



## Mercury in the tissues of five cephalopods species: First data on the nervous system



Antoine Minet<sup>a</sup>, Alain Manceau<sup>b</sup>, Anaïs Valada-Mennuni<sup>a</sup>, Maud Brault-Favrou<sup>a</sup>, Carine Churlaud<sup>a</sup>, Jérôme Fort<sup>a</sup>, Thành Nguyen<sup>a,c</sup>, Jérôme Spitz<sup>d,e</sup>, Paco Bustamante<sup>a,f</sup>, Thomas Lacoue-Labarthe<sup>a,\*</sup>

<sup>a</sup> Littoral Environnement et Sociétés (LIENSs), UMR 7266 CNRS - La Rochelle Université, 2 rue Olympe de Gouges, 17000 La Rochelle, France

<sup>b</sup> Univ. Grenoble Alpes, ISTERre, CNRS, CS 40700, 38058 Grenoble, France

<sup>c</sup> Université des Sciences et des Technologies de Hanoï (USTH), 18 Hoàng Quốc Việt, Nghĩa Đô, Cầu Giấy, Hà Nội, Viet Nam

<sup>d</sup> Centre d'Études Biologiques de Chizé (CEBC), UMR 7372 CNRS - La Rochelle Université, 5 Allées de l'Océan, 17000 La Rochelle, France

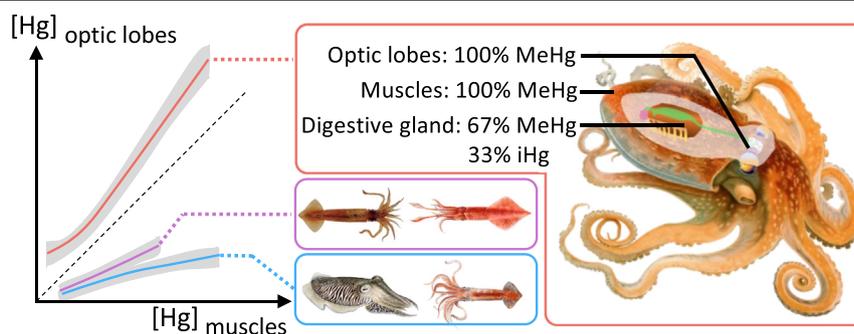
<sup>e</sup> Observatoire PELAGIS, UMS 3462 CNRS - La Rochelle Université, 5 Allées de l'Océan, 17000 La Rochelle, France

<sup>f</sup> Institut Universitaire de France (IUF), 1 rue Descartes, 75005 Paris, France

### HIGHLIGHTS

- Hg levels were measured in digestive gland, muscle and brain in 5 cephalopod species.
- Hg concentrations in the optic lobes can be predicted from muscle ones.
- Highest Hg concentrations were found in the optic lobes of the octopus *E. cirrhosa*.
- XANES showed 33% of iHg in octopus digestive gland suggesting demethylation.
- 100% of MeHg in brain and muscle implies dietary MeHg storage in these tissues.

### GRAPHICAL ABSTRACT



### ARTICLE INFO

#### Article history:

Received 30 August 2020

Received in revised form 27 October 2020

Accepted 18 November 2020

Available online 3 December 2020

Editor: Daniel A. Wunderlin

#### Keywords:

Organotropism  
Mantle muscle  
Digestive gland  
Optic lobes  
MethylHg  
Speciation  
HR-XANES

### ABSTRACT

Mercury (Hg), one of the elements most toxic to biota, accumulates within organisms throughout their lifespan and biomagnifies along trophic chain. Due to their key role in marine systems, cephalopods constitute a major vector of Hg in predators. Further, they grow rapidly and display complex behaviours, which can be altered by neurotoxic Hg. This study investigated Hg concentrations within 81 cephalopod specimens sampled in the Bay of Biscay, which belonged to five species: *Eledone cirrhosa*, *Sepia officinalis*, *Loligo vulgaris*, *Todaropsis eblanae* and *Illex coindetii*. Hg concentrations were measured in the digestive gland, the mantle muscle and the optic lobes of the brain. The digestive gland and the mantle were tissues with the most concentrated Hg among all species considered (up to  $1.50 \mu\text{g}\cdot\text{g}^{-1}$  dw), except *E. cirrhosa*. This benthic cephalopod had 1.3-fold higher Hg concentrations in the brain (up to  $1.89 \mu\text{g}\cdot\text{g}^{-1}$  dw) than in the mantle, while other species had 2-fold lower concentrations of Hg in the brain than in the mantle. Brain-Hg concentrations can be predicted from muscle-Hg concentrations for a given species, which facilitates the assessment of Hg toxicokinetics in cephalopods. In the most contaminated *E. cirrhosa* individual, the chemical form of Hg in its digestive gland, mantle muscle and optic lobes, was determined using High energy-Resolution X-ray Absorption Near Edge Structure (HR XANES) spectroscopy. In the digestive gland,  $33 \pm 11\%$  of total Hg was inorganic Hg speciated as a dicysteinate complex ( $\text{Hg}(\text{Cys})_2$ ), which suggested that the demethylation of dietary MeHg occurs in this organ. All Hg found in the mantle muscle and the optic lobes is methylated and bound to one cysteinyl group (MeHgCys

\* Corresponding author at: UMR 7266 CNRS-La Rochelle Université, Institut du Littoral et Environnement, 2 rue Olympe de Gouges, 17000 La Rochelle, France.  
E-mail address: [tlacouel@univ-lr.fr](mailto:tlacouel@univ-lr.fr) (T. Lacoue-Labarthe).

complex), which implies that dietary MeHg is distributed to these tissues via the bloodstream. These results raised the questions regarding interspecific differences observed regarding Hg brain concentrations and the possible effect of Hg on cephalopod functional brain plasticity and behaviour.

© 2020 Elsevier B.V. All rights reserved.

