Ecomorphological Comparison of the Brain in Different Species of Fish from the Persian Gulf

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ABSTRACT

The present study aimed to compare the brain structure of 14 fish species with different ecological characteristics from the Persian Gulf. After precise dissection of the brain and weighing, fixation was performed using Bouin's solution, followed by tissue processing, embedding in paraffin, sectioning to a thickness of 12 µm, and staining with hematoxylin and eosin. Sections were observed under microscope and photographed to precisely describe the brain structures. The results showed that the grey bamboo shark (*Chiloscyllium griseum*) differed considerably in structure of the brain compared to bony fish, and it showed the highest brain-to-body mass ratio (0.8±0.02) ($p<0.05$). The crista cerebellaris and granular section were more obvious in the croaker (*Otolithes ruber*), maybe due to its well developed lateral line. A plankton-feeding shad, *Tenualosa ilisha*, had less brain-to-body mass ratio and a more simple structural brain compared to the narrow-barred Spanish mackerel (*Scomberomorus commerson*), which occupies the top of the food chain. Moreover, duskytail grouper (*Epinephelus bleekeri*), living in the coral reef ecosystem, had a greater brain-to-body mass ratio and more complex brain structure compared to flounders occupying a simpler environment. This study highlights that phylogenetics, trophic level, and complexity of environment have important relationships with brain anatomy of fishes in the Persian Gulf.

Keywords: Anatomy, Brain, Ecomorphology, Fish, Persian Gulf

INTRODUCTION

Apart from a few groups of invertebrates, such as sponges, corals, and echinoderms, the brain is present in all animals, and functions as the most complex organ in vertebrates (Pelvig *et al*., 2008). While the first vertebrates appeared more than 500 million years ago during the Cambrian period (Shu *et al*., 2003), sharks, mammals, and teleost appeared around 450, 200, and 175 million years ago, respectively (Sternberg and Kaufman, 2013). Different size and complexity has been observed in brains from hagfishes to mammals, depending on the evolutionary history of each animal (Striedter, 2006). Generally, the vertebrate brain possesses a set of similar anatomical parts and is divided into three major regions, namely the prosencephalon (olfactory lobes or telencephalon and diencephalon), the mesencephalon (optic tectum), and the rhombencephalon (cerebellum and myelencephalon) (Kotrschal *et al*., 1998).

The brains of fishes are relatively similar to those of other vertebrates, and the similarity to mammals even involves functional, learning, and diagnostic aspects (Rodríguez *et al*., 2005). The

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common forms of the teleost brain include an obvious rhombencephalon, a large single cerebellum, two obvious tectal halves, diencephalon, two anterior hypothalamic lobes, a small telencephalon, and large olfactory lobes (Nieuwenhuys *et al*., 2014). Despite this shared neuroanatomical scheme, there is large morphological variation in the brains of teleosts (Rodriguez *et al*., 2005). Previous studies have shown that sharks have a larger brain relative to body size (encephalization) compared to bony fish. Globally, several studies have been performed to compare the brains of fishes based on anatomy and ecomorphology (e.g., Lisney and Collin, 2006). Bani and Jadidi (2008) studied the brain morphology of the Caspian Sea sturgeons, *Acipenser stellatus* and *Acipenser persicus*. Eastman and Lannoo (2007) studied brain histology and anatomy of two closely related species in the thornfish family (non-polar and Antarctic) and provided accurate maps of the brain and skull nerves from both species. Moreover, Lecchini *et al*. (2014) examined variation in the brain organization of coral reef fish larvae.

The Persian Gulf, with its geographical and climatic characteristics, as well as favorable ecological conditions, is considered one of the most important regions of the Palearctic region, which has a special status in biogeography. In this region, 907 fish species (814 bony fishes and 93 cartilaginous fishes) belonging to 157 families have been identified and reported (Owfi, 2015). Although the number of native species (1.5 %) is very low compared to the Red Sea and Caribbean Gulf, their biodiversity in the form of three groups of fishes-pelagic, benthic-neritic, and corallian-as well as behavioral patterns of nutrition, reproduction, and migration has led to a large number of related studies in this area (Owfi, 2015).

