at isthmus. Gill membrane connected to side of isthmus. Gill rakers short, 7-8 rakes on outer arch, two on upper ~~arch~~limb, one at the angle, and 4-5 on lower ~~arch~~limb. Anterior nostril, a tube, close above upper lip. Posterior nostril, a pore, in front of eye.

Scales: Body covered with cycloid scales, including abdomen and pre-pelvic region; 59-61 scales in longitudinal series; 20-21 mid-pre~~-~~dorsal scales reaching ca. 3/4 of the distance between dorsal fin and interorbital; 19-21 series of scales from origin of first dorsal fin to mid-abdomen.

Fins: First dorsal fin with six spines, third and fourth spines elongate reaching the third ray of second dorsal fin. Second dorsal fin with a single spine and ten segmented rays (last one branched). Rays long, the last three reach the caudal fin. Anal fin with one spine and nine segmented rays (last one branched). Pectoral fins with 14-15 rays. Pelvic fins completely united to form of disc, with a well-developed fraenum. Caudal fin with 17 segmented rays, 13 of them branched.

Selected meristic characteristics and proportions are given in Table 1.

Cephalic sensory system: The skin of the head of all three type specimens was severely damaged in the commercial trawl net, hindering detection of the cephalic canal and papillae. Figure 2 presents the cephalic system of the ~~best preserved~~ specimen in the best condition (holotype). Nasal pores (pair) in front of eye, close to ~~second~~ posterior nostril ~~pore~~opening. Anterior interorbital pore (single) is above anterior margin of eye. Posterior interorbital pore is above 1/6 posterior of eye. Post~~-~~orbital pores (pair) are above posterior margin of eye. Three pores in anterior oculoscapular canal. Posterior canal could not be detected (or does not exist). Two pre~~-~~opercular pores. Papillae on head arranged in a transverse~~cal~~ pattern (Fig. 2).

Color (preserved): Body yellow with dark brown pigmentation that becomes denser on back and head. Three irregular wide darker bars on each side of body: the first bar under 1st dorsal fin and second and third bars under anterior and posterior parts of 2nd dorsal fin.

Genetic analysis

Comparing the genetic sequences of both *COI* and *Cytb* with previously published data have shown great differences with any known gobies, with minimum distances of 17.41% of nucleotide diversity between the new species and *Cryptocentrus albidorsus* and *C. nigrocellatus* (BOLD vouchers GBGCA2109-13 and GBGCA1963-13, respectively) in *COI* (Table 3), and 12.8% differences between *C. cinctus* in *Cytb* (NCBI voucher MT199211). Although clustered with relatively low bootstrap values, phylogenetic analysis of available *COI* sequences has shown monophyletic relationship for *Cryptocentrus* species, including the newly described species, as well as clustering with all species of silt shrimp gobies (Thacker and Roje, 2011) from the genera *Lotilia*, *Myersina* and *Stonogobiops*, and sister-grouping with *Mahidolia* spp. (Fig. 3). Other phylogenetic studies regarding these taxa, have also related *Stonogobiops* and *Mahidolia* spp. within the *Cryptocentrus* ~~species complex~~clade, while *Lotila* and *Myersina* were absent from their dataset (Thacker and Roje, 2011; Thacker, 2015; McCraney, Thacker and Alfaro, 2020). In fact, to the best of our knowledge this present study is the first to incorporate these genera, as well as *Psilogobius* spp. in a phylogenetic evaluation of shrimp-associated gobies.

Commented [SB3]: This is not true. With inclusion in analysis Lotilia, Mahidolia, and Psilogobius, the present analysis confirms proposal by Hoese & Larson (2004) that the genus Cryptocentrus is paraphyletic.
The generic name Cryptocentrus is available for C.cryptocentrus and close related species. Hence generic name for C.steingardti is provisional and more species of "Cryptocentrus" should be included in further analysis. More likely group of species with white mid-predorsal band forms a monophyletic group and may be form a separate genus. A low bootstrap support of Lotilia and C.reingardti cannot show a real relationships of them with other Cryptocentrus previously assigned to that genus (i.e. from C.leptocephalus to C.maudae).
i.e. authors need to add more details in discussion of the result of phylogenetic analysis.

Moreover, the cluster of reef shrimp gobies has revealed two possible misidentifications: (1) *Tomiyamichthys lanceolatus*, which may be regarded as a *Vanderhorstia* species (see Fig. 1 in Thacker, Thompson and Roje 2011), (2) and *Vanderhorstia mertensi*, which is shown here based on a single sequence from its invasive population in the Mediterranean Sea. Both putative species in this case are suspected to be a result of a wrong assignment, considering the weak diagnostic characteristics of the genus (Shibukawa and Suzuki, 2004).