## 1. Introduction

Mercury (Hg) is a globally distributed pollutant that poses considerable risk to the health of humans and wildlife (Scheuhammer et al., 2007). Special attention to this contaminant within the marine environment, a final receptor for a large proportion of atmospheric, freshwater and terrestrial Hg contamination is needed (Driscoll et al., 2013). Mercury is mostly derived from anthropogenic sources and is principally found in inorganic (iHg) free forms and complexed ions, and as organic forms, which include methylmercury (MeHg) (Mason and Benoit, 2003). In fact, under anaerobic conditions in sediments or deep waters, microorganisms such as iron and sulphate reducing bacteria convert iHg to MeHg (Benoit et al., 2002; Hammerschmidt and Fitzgerald, 2004). Recently, metagenome and metatranscriptome analyses have revealed that aerobic microorganisms are also potentially involved in MeHg production in subsurface oxic seawater (Villar et al., 2020). Hg mobility and toxicity depend on its molecular speciation (Weiner and Suchanek, 2008), which confers strong neurotoxic properties to MeHg against biota including humans (Farina et al., 2011; Eagles-Smith et al., 2018). Furthermore, MeHg accumulates in marine organisms throughout their lifespan and biomagnifies along trophic chains to reach concentrations well above its toxicity threshold in top predators (Lemos Bisi et al., 2012; Van der Velden et al., 2013; Chouvelon et al., 2018; López-Berenguer et al., 2020).

Among the oceanic trophic compartments, cephalopods are a central link in food webs and play a role as vector for many contaminants such as cadmium (Cd) and Hg (Clark, 1996; Bustamante et al., 1998; Maz-Courrau et al., 2012). Our knowledge of Hg in cephalopods is essentially limited to the species of interest to fisheries (e.g. Penicaud et al., 2017) and levels are generally measured in edible portions of organisms (i.e. muscles of the mantle and arms of squids and octopods, respectively) that store more than 70% whole body Hg burden (Seixas et al., 2005; Bustamante et al., 2006; Lacoue-Labarthe et al., 2009). Most of the Hg found in cephalopod muscles is in its organic form (Bustamante et al., 2006; Seco et al., 2020), and the speciation of Hg in tissues other than muscles has not been well documented to date (see below).

Mercury concentrations reported in cephalopod muscles vary by two orders of magnitude among species (Bustamante et al., 2006). Overall, median Hg concentrations in cuttlefish, octopods and squids range from 0.2 and 0.5  $\mu\text{g}\cdot\text{g}^{-1}$  dry weight (dw) (Penicaud et al., 2017). These levels are moderately high with respect to their central trophic position and their short lifespan (an average of two years) that limits the Hg bioaccumulation within their tissues (Chouvelon et al., 2011). Higher concentrations were reported in some species or individuals, up to 1.76  $\mu\text{g}\cdot\text{g}^{-1}$  dw in the curled octopus, *Eledone cirrhosa*, from Mediterranean Sea (i.e. 0.44  $\mu\text{g}\cdot\text{g}^{-1}$  wet weight (ww) reported by Storelli et al., 2010 assuming 75% water content as reported in Spitz et al., 2010). Hg concentrations in mantle muscle and in the digestive gland have been used to infer Hg environmental contamination, since Hg mostly accumulates in its organic form in muscles and is highly concentrated in the digestive gland, where Hg detoxification occurs (Bustamante et al., 2006; Lacoue-Labarthe et al., 2009). However, reports of Hg concentrations in tissues that are likely sensitive to Hg, such as the nervous system, are scarce.

Although Hg neurotoxicity has been recognised, information regarding Hg brain tropism in marine organisms are scattered (Berntssen et al., 2004). Previous studies have focused on fish providing nervous system Hg based on concentrations present in the environment. Alternatively,

they assessed classically targeted organs such as muscle and liver. Hg concentrations in the tissues of bluefish, *Pomatomus saltatrix* from New Jersey showed Hg levels one order of magnitude lower in the brain than muscles and kidneys (Burger et al., 2013). In more contaminated fish such as the spotted seatrout, *Cynoscion nebulosus* and the European bass, *Dicentrarchus labrax* that were isolated from polluted areas, brain Hg concentrations were less than 3-fold lower than those reported in muscles and liver (Adams et al., 2010; Mieiro et al., 2012). In addition, Hg in the brain of the golden grey mullet, *Liza aurata*, from different areas of the Portuguese coastline faithfully reflected local water and sediment contamination variability (Pereira et al., 2014). Through an experimental approach, autoradiography revealed a specific affinity of  $^{203}\text{iHg}$  in the brain of the brown trout *Salmo trutta* and the rainbow trout *Oncorhynchus mykiss* following waterborne exposure, suggesting that the transport of this metal occurs from sensory or motor systems to the brain (Rouleau et al., 1999). Hg exposure and its subsequent accumulation in the nervous system can then lead to oxidative stress, metallothionein production, brain lesions, morphometric alterations and consequently affect swimming behaviour in the Atlantic salmon *Salmo salar*, the European bass *Dicentrarchus labrax*, the zebrafish *Danio rerio*, and the white seabream *Diplodus sargus* (Berntssen et al., 2003; Mieiro et al., 2011; Gentès et al., 2015; Pereira et al., 2016).