Behavior of animals is reflected in the organization of their central nervous system, and thus the study of the brain can provide important information about the biology of the animal (Lisney and Collin, 2006). Accordingly, it is possible to study the correlation between fish biodiversity and brain structure, and subsequently, to investigate the adaptations of fish brains and evolutionary relationships, as well as to provide a natural view of different parts of the brain in different fish species. Due to the presence of various marine ecosystems (e.g., coral reefs, mangroves, seagrass beds, sandy shores, rocky shores, and estuarine ecosystems) and the high species diversity of fish in the Persian Gulf, the effect of habitat diversity on Persian Gulf fish behavior can be better reflected by their brains and nervous systems. Despite several studies on the brain of individual fish species, there is no study to broadly focus on the brains of fishes from the Persian Gulf. The aim of this present study is to investigate the eco-morphological characteristics of some common fish species from the Persian Gulf using histological techniques.

MATERIALS AND METHODS

Fish samples were collected from Choebdeh-Abadan port (S1) (N 29.92216, E 48.61748), Bandar Imam Khomeini creeks (S2) (N 30.32483, E 48.91823) and Mahshahr (S3) (N 30.41962, E49.13658), as the most important fishing regions, in collaboration with the Imam Khomeini Fish Research Center (Figure 1).

Fourteen species of fish (with 3 replicates) were selected for study, based on their ecology and abundance (Table 1). After catching fish by hook and trawling, the specimens were transferred to the lab for the following studies. First, biometric measurements (length and weight) were made for each specimen. Then, the fish were beheaded, the brains were removed from the skull, weighed, fixed in Bouin's solution, and imaged. For histological studies, the brain samples were taken and tissue processing was performed by using a stockinette machine (Leica TP1020) according to the manufacturer's protocol and schedule (21 h). Then the processed brains were embedded in paraffin, sectioned to a thickness of 12 µm (for anatomical purposes), and stained with hematoxylin and eosin (H&E) (Movahedinia *et al*., 2018). The prepared slides were studied by using a stereomicroscope (Nikon: SMZ-1) equipped with digital lenses and DinoCapture 2.0 software.

Table 1. The 14 fish species studied include 13 bony fishes and 1 cartilaginous fish. The weight and standard length of specimens are also shown (n = 3). (A figure is attached for taxonomic classification)

Scientific name	Common name	Standard length (mm) (max-min)	Weight (g)	Ecology
Liza abu	Abu mullet	123.34±7.12 (119-132)	43.50±8.10	Pelagic
Liza klunzingeri	Klunzinger's mullet	119.56±2.02 (116-123)	42.60±2.61	Demersal
Scomberomorus commerson	Narrow-barred Spanish mackerel	133.23±5.36 (128-140)	41.42±3.81	Pelagic
Acanthopagrus latus	Yellowfin seabream	128.14±3.75 (120-132)	75.54±8.62	Demersal
Epinephelus bleekeri	Duskytail grouper	225.54±17.78 (210-240)	248.33±7.23	Demersal
Otolithes ruber	Tigertooth croaker	245.34±13.66 (233-260)	171.33±1.11	Benthopelagic
Johnius belangerii	Belanger's croaker	144.65±20.37 (120-160)	63.76±2.61	Demersal
Tenualosa ilisha	Hilsa shad	236.12±6.66 (229-245)	198.93±2.91	Pelagic-neritic
Ilisha megaloptera	Bigeye ilisha	NA	NA	Pelagic-neritic
Platycephalus indicus	Bartail flathead	199.31±4.17 (191-205)	60.31±4.97	Reef-associated
Cynoglossus arel	Largescale tonguesole	192.76±12.34 (180-205)	128.93±3.23	Demersal
Euryglossa orientalis	Oriental sole	221.12±29 (199-250)	96.15±4.24	Demersal
Pseudorhombus arsius	Largetooth flounder	208.71±5.92 (203-213)	69.33±1.76	Demersal
Chiloscyllium griseum	Brownbanded bamboo shark	340.81±17.33 (324-360)	91.53±1.55	Reef-associated

Figure 1. Location of stations (S1, S2, and S3) used for collection of fish samples in this study.

The data collected from brains (brain-to-body mass ratio) and whole fish (weight and length) were calculated as mean±standard deviation and analyzed by SPSS ver. 24 software (IBM corp., USA). One-way ANOVA followed by Tukey HSD were used to compare means among fish species. The significance level was set at $p<0.05$.