Commented [SB4]: Change name to Vanderhorstia lanceolata in the tree to avoid confusion.
Authors need to add Tomiyamichthys oni, included in Thacker et al. (2011).

Etymology

The new species is named after Michael H. Steinhardt in recognition of his immensely important contribution to the establishment and construction of the Steinhardt Museum of Natural History at Tel Aviv University, Israel.

DISCUSSION

As evident from the genetic results of this study, as well as from the findings of Thacker and Roje (2011), Thacker (2015) and McCraney et al. (2020), the generic status and validity of some shrimp-associated gobies are yet to be settled, and required further revisional examinations with more species involved. In the present study, we followed the status of the genera and species as presented by Fricke et al. (2020).

Thacker et al. (2011) recognized two different clades in this group: one clade includes the genera *Amblyeleotris, Ctenogobiops* and *Vanderhorstia* and the other includes *Cryptocentrus*, *Mahidolia, Tomiyamichthys* and *Stonogobiops*. Later studies by Thacker (2015) and McCraney et al. (2020) followed this approach and assigned the genera *Amblyeleotris*, *Ctenogobiops* and *Vanderhorstia* to the lineage *Asterropteryx* and the eight other genera to the lineage "*Cryptocentrus*".

Commented [SB5]: Authors incorrectly interpreted Thacker, Thompson & Roje 2011 where theses authors focused on shrimp-associated gobies. They clearly showed and in other articles too (e.g. McCraney) two clades. Asterropteryx is not associated with shrimps, and it is clear from analysis in all these articles. So unclear why authors of present article decided that Amblyeleotris, Ctenogobiops and Vanderhorstia belongs to lineage Asterropteryx. This is a wrong conclusion.

The shrimp-associated gobies belonging to the *Asterropteryx* lineage are all characterized by longitudinal suborbital papillae rows (*sensu* Miller, 1986), while the species of the lineage *Cryptocentrus* are characterized by transverse rows (with the exception of *Tomiyamichthys*).

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Cryptocentrus~~.~~ *stein~~n~~hardti* differs from species of *Cryptocentroides* spp. by its wide gill opening, reaching to below the pre~~-~~opercular margin, while *Cryptocentroides* species are characterized by a restricted gill opening, extending to below pectoral-fin base. *Lotilia* spp. and *Mahidolia* spp. differ from the new species by their naked nape and lower scale count along the body (less than 53 in *Lotilia* spp. and less than 40 in *Mahidolia* spp.). *Myersina* spp. differ from *C. steinhardti* by their lack of scales on mid nape. *Psilogobius* spp. differ from the new species in possessing ctenoid scales on body, at least on its posterior part. *Stonogobiops* spp. differ from the new species by their large vomerine teeth.

The genus *Cryptocentrus* currently comprises 36 species (Froese and Pauly, 2020). Allen and Randall (2011) distinguished a group of four species characterized by possessing fewer than 70

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~~series of~~ scales in longitudinal series along the body. They included the following four species in this group: *C. caeruleomaculatus* (Herre, 1933), *C. cyanospilotus* Allen & Randall, 2011, *C. insignitus* (Whitley, 1956) and *C. strigilliceps* (Jordan & Seale, 1906). The group was expanded with the descriptions of *C. epakros* Allen, 2015 (Allen, 2015) and *C. altipinna* Hoese, 2019 (Hoese, 2019). None of these species have been reported to date from the Red Sea (Golani and Fricke, 2018).

Cryptocentrus~~.~~ *steinhardti* differs from all other members of this group, except *C. insignitus*, in possessing cycloid scales only. It differs from *C. insignitus* in possessing a higher number of scales along the body and the presence of mid-pre~~-~~dorsal scales (Table 2).

The finding of a new Indo-Pacific invasive species in the Mediterranean prior to its discovery in the Indo-Pacific Ocean or Red Sea is an unusual event, although other such events have been documented. The snapping shrimp *Alpheus migrans* Lewinsohn & Holthuis, 1978, which belongs to an Indo-Pacific species group, was first described from the Mediterranean (Lewinsohn and Holthuis, 1978); the jellyfish *Marivagia stellata* Galil and Gershwin, 2010 was described from the Mediterranean and later on also reported from India (Galil, Kumar and Riyas, 2013); t~~T~~he flounder *Arnoglossus nigrofilamentosus* Fricke, Golani and Appelbaum-Golani 2017 (Fricke, et al. 2017) that is probably a Red Sea species, and the jellyfish *Rhopilema nomadica* Galil, Spanier & Ferguson, 1990 (Galil et al., 1990) was described on the basis of types from the Mediterranean although it is an Indo-~~-~~Pacific species.