Cephalopods are known as an alternative model to vertebrates for the evolution of complex brains and high intelligence, and they are renowned for their advanced cognitive performances (O'Brien et al., 2018) and complex behaviours (Hanlon and Messenger, 2018). Such abilities require a much more evolved and developed brain than is needed in mollusks like bivalves and gastropods (Hanlon and Messenger, 2018). The cephalopod nervous system is composed of the central brain (around 40 interconnected ganglia), two optic lobes and the peripheral nervous system. Their large-sized brain, compared to other invertebrates, is involved in behavioural plasticity, cognitive capacity as well as skin control (Shigeno et al., 2018) and is of increased concern when considering impacts of neurotoxicants (e.g. Chabenat et al., 2019). Very few studies have examined the accumulation of Hg in tissues of the nervous system, and Hg levels in the muscular mantle, branchial hearts, kidneys, gills, ink sack and the digestive gland (Seixas et al., 2005; Pereira et al., 2009). In fact, to the best of our knowledge, only one study that examined Hg concentration in the brain of one individual of giant squid, *Architeuthis dux* (1.25  $\mu\text{g}\cdot\text{g}^{-1}$  dw; Bustamante et al., 2008) in which Hg concentration was in the same order of magnitude of the other tissues. The extent to which Hg bioaccumulation occurs and its speciation in the brains of cephalopods requires further examination.

In this context, the current study aims to investigate levels of Hg contamination in five different species of cephalopods from the Bay of Biscay including *Eledone cirrhosa*, *Sepia officinalis*, *Loligo vulgaris*, *Todaropsis eblanae* and *Illex coindetii*. Hg concentrations were measured in the tissues with major roles in Hg bioaccumulation and detoxification including the mantle muscles, which are responsible for storing the majority of the Hg burden, and the digestive gland, which can demethylate and depurate Hg from the body. Hg concentrations were also determined in the optic lobes of the brain, since this tissue is potentially sensitive to Hg toxicity. In addition, the molecular form of Hg in the digestive gland, the mantle muscle and in the optic lobes of the most contaminated curled octopus, *E. cirrhosa*, individuals were investigated via high energy-resolution XANES spectroscopy.

## 2. Material and methods

### 2.1. Sample collection and sample preparation

In this study, 81 cephalopods were sampled along the continental shelf of the Bay of Biscay during EVHOE surveys conducted by the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) in autumn of 2016 and 2017 (Léauté et al., 2016; Duhamel et al., 2017). Collected organisms belonged to five cephalopod species from four different families (see Table 1), as follows: curled octopus, *E. cirrhosa* ( $n = 20$ ); common cuttlefish, *S. officinalis* ( $n = 21$ ); common squid, *L. vulgaris* ( $n = 20$ ); the lesser flying squid, *T. eblanae* ( $n = 9$ ); and southern shortfin squid, *I. coindetii* ( $n = 11$ ). Specimens were frozen at  $-20^{\circ}\text{C}$  on board and then stored in the laboratory prior to dissection and sample preparation.

In the laboratory, individuals were thawed and weighed (g). Dorsal mantle length (DML; mm) was measured as a reference for measuring the size of the cephalopod. Whenever possible, sex was determined by visual observation of gonads and hectocotylied arms (Table 1). During dissection, the digestive gland, the mantle and the optic lobes were collected and wet weighed (g ww). The sampled tissues were frozen and freeze-dried for 48 h. Samples were dry weighed (g dw), ground manually with a porcelain pestle and mortar into a fine powder, and hermetically stored in 40 mL plastic vials.

### 2.2. Mercury analyses

Total Hg concentrations within samples were analysed at the Littoral ENvironnement et Sociétés laboratory (LIENSs, La Rochelle, France) using an Advanced Mercury Analyser spectrophotometer (Altec AMA 254) as described in Chouvelon et al. (2009). All analyses were carried out in duplicate or triplicate, and had relative standard deviation values  $<10\%$ . Mercury analyses were run according to a thorough quality control programme that included an analysis of procedural blanks at the beginning of each analytical sessions and a certified reference material (CRM) was assessed every 10 samples. Thus, the accuracy of the analytical procedure was verified with CRM TORT-2 (lobster hepatopancreas, NRC, Canada; Hg concentration of  $0.27 \pm 0.06 \mu\text{g}\cdot\text{g}^{-1}$  dw). Results indicated an average Hg concentration of  $0.257 \pm 0.009 \mu\text{g}\cdot\text{g}^{-1}$  dw, with an average recovery of  $95 \pm 3\%$ , and were in good agreement with certified values. The detection limit of the method was  $0.005 \mu\text{g}\cdot\text{g}^{-1}$  dw. Mercury concentrations are further expressed as  $\mu\text{g}\cdot\text{g}^{-1}$  dw.

### 2.3. HR-XANES measurements

Freeze-dried powdered digestive gland, mantle muscle and optic lobe of *E. cirrhosa* were pressed into pellets, and their Hg  $L_{3\text{-edge}}$  XANES (for X-ray Absorption Near Edge Structure) spectra were measured using high energy-resolution (HR-XANES) with high-luminosity analyser crystals on beamline ID26 at the European Synchrotron Radiation Facility (ESRF, Rovezzi et al., 2017). Mantle muscles and the digestive gland of the most contaminated individual were selected for further examination, whereas the optic lobes of the six individuals that were most contaminated were pooled because each lobe had low mass ( $\sim 50\text{--}80$  mg). Spectra were collected at a temperature of  $10\text{--}15$  K and

a scan time of 15 s to reduce exposure, and repeated at using pristine positions of the sample to increase the signal-to-noise ratio. Scans were monitored carefully for any evidence of radiation damage. Incident energy was scanned from 12,260 to 12,360 eV in increment of 0.2 eV and the spectra were normalised to unity at  $E = 12,360$  eV. The identities and relative proportions of Hg species were determined using a spectral database (Bourdineaud et al., 2019). The precision of the fit of components was estimated to be equal to the variation of their best-fit values when the fit residual (NSS) was increased by 20%. NSS was defined as the normalised sum-squared difference between data and fit, was expressed as follows:  $\Sigma[(Y_{\text{data}} - Y_{\text{fit}})^2] / \Sigma(Y_{\text{data}}^2)$ . Details regarding data acquisition and analysis were performed as previously described (Manceau et al., 2019).