RESULTS

The general structure of the brain in studied fishes

According to the observations, the brain of Abu mullet (*Liza abu*) had relatively large olfactory lobes. The corpus cerebellum and optic lobes (optic tectum) were similar in size (Figure 2a). The structure of the brain in Klunzinger's mullet (*Liza klunzingeri*) was similar to that in Abu mullet (Figure 2b). In the narrow-barred Spanish mackerel (*Scomberomorus commerson*), the telencephalon and mesencephalon had similar size (Figure 2c). In the yellowfin seabream (*Acanthopagrus latus*), the telencephalon was oblong, and the corpus cerebellum was more obvious compared to the optic tectum (Figure 2d). In grouper (*Epinephelus bleekeri*), the dorsal-medial section of the cerebrum was obvious and this characteristic was not observed in other fishes (Figure 2e). In tigertooth croaker (*Otolithes ruber*), it appeared that the brain had more lobes due to large eminentia granularis and crista cerebellaris, compared to the brains of other species (Figure 2f). While telencephalon, mesencephalon, and corpus cerebellum were proportional in size in Belanger's croaker (*Johnius belangerii*), the brain in hilsa shad (*Tenualosa ilisha*) had rectangular telencephalon, oval optic tectum and smaller corpus cerebellum (Figure 2h), and anatomically had high similarity to the brain of bigeye ilisha (*Ilisha megaloptera*) (Figure 2i). In bartail flathead (*Platycephalus indicus*), the brain had larger optic lobes compared to the telencephalon and corpus cerebellum (Figure 2j). Despite some changes in the structure of the head and eyes during the maturation in Oriental sole (*Euryglossa orientalis*) and largetooth flounder (*Pseudorhombus arsius*), there was no change in the orientation or location of the brains (Figure 2k and 2l). The telencephalon of largetooth flounder was smaller compared to the optic lobes and corpus cerebellum, and eminentia granularis and crista cerebellaris were obvious (Figure 2m). A large and oblong brain along with developed olfactory lobes, undivided and large telencephalon, and relatively small mesencephalon mostly covered with large and oblong cerebellum with several lobes were characteristic in brownbanded bamboo shark (*Chiloscyllium griseum*) (Figure 2n).

Different parts of the brain in the fish

The brain sections showed that the ventricles in bony fish were wide and developed, and more stainable in the center of the telencephalon and optic olfactory lobes than at the periphery (Figure 3). In the brain of yellowfin seabream, the valvula cerebelli was expanded and occupied some parts of the mesencephalon (Figure 3d). The torus longitudinalis had a high stainability with hematoxylin in hilsa shad (Figure 3h). In largescale tonguesole (*Cynoglossus semilaevis*), the mesencephalon had a large torus semicircularis and a small torus longitudinalis (Figure 3m). Obvious ventricles of the telencephalon, cross-divided cerebellum, and thick wall of the cerebellum were characteristics of the brain sections of brownbanded bamboo sharks (Figure 3p).

Brain-to-body mass ratios

The comparison of brain-to-body mass ratios among 10 fish species showed a significant difference in most cases ($p<0.05$). While brownbanded bamboo shark had the highest brain-to-body mass ratio, hilsa shad had the smallest ratio (Table 3). Apart from the shark, brain-to-body mass ratios of narrow-barred mackerel and bartail flathead were significantly higher than most of the other species.