Finding ~~this~~ the new shrimp-associated goby, however, which is also the third such goby to be documented as an invasive species in the Mediterranean, raises the question of its current association with an alpheid shrimp. Since this taxon of gobies possesses either an obligatory or facultative association with shrimps (Lyons, 2013), pairing with one of the approx. twenty

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candidate species of alpheids shrimp from the Mediterranean and the Red Sea (Karplus, 2014) is a key factor for its survival and population establishment success in the invaded territory. Unfortunately, the catch of *C. steinhardti* in this study was not associated with any shrimp species, thus the question of its possible symbiosis in the Mediterranean remains open and required further observations.

Cryptocentrus~~.~~ s~~S~~teinhardti was collected at depths of 60 to 80 m during night trawls. Finding this species during the period of dark and beyond the depth limits of recreational diving, despite this possibly having been accidental, could be an additional reason for overlooking this species and its possible shrimp associates to date in its native origin.

ACKNOWLEDGMENTS

We thank Mr. O. Rittner for the photographs of the fish and to Ms. N. Paz for editing the manuscript.

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Commented [SB9]: Whitley (1956) cited in Table 2 but missing in References

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Table 1 Selected meristic characteristics and proportions (Measurements in mm; proportion in %)

Measurements and counts	**Fish catalogue number (SMHTAU)**		
	16037	**16038**	**14556**
Total length	81.9	72.8	71.46
Standard length	58.5	51.1	49.95
Head length	14.8	14.2	12.9
Body depth	8.9	7.8	7.6
Head width	5.8	5.4	5.1
Eye diameter	3.44	4	3.6
Interorbital	1.1	1.1	1
Distance snout to origin of first dorsal fin	18	16.9	14.8
Distance snout to origin of second dorsal fin	30.2	29.2	25.8
Distance snout to origin of anal fin	33.4	30.5	28
No. of scale series along the body	61	59	60
No. of scale in transversal series	20	21	19
No. pre-dorsal scales	21	20	20
No. of spines in first dorsal fin	6	6	6
No. of spines/ segmented rays in second dorsal fin	I,~~+~~10	I,~~+~~10	I,~~+~~10
No. of spines/ segmented rays in anal fin	I,~~+~~9	I,~~+~~9	I,~~+~~9
No. of rays in pectoral fin (left side)	15	15	15
No. of caudal rays	17	17	17
Count of gill rakers on upper ~~arch~~limb	2	2	2
Count of gill rakers on upper ~~arch~~limb	5	4	4
Count of gill rakers at arch angle	1	1	1
Total count of gill rakers	8	7	7
Proportions (in %)			
Standard length of total length	71.4	70.2	69.9
Head length of standard length	25.3	27.8	25.8
Body depth of standard length	15.2	15.3	15.2
Eye diameter of head length	23.2	28.2	27.9
Interorbital space of head length	7.4	7.7	7.8
Distance snout to origin of first dorsal fin	30.8	33.1	29.6
Distance snout to origin of second dorsal fin	51.6	57.1	51.7
Distance snout to origin of anal fin	57.1	59.7	56.1

Table 2 Selected meristic counts of "*Cryptocentrus* low scale count" group.

Species	LL	2nd D	A	PreD-Mid line
Cryptocentrus steinhardti n. sp.	59-61[1]	I,~~+~~10	I,~~+~~9	20-21
Cryptocentrus cyanospilotus	49-59[2]	I,~~+~~10	I,~~+~~9	10-13
Cryptocentrus caeruleomaculatus	60[2]	I,~~+~~10	I,~~+~~9	none
Cryptocentrus strigilliceps	50-71[2]	I,~~+~~10	I,~~+~~9	"Predorsal midline and sides scaled to a point just before to just behind posterior preopercular margin" (Hoese, 2019)
Cryptocentrus insignitus	52-55[1]	I,~~+~~12	I,~~+~~11	Nape and shoulders incompletely scaled (Whitley, 1956).
Cryptocentrus altipinna	56-65[2]	I,~~+~~10	I,~~+~~9	none
Cryptocentrus epakros	47[2]	I,~~+~~10	I,~~+~~9	19

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