### 2.4. Statistical and data analyses

Statistics were computed using R version 3.6.1 (R Core Team, 2017). The influence of the tissue on Hg concentrations was tested by using generalised linear models (GLM) with a gaussian distribution and an identity link function. Model selection was based on Akaike's Information Criteria adjusted for small sample sizes (AICc) (Burnham and Anderson, 2002).

Concentrations of Hg analysed in the mantle, digestive gland and optic lobes of the five species assessed were compared using a one-way ANOVA followed by a Tukey test. Normality and heteroscedasticity of values were tested using a Barlett and Shapiro test, respectively, and each of the cephalopods relative to the others were considered separately. When the conditions of the statistical tests were not met, non-parametric tests of Wilcoxon followed the post-hoc test of Nemenyi were applied. A linear model was applied to describe relationships between Hg concentrations in the optic lobe and mantle muscle and an analysis of covariance (ANCOVA) was used to test differences in the slopes of regression lines for the five species considered.

Hg concentrations reported from the literature were converted when necessary from ww to dw using measured moisture values from the different tissues, as follows: dw represents 20% of the ww for muscle and brain tissues and 35% of the ww of the digestive gland (Suppes et al., 1967; Arai et al., 2016 and personal data).

## 3. Results

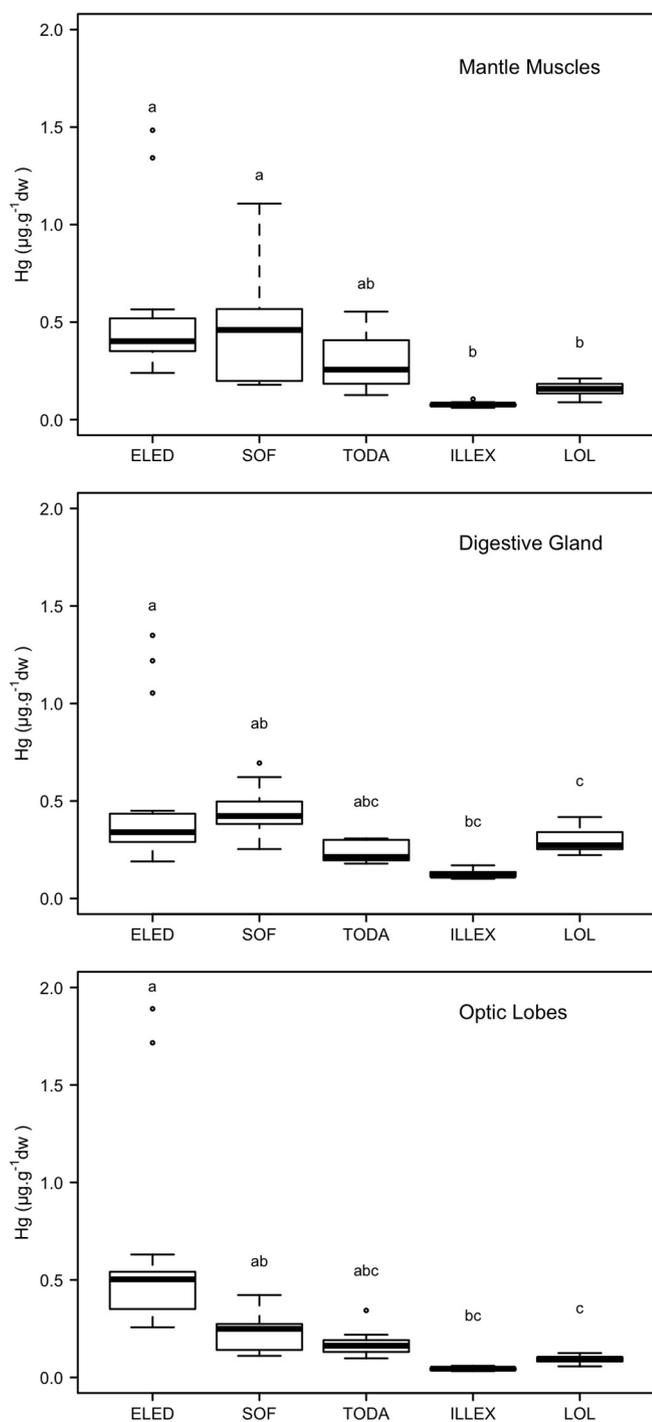
The mantle size and weight of animals varied from 4.2 to 19.0 cm and 19 to 764 g ww, respectively. Measured Hg concentrations were  $0.02\text{--}1.48 \mu\text{g}\cdot\text{g}^{-1}$  dw, from  $0.09\text{--}1.35 \mu\text{g}\cdot\text{g}^{-1}$  dw, and  $0.03\text{--}1.89 \mu\text{g}\cdot\text{g}^{-1}$  dw in mantle muscles, the digestive gland and optic lobes, respectively (Table 1).

GLMs revealed that Hg concentrations differed according to species and tissue assessed (Fig. 1; Table 2). Overall, although concentrations among the three analysed tissues were of the same order of magnitude, Hg concentrations were significantly higher in the mantle muscles and the digestive gland than the optic lobes in all species assessed, except in *E. cirrhosa*. Relative Hg concentrations in the mantle muscles of species assessed were as follows: *E. cirrhosa*  $\approx$  *S. officinalis*  $\approx$  *T. eblanae*  $>$  *L. vulgaris*  $>$  *I. coindetii* (values measured were  $0.52 \pm 0.35$ ,  $0.46 \pm 0.24$ ,  $0.29 \pm 0.06$ ,  $0.16 \pm 0.03$ , and  $0.08 \pm 0.01 \mu\text{g}\cdot\text{g}^{-1}$  dw, respectively).

**Table 1**

Mantle size range and mean ( $\pm$  sd in cm), mantle weight range and mean ( $\pm$  sd in g) and total Hg concentrations (mean  $\pm$  sd in  $\mu\text{g}\cdot\text{g}^{-1}$  dw) in mantle muscles, digestive gland and optic lobes of *Eledone cirrhosa* ( $n = 20$ ), *Illex coindetii* ( $n = 11$ ), *Todaropsis eblanae* ( $n = 9$ ), *Loligo vulgaris* ( $n = 20$ ), *Sepia officinalis* ( $n = 21$ ).