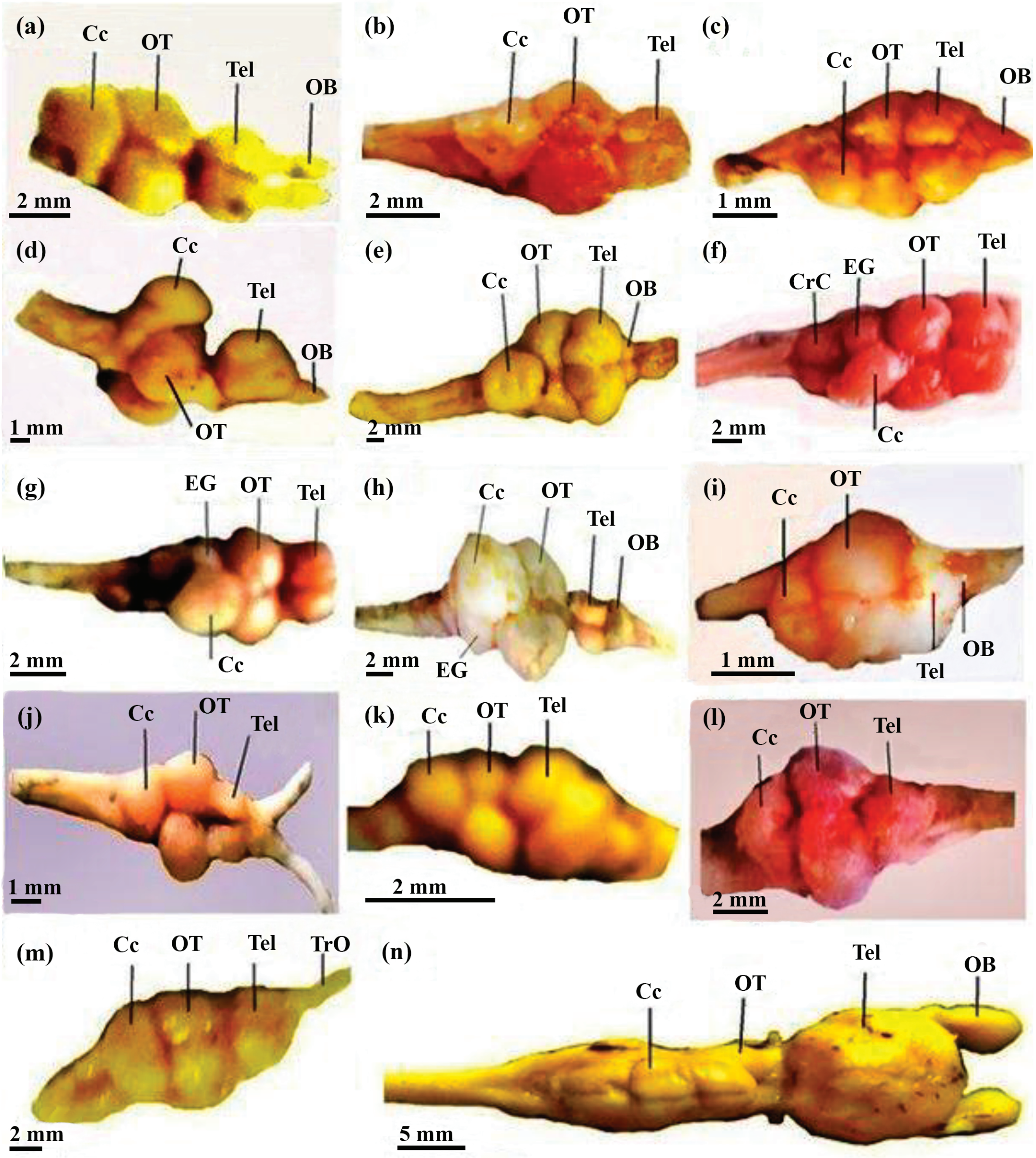

Figure 2. General structure of the brains of Persian Gulf fishes including (a) *Liza abu*; (b) *Liza klunzingeri*; (c) *Scomberomorus commerson*; (d) *Acanthopagrus latus*; (e) *Epinephelus bleekeri*; (f) *Otolithes ruber*; (g) *Johnius belangerii*; (h) *Tenualosa ilisha*; (i) *Ilisha megaloptera*; (j) *Platycephalus indicus*; (k) *Euryglossa orientalis*; (l) *Pseudurhombus arsius*; (m) *Cynoglossus arel*; and (n) *Chiloscyllium griseum*.

Note: OB = olphactory bulb; Tel = telencephalon; Cc = corpus cerebellum; TrO = tractus olfactorius; OT = optic tectum; CrC = crista cerebellaris; EG = eminentia granularis