Tissues Species	Family	Mantle size range (cm)	Mantle size mean $\pm$ sd (cm)	Weight range (g)	Weight mean $\pm$ sd (g)	[Hg] mantle muscles	[Hg] digestive gland	[Hg] optic lobes
<i>Eledone cirrhosa</i>	Octopodidae	4.2–14.9	$8.3 \pm 2.4$	19–764	$197 \pm 177$	$0.52 \pm 0.35$	$0.47 \pm 0.34$	$0.60 \pm 0.47$
<i>Sepia officinalis</i>	Sepiidae	12.5–17.0	$14.6 \pm 1.2$	240–544	$397 \pm 105$	$0.46 \pm 0.24$	$0.43 \pm 0.12$	$0.23 \pm 0.09$
<i>Loligo vulgaris</i>	Loliginidae	13.2–19.0	$16.6 \pm 1.8$	83–198	$139 \pm 34$	$0.16 \pm 0.03$	$0.29 \pm 0.06$	$0.09 \pm 0.02$
<i>Illex coindetii</i>	Ommastrephidae	14.3–18.0	$15.5 \pm 1.4$	62–131	$85 \pm 19$	$0.08 \pm 0.01$	$0.12 \pm 0.02$	$0.04 \pm 0.01$
<i>Todaropsis eblanae</i>	Ommastrephidae	7.8–13.0	$10.6 \pm 1.8$	43–167	$105 \pm 46$	$0.29 \pm 0.15$	$0.24 \pm 0.06$	$0.18 \pm 0.07$



**Fig. 1.** Hg concentrations ( $\mu\text{g.g}^{-1}\text{ dw}$ ) in the mantle muscles, digestive gland, and the optic lobes of the five studied cephalopods species: ELED: *Eledone cirrhosa* ( $n = 20$ ); ILLEX: *Illex coindetii* ( $n = 11$ ); LOL: *Loligo vulgaris* ( $n = 20$ ); SOF: *Sepia officinalis* ( $n = 21$ ); TODA: *Todaropsis eblanae* ( $n = 9$ ). Statistical differences are denoted by different letters when significant ( $p\text{-value} < 0.05$ ).

In the digestive gland, the same trend was observed, and significantly higher levels of Hg were measured in *E. cirrhosa* and *S. officinalis* than in other squid species. Relative values were as follows: *E. cirrhosa*  $\approx$  *S. officinalis*  $>$  *L. vulgaris*  $\approx$  *T. eblanae*  $>$  *I. coindetii* ( $0.47 \pm 0.34$ ,  $0.43 \pm 0.12$ ,  $0.29 \pm 0.06$ ,  $0.24 \pm 0.06$ , and  $0.12 \pm 0.02 \mu\text{g.g}^{-1}\text{ dw}$ , respectively). In the optic lobes, relative Hg concentrations were similar, however, a greater difference between *E. cirrhosa* and other species was observed, as follows: *E. cirrhosa*  $>$  *S. officinalis*  $\approx$  *T. eblanae*  $>$  *L. vulgaris*  $\approx$  *I. coindetii* ( $0.60 \pm 0.47$ ,  $0.23 \pm 0.09$ ,  $0.18 \pm 0.07$ ,  $0.09 \pm 0.02$ , and

$0.04 \pm 0.01 \mu\text{g.g}^{-1}\text{ dw}$ , respectively). Interestingly, two *E. cirrhosa* individuals (53 and 90 mm mantle size) had elevated Hg concentrations that reached more than  $1 \mu\text{g.g}^{-1}$  in the mantle and the digestive gland and more than  $1.5 \mu\text{g.g}^{-1}$  in the optic lobes, whereas values rarely exceeded  $0.5 \mu\text{g.g}^{-1}\text{ dw}$  in other species, in any tissue assessed.

The concentrations of Hg in the optic lobes were linearly and strongly associated with those of mantle muscle (Fig. 2, Table 3). ANCOVA revealed that slopes of the regressions were significantly different among when *E. cirrhosa* ( $R^2 = 0.978$ ), *S. officinalis* and *T. eblanae* ( $R^2 = 0.829$ ), and *I. coindetii* and *L. vulgaris* ( $R^2 = 0.663$ ) were compared. This implies that the ratio of brain and muscle Hg concentrations differed among the three groups. Interestingly, *E. cirrhosa* had an optic lobes Hg concentration that was slightly higher (1.15-fold greater) than that of mantle muscles, whereas *S. officinalis*/*T. eblanae* and *I. coindetii*/*L. vulgaris* had optic lobes concentrations that were 0.35 and 0.50-fold lower, respectively, than those of mantle muscles.

HR-XANES spectra of the optic lobes and mantle muscles were statistically indistinguishable, indicating similar or identical chemical forms of Hg were present in each tissue (Fig. 3a). The best spectral match with our database of model compounds was obtained with MeHg bound to cysteine residues in fish (Fig. 3b). In this complex, Hg is linearly bound to a methyl group and the aliphatic thiol from a cysteinyl group (forming a MeHgCys complex). This geometry gives a characteristic absorption peak at 12,279.8 eV, which is not observed when Hg is coordinated to three or four thiols (Bourdineaud et al., 2019). This peak occurs at 12,279.6 eV in the digestive gland and its intensity was lower (Fig. 3c). These two features are diagnostic of the linear coordination to two thiol groups, as it is observed in an inorganic Hg (Cys)<sub>2</sub> complex (Manceau et al., 2016). Proportions of methylated and inorganic Hg, as determined by a linear combination fit of the optic lobe spectrum and the Hg(Cys)<sub>2</sub> standard, were  $68 \pm 11\%$  for MeHgCys and  $33 \pm 11\%$  for Hg(Cys)<sub>2</sub> (Fig. 3d).

#### 4. Discussion

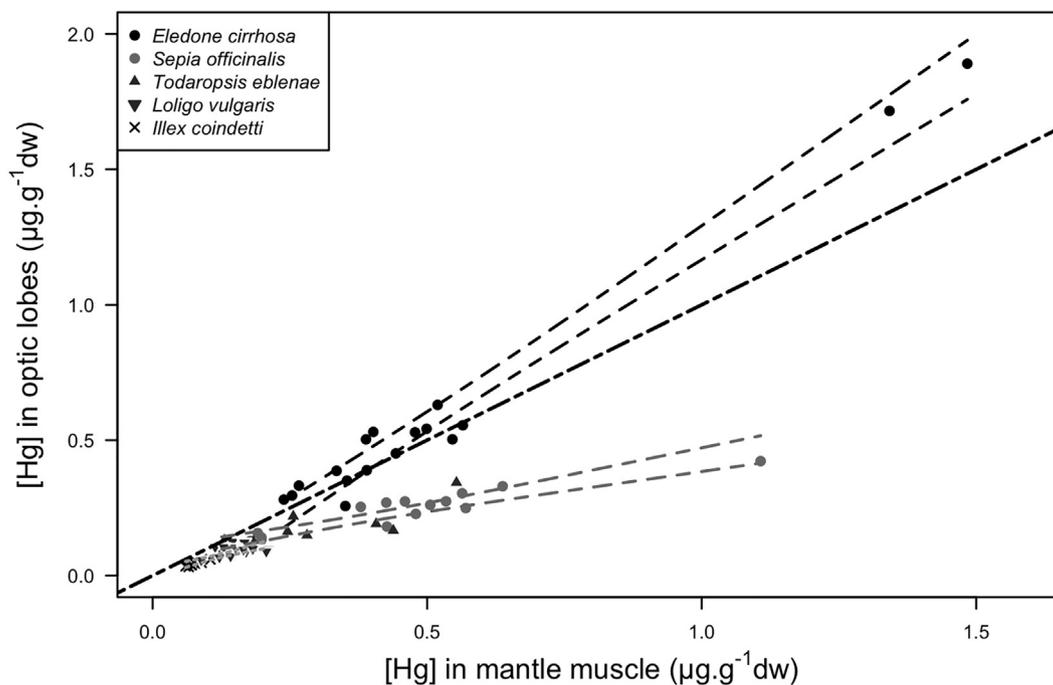
Among marine organisms, most available information regarding Hg contamination has been determined in bivalves, fish and top predators (mammals and birds), mainly due to their importance as a food source for humans and their roles as bioindicators of Hg contamination of the ocean (Renzone et al., 1998). In contrast, the information regarding Hg contamination in cephalopod tissues remains scarce, despite the fact that mollusks are known to efficiently accumulate chemical contaminants, including non-essential metals that may be concentrated at very high levels in their tissues (Dorneles et al., 2007; Lischka et al., 2018). Although Hg concentrations are moderate in cephalopods, significant differences between taxons have been observed, and values vary by two orders of magnitude among cephalopod families (Penicaud et al., 2017). The cephalopods have a pivotal place in trophic webs, and have a key role in the Hg intake of top predators including humans (Jackson et al., 2007), therefore a better understanding of the Hg bioaccumulation processes in cephalopods is needed. Finally, despite their invertebrate status, cephalopods have an exceptionally developed

**Table 2**

AICc model ranking for log Hg concentrations within the five studied cephalopod species from Bay of Biscay. Models are GLMs with a gaussian distribution and an identity link function. Abbreviations: AICc, Akaike's Information Criteria adjusted for small sample-sizes values;  $w_i$ , AICc weights.

Models	N° parameters	AIC <sub>c</sub>	$\Delta\text{AIC}_c^a$	$w_i$
Cephalopods ( $n = 240$ )				
Tissue * Species	16	225	0	1
Tissue + Species	8	276	51	0
Species	6	330	105	0
Tissue	4	499	274	0
Null	2	519	294	0

<sup>a</sup> Scaled  $\Delta\text{AIC}_c$ ;  $\Delta\text{AIC}_c = 0.00$  is interpreted as the best fit to the data among the models.



**Fig. 2.** Hg concentrations ( $\mu\text{g.g}^{-1}\text{ dw}$ ) in optic lobes as a function of Hg concentrations in mantle muscle for the five cephalopods species: *Eledone cirrhosa* (black points), *Sepia officinalis* (grey points), *Todaropsis eblanae* (black triangles), *Loligo vulgaris* (inversed black triangles), *Illex coindetii* (black crosses). Linear models for *E. cirrhosa*, *S. officinalis* and *T. eblanae*, and *I. coindetii* and *L. vulgaris* are represented by the 95% confidence intervals (black, grey and light grey curves, respectively). The black dashed-dotted line is the bisector of the plan. See parameters of the linear models in the Table 3.

nervous system and display complex cognitive abilities that confer great adaptive capacity, despite the short lifespan of the animals (Hanlon and Messenger, 2018). However, the effects of Hg in the brain of cephalopods remain unknown, despite the fact that Hg is known for its high degree of toxicity on the nervous system of vertebrates (Syversen and Kaur, 2012).