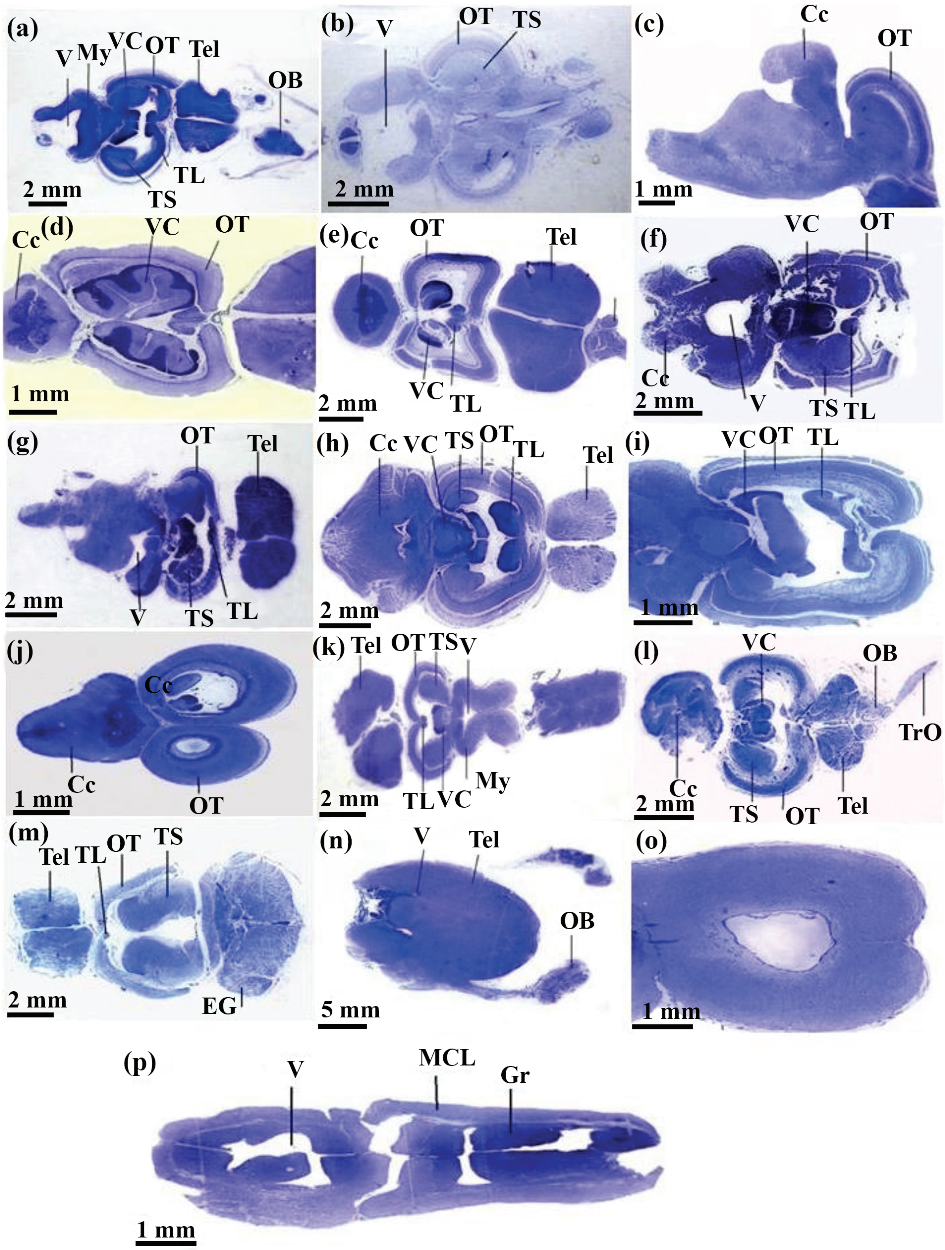

Figure 3. Brain sections of Persian Gulf fish. (a) upper view of the medial section in the brains of *Liza abu* and (b) *Liza klunzingeri*; (c) lateral view of the section in the brain of *Scomberomorus commerson*; (d) upper view of a section in mesencephalon and cerebellum of *Acanthupagrus latus*; (e) upper view of the medial section in the brains of *Epinephelus bleekeri*, (f) *Otolithes ruber*, (g) *Johnius belangerii* and (h) *Tenualosa ilisha*; (i) upper view of a section in the mesencephalon of *Ilisha megaloptera*; (j) upper view of a medial section in mesencephalon and cerebellum of *Platycephalus indicus*; (k) upper view of the medial section in the brains of *Euryglossa orientalis*; (l) *Pseudurhombus arsius*; and (m) *Cynoglossus arel*; (n) upper view of a section in the telencephalon of *Chiloscyllium griseum*; (o) upper view of a medial section in the brain of *Chiloscyllium griseum*; (p) upper view of a section in the brain of *Chiloscyllium griseum*.

Note: OB = olphactory bulbe; Tel = telencephalon; Cc = corpus cerebellum; OT = optic tectum; TS = torus semicircularis; VC = valvula cerebelli; TL = torus longitudinalis; My = myelencephalon; TrO = tractus olfactorius; V = ventricle; Gr = granular section; MCL = molecular section

Table 2. Percentage of brain weight (g)/body weight (g) in 10 fish species from the Persian Gulf. Different superscripts denote significant ($p<0.05$) differences between fishes.

Species	Brain weight/Body weight (%)
Liza abu	$0.49±0.03^{c}$
Liza klunzingeri	$0.33±0.02^{abc}$
Scomberomorus commerson	$0.49±0.02^{c}$
Otolithes ruber	$0.17±0.01^{ab}$
Johnius belangerii	$0.34±0.14^{abc}$
Tenualosa ilisha	$0.09±0.01^{a}$
Platycephalus indicus	$0.43±0.01^{bc}$
Euryglossa orientalis	$0.15±0.06^{ab}$
Cynoglossus arel	$0.15±0.01^{ab}$
Chiloscyllium griseum	$0.8±0.02^{d}$

DISCUSSION

As there are more than 32,000 fish species worldwide, their brains show a great degree of diversification, and both ecology and phylogenetic distance have an important role in this differentiation (Kotrschal *et al*., 1998; Edmunds *et al*., 2016). Also, differences in brain structure can be an indicator of their environment, showing the adaptation of a species to its specific niche in the ecosystem (Edmunds *et al*., 2016). In other words, more interaction between fish and environments with high complexity can lead to more cognitive demands and consequently a higher amount of neural processing and brain tissue (Niven and Laughlin, 2008; Navarrete *et al*., 2011). The brain-to-body mass ratio has been extensively used as a tool for comparing encephalization within species and estimating the intelligence of an animal, and it is better at showing cognitive abilities compared to the absolute size of the brain (Cairó, 2011).

In the present study, the brownbanded bamboo shark, as a representative of cartilaginous fish, had considerable differences in structures of the brain compared to those of the bony fishes. Also, this shark showed the highest brain-to-body mass ratio. It seems that some behavioral factors, including a predatory lifestyle, active and fast swimming, and often highly maneuverable locomotory pattern are important factors that may explain the difference in brain structure (Lisney and Collin, 2006). A previous study showed that the encephalization level (EQ = 1.303) in cartilaginous fish is more than that in teleosts and even amphibians (Ari, 2011). Moreover, Schluessel and Bleckmann (2012) showed that the brownbanded bamboo shark had a high ability in solving and memorizing spatial tasks. The brownbanded bamboo shark is a common inshore shark that feeds on invertebrates (Compagno, 2001). The results of the present study showed that this bottom-feeding shark had a large telencephalon and small mesencephalon, probably related to its feeding and habitat. To confirm this hypothesis, future studies should include other species of demersal sharks.

There was no obvious difference in the brain morphology of largetooth flounder, Oriental sole, or largescale tongue sole (all members of the order of Pleuronectiformes), despite the left or right rotation of their eyes. Also, there was no difference histologically between the left and right sides of the brain in these three fishes. However, some differences in the size of the telencephalon were noted. Despite the occurrence of eye rotation, some specializations for benthic life are seen in these fish, probably leading to nsomechange in the brain morphology, including modifications for feeding on or near the substrate, mechanisms that enable flatfishes to adhere to and rapidly separate from substrates, adaptations to facilitate color changes in the skin to enhance crypsis, and burying behaviors (Fox *et al*., 2018). Kotrschal *et al*. (1998) showed that these fish have a symmetrical brain at the beginning of their life, and then the asymmetry appears in subsequent stages. Apart from the hilsa shad, these three fishes had the lowest brain-to-body ratio among the remaining 13 fishes. According to their feeding on benthic animals, this result was not unexpected.

Hilsa shad had the lowest brain-to-body mass ratio among the 14 species. This fish is a bottom feeder and consequently occupies a lower level of the food chain (Hasan *et al*., 2016). It has been suggested that the small size of brains in planktivorous fish can result from their opportunistic and passive predation strategy. This strategy is less cognitively demanding in terms of sensory and/or motor requirements compared to more agile hunters. Diet, foraging strategy, and strategic hunting have been linked to brain size in various vertebrate groups, such as teleosts, birds and mammals (Yopak and Frank, 2009). Edmunds *et al*. (2016) showed that the potential of fish to use habitat and their position in the food web affects brain morphology. According to this theory, the hilsa shad must have a smaller brain compared to the other fishes because it is located at the bottom of the food chain. Inversely, the narrow-barred mackerel is an epipelagic top-level predator (Lee and Mann, 2017), and consequently had the largest brain among the fishes studied. However, this theory was not confirmed by the results obtained from the brain of Abu mullet. This fish is a detritus feeder, occupying the bottom level of the food chain, and we had expected that it would have a small brain; instead, it had the highest brain-to-body mass ratio among the bony fishes, and was similar to narrow-barred mackerel. Detritus-feeding behavior and consequently large olfactory lobe and telencephalon of Abu mullet can explain this apparent contradiction. In other words, feeding on food particles (detritus feeding) requires chemical senses, and consequently, the relevant parts of the brain (olfactory lobe and telencephalon) are more developed to detect these particles in the environment.