Mercury concentrations varied among species collected in the same geographical location (*i.e.* the Bay of Biscay) at the same time, suggesting that individuals were exposed to Hg to variable extents. More precisely, *E. cirrhosa* and *S. officinalis* had the highest levels of Hg in their tissues, relative to levels in other species assessed. This is congruent with the previous observation that benthic octopus and nektobenthic cuttlefish (*i.e.* Octopodidae and Sepiidae) generally display significantly higher Hg concentrations in their tissues than pelagic squids, including Ommastrephidae and Loliginidae, from the same area (Penicaud et al., 2017). For example, among seven cephalopods from the Mediterranean Sea, Octopodidae (*E. moschata*, *E. cirrhosa*, and *Octopus salutii*) had the highest Hg concentrations, followed by Sepiidae (*Sepia elegans* and *Sepia orbignyana*). The lowest concentrations were found in Ommastrephidae (*I. coindetii*) and Loliginidae (*L. vulgaris*) (Storelli et al., 2010). To date, these inter-specific differences have mainly been attributed to ecological factors, such as the proximity of benthic species to sediment where Hg methylation occurs (Storelli et al., 2005). Nevertheless, squids generally displayed higher trophic levels than octopus and cuttlefish, indicating that they likely feed on MeHg-enriched prey such as fish and/or cephalopods (Pierce et al., 1994; Coelho et al., 1997) compared to benthic cephalopods, which prey on invertebrates including crustaceans and bivalves with lower concentrations of Hg and lower proportions of MeHg. This incongruity indicates that species-dependent physiological processes, such as demethylation and elimination capacities, could also explain the interspecific Hg variation.

Mercury concentrations in the mantle muscles ranged from 0.06 to  $1.48 \mu\text{g.g}^{-1}\text{ dw}$  and were similar to those reported by Rjeibi et al. (2015) in cephalopods from Tunisia (0.01 to  $0.95 \mu\text{g.g}^{-1}\text{ dw}$ ). They were also comparable to concentrations reported for cephalopods from the Adriatic Sea (*L. vulgaris* from 0.20 to  $1.50 \mu\text{g.g}^{-1}\text{ dw}$ , *O. vulgaris*

from 0.12 to  $1.30 \mu\text{g.g}^{-1}\text{ dw}$ , *S. officinalis* from 0.25 to  $4.78 \mu\text{g.g}^{-1}\text{ dw}$ ) and the Atlantic Ocean (*S. officinalis*  $> 1 \mu\text{g.g}^{-1}\text{ dw}$ ) (Brambilla et al., 2013; Pereira et al., 2009), which showed an homogeneous level of contamination between locations.

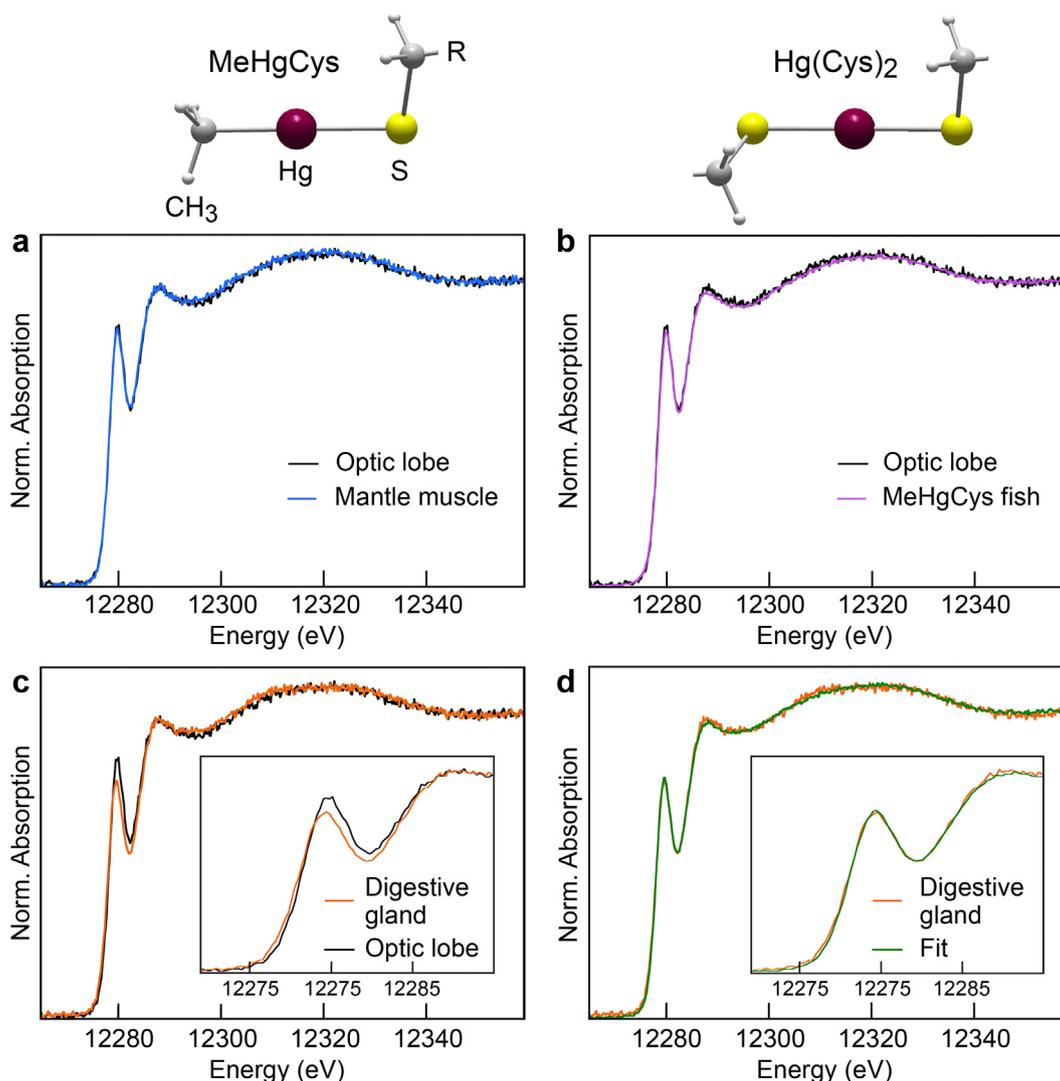
Heterogeneity in Hg concentrations among tissues (Lischka et al., 2018; Manso et al., 2007) is driven by uptake, detoxification, storage and/or excretion (including MeHg) differences (Penicaud et al., 2017). Hg concentrations were highest in the digestive gland and in the mantle muscles in all species considered, except for the curled octopus, *E. cirrhosa*, for which higher Hg concentrations were found in the optic lobes (see discussion thereafter). High Hg concentrations in the digestive gland of cephalopods have previously been documented in several species (Bustamante et al., 2006; Manso et al., 2007; Rjeibi et al., 2014). Mercury, and notably MeHg within prey, mainly accumulates via food consumption (Lacoue-Labarthe et al., 2009; Chouvelon et al., 2011), which implies that the physiological functions of digestion and absorption of the digestive gland contribute to the high Hg levels found in the tissue (Boucaud-Camou and Yim, 1980; Boucher-Rodoni et al., 1987).