The crista cerebellaris and granular section were more obvious in the tigertooth croaker than in the other fishes, and a lobed brain was also observed. The granular section changes in size with the development of the lateral line and auditory system, nerve fibers from the internal ear and lateral line terminate in this section, and the crista cerebellar processes these inputs (Kotrschal *et al*., 1998). Croakers or drums are a group of noisy and demersal fish that have lateral lines indicating their dark habitats (Ramcharitar *et al*., 2006). In tigertooth croaker, there is a relationship between the way of life and the structure of the brain. These fish use various mechanisms to produce sounds, including muscular vibration of the swim bladder, muscular vibration of the peritoneum, and pharyngeal teeth. Sciaenid sounds typically consist of a series of rapid pulses, and a significant correlation has been found between the swim bladder-inner ear relationship and the range of frequencies detected (Lee *et al*., 2022). In fishes, the relative size of the sensory brain region correlates positively with the relative importance of the sensory system. Thus, a significant increase in the relative size of the olfactory tract and swim bladder-inner ear distance related to foraging habitat during ontogeny is seen in these fish (Ramcharitar *et al*., 2006; Deary *et al*., 2016).

The ventral-medial part of the telencephalon in grouper was prominent and had a lobed cerebrum. Carnivorous fish species like grouper may have larger brain sizes because of a more complex foraging strategy involving selection for rapid prey detection, pursuit, capture and consumption (Gittleman, 1986). Also, there was no significant difference in the brain-to-body mass ratio in this species compared to the highest ratio measured in this study, probably because it lives in the coral reef ecosystem, which is a complex environment.

CONCLUSION

This study showed that a cartilaginous fish (*Chiloscyllium griseum*) had considerable differences in the structure of the brain compared to bony fishes, and it showed the highest brain-to-body mass ratio. A plankton-feeding fish (*Tenualosa ilisha*) occupying a low trophic level had a lower brain-to-body mass ratio and more simple brain structure compared to a carnivorous species (*Scomberomorus commerson*). Moreover, a coral-reef dweller (*Epinephelus bleekeri*) had a higher brain-to-body mass ratio and more complex brain structure compared to flounders occupying a simple environment. Generally, this study showed that phylogenetic distance, trophic level, and complexity of the environment are important factors in the brain anatomy of fishes living in the Persian Gulf.

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LITERATURE CITED

Ari, C. 2011. Encephalization and brain organization of mobulid rays (*Myliobatiformes*, *Elasmobranchii*) with ecological perspectives. **The Open Anatomy Journal** 3(1): 1-13.

Bani, A.F. and N. Jadidi. 2008. Brain morphology in *Acipenser stellatus* and *Acipenser persicus*. **Iranian Journal of Biology** 21(2): 341-350.

Cairó, O. 2011. External measures of cognition. **Frontiers in Human Neuroscience** 5: 108. DOI: 10.3389/fnhum.2011.00108.

Compagno, L.J. 2001. **Sharks of the World: An Annotated and Illustrated Catalogue of Shark Species Known to Date,** 1st ed. Food and Agriculture Organization of the United Nations, Rome, Italy. 269 pp.

Deary, A.L., B. Metscher, R.W. Brill and E.J. Hilton. 2016. Shifts of sensory modalities in early life history stage estuarine fishes (Sciaenidae) from the Chesapeake Bay using X-ray micro computed tomography. **Environmental Biology of Fishes** 99(4): 361-375.

Eastman, J.T. and M.J. Lannoo. 2007. Brain and sense organ anatomy and histology of two species of phyletically basal non-Antarctic thornfishes of the Antarctic suborder Notothenioidei (Perciformes: Bovichtidae). **Journal of Morphology** 268(6): 485-503.

Edmunds, N.B., K.S. McCann and F. Laberge. 2016. Food web structure shapes the morphology of teleost fish brains. **Brain, Behavior and Evolution** 87(2): 128-138.

Fox, C.H., A.C. Gibb, A.P. Summers and W.E. Bemis. 2018. Benthic walking, bounding, and maneuvering in flatfishes (Pleuronectiformes: Pleuronectidae): New vertebrate gaits. **Zoology** 130: 19-29.

Gittleman, J.L. 1986. Carnivore brain size, behavioral ecology, and phylogeny. **Journal of Mammalogy** 67(1): 23-36.

Hasan, K.M.M., Z.F. Ahmed, M.A. Wahab and E.Y. Mohammed. 2016. **Food and feeding ecology of hilsa (*Tenualosa ilisha*) in Bangladesh's Meghna River basin.** International Institute for Environment and Development, London, UK. 20 pp.

Kotrschal, K., M.J. Van Staaden and R. Huber. 1998. Fish brains: evolution and anvironmental relationships. **Reviews in Fish Biology and Fisheries** 8(4): 373-408.

Lecchini, D., G. Lecellier, R.G. Lanyon, S. Holles, B. Poucet and E. Duran. 2014. Variation in brain organization of coral reef fish larvae according to life history traits. **Brain, Behavior and Evolution** 83(1): 17-30.

Lee, B. and B. Mann. 2017. Age and growth of narrow-barred Spanish mackerel *Scomberomorus commerson* in the coastal waters of southern Mozambique and KwaZulu-Natal, South Africa. **African Journal of Marine Science** 39(4): 397-407.

Lee, H.T., B.Q. Huang and C.H. Liao. 2022. functional adaptation of vocalization revealed by morphological and histochemical characteristics of sonic muscles in blackmouth croaker (*Atrobucca nibe*). **Biology** 11(3): 438. DOI: 10.3390/biology11030438.

Lisney, T. and S. Collin. 2006. Brain morphology in large pelagic fishes: a comparison between sharks and teleosts. **Journal of Fish Biology** 68(2): 532-554.

Movahedinia, A., N. Salamat and P. Kheradmand. 2018. Effects of the environmental endocrine disrupting compound benzo [a] pyrene on thyroidal status of abu mullet (*Liza abu*) during short-term exposure. **Toxicology Reports** 5: 377-382.

Navarrete, A., C.P. Van Schaik and K. Isler. 2011. Energetics and the evolution of human brain size. **Nature** 480(7375): 91-93.

Nieuwenhuys, R., H.J. ten Donkelaar and C. Nicholson. 2014. **The Central Nervous System of Vertebrates,** 1st ed. Springer, Heidelberg, Germany. 327 pp.

Niven, J.E. and S.B. Laughlin. 2008. Energy limitation as a selective pressure on the evolution of sensory systems. **Journal of Experimental Biology** 211(11): 1792-1804.

Owfi, F. 2015. **A review on systematic and taxonomic of the Persian Gulf fish species, based on geographical distribution pattern and habitat diversity, using by GIS.** Ph.D. Thesis, Islamic Azad University, Tehran, Iran. 180 pp.

Pelvig, D., H. Pakkenberg, A.K. Stark and B. Pakkenberg. 2008. Neocortical glial cell numbers in human brains. **Neurobiology of Aging** 29(11): 1754-1762.

Ramcharitar, J., D.P. Gannon and A.N. Popper. 2006. Bioacoustics of fishes of the family Sciaenidae (croakers and drums). **Transactions of the American Fisheries Society** 135(5): 1409-1431.

Rodriguez, F., E. Durán, A.Gómez, F.M. Ocana, E. Alvarez, F. Jiménez-Moya, C. Broglio and C. Salas. 2005. Cognitive and emotional functions of the teleost fish cerebellum. **Brain Research Bulletin** 66(4-6): 365-370.

Schluessel, V. and H. Bleckmann. 2012. Spatial learning and memory retention in the grey bamboo shark (*Chiloscyllium griseum*). **Zoology** 115(6): 346-353.

Shu, D.G., S.C. Morris, J. Han, Z.F. Zhang, K. Yasui, P. Janvier, L.I.N.G. Chen, X.L. Zhang, J.N. Liu, Y.O.N.G. Li and H.Q. Liu. 2003. Head and backbone of the Early Cambrian vertebrate *Haikouichthys*. **Nature** 421 (6922): 526. DOI: 10.1038/nature01264.

Sternberg, R.J. and J.C. Kaufman. 2013. **The Evolution of Intelligence,** 1st ed. Psychology Press, Taylor and francis group, New York, USA. 383 pp.

Striedter, G.F. 2006. Précis of principles of brain evolution. **Behavioral and Brain Sciences** 29(1): 1-12.

Yopak, K.E. and L.R. Frank. 2009. Brain size and brain organization of the whale shark, *Rhincodon typus*, using magnetic resonance imaging. **Brain, Behavior, and Evolution** 74(2): 121-142.