The digestive gland is also known as the main organ of metal detoxification and storage in cephalopods (Martin and Flegal, 1975; Miramand and Bentley, 1992; Lacoue-Labarthe et al., 2016; Bustamante et al., 2002). Although the digestive gland represents only 6 to 10% of the mass of an animal, this organ may contain more than 80% of the body burden of some metals such as Ag, Cd, and Co (Penicaud et al., 2017). However, Hg in the digestive gland contributes to far less of the total body burden than muscles (Bustamante et al.,

**Table 3**

Parameters of the linear relationships between Hg concentrations in the optic lobes  $[\text{Hg}]_{\text{ol}}$  and the mantle muscles  $[\text{Hg}]_{\text{m}}$ . When the slopes between species were not significantly different, only one model was fitted within pooled data. See Fig. 2.

Species	Model Equation	P value	R <sup>2</sup>
<i>E. cirrhosa</i>	$[\text{Hg}]_{\text{ol}} = 1.32 \times [\text{Hg}]_{\text{m}} - 0.09$	$p < 0.001$	0.978
<i>S. officinalis</i> – <i>T. eblanae</i>	$[\text{Hg}]_{\text{ol}} = 0.35 \times [\text{Hg}]_{\text{m}} + 0.08$	$p < 0.001$	0.829
<i>I. coindetii</i> – <i>L. vulgaris</i>	$[\text{Hg}]_{\text{ol}} = 0.50 \times [\text{Hg}]_{\text{m}} + 0.01$	$p < 0.001$	0.663



**Fig. 3.** Chemical forms of Hg determined by Hg  $L_3$ -edge HR-XANES spectroscopy and ball-and-stick representation of the MeHgCys and Hg(Cys) $_2$  complexes. a-c) Comparison of the spectrum for the optic lobes with the spectra (a) for the mantle muscle, (b) for MeHgCys in fish muscle, and (c) for the digestive gland. d) Linear combination fit of the spectrum for the digestive gland with  $68 \pm 11\%$  of the optic lobes spectrum and  $33 \pm 11\%$  of the dicysteinate complex Hg(Cys) $_2$ .  $NSS = 1.50 \times 10^{-4}$ .

2006; Kojadinovic et al., 2011). Concentrations of Hg were in the same order of magnitude in both tissues, but as muscles accounted for more than 70% of the total body weight, and contained 70 to 90% of the total Hg body burden (Bustamante et al., 2006; Seco et al., 2020). This tissue distribution is likely due to two main mechanisms: 1) translocation and binding of MeHg to muscle proteins because they are rich in sulfhydryl groups with a high affinity for Hg, as shown in fish (Bloom, 1992). Consequently, the muscles constitute a good bioindicator tissue of MeHg exposure in cephalopods as like in many organisms, most of the Hg found in the muscular parts is under organic form (Bustamante et al., 2006; Seco et al., 2020; Chételat et al., 2020). Relatively similar Hg concentrations observed in the digestive gland compared to mantle muscles may also result from 2) the demethylation of MeHg, which facilitates iHg elimination by the digestive gland. Indeed, more than 70% of the Hg within the muscles of cephalopods is methylated, but more than a half of the Hg found in their digestive gland is inorganic (Bustamante et al., 2006; Seco et al., 2020). Here, HR-XANES spectrometry speciation analyses revealed that one third of the total Hg within the digestive gland of *E. cirrhosa* was made up of an inorganic form bound to peptides (e.g. glutathione, GSH) or proteins as a dicysteinate complex, which was modeled using the Hg(Cys) $_2$  reference. This suggests that 1) iHg may come from the environment (Sun et al., 2020) through both dissolved and trophic pathways. Indeed, it has been

demonstrated that cuttlefish efficiently bioconcentrate dissolved  $^{203}\text{iHg}$ , which is then distributed throughout the digestive gland (Lacoue-Labarthe et al., 2009). Thus, this organ contained 20% of accumulated  $^{203}\text{iHg}$  after 10 days of exposure. In addition, ~90% of the  $^{203}\text{iHg}$  from prey is assimilated and then mostly (~70%) found in the digestive gland. Alternatively, 2) iHg may result from *in vivo* MeHg demethylation (Sun et al., 2020), which likely occurs in the digestive gland, facilitating the rapid elimination of produced iHg, based on experimental findings in which a short biological half-life (i.e. 4 days) of dietary  $^{203}\text{iHg}$  was reported (Lacoue-Labarthe et al., 2009). The biochemical mechanism of demethylation that occurs in the digestive gland has not been determined yet.

Assuming that cephalopods are exposed to MeHg by prey, remaining MeHg from the pool of ingested Hg entering the bloodstream may become distributed throughout other tissues. Some studies have investigated the binding and transport of Hg(II) to hemocyanin (Brouwer et al., 1982, 1983), but little is known regarding MeHg binding to hemocyanin (blood oxygen transport proteins) in cephalopods. Nevertheless, it can be assumed that its transport is facilitated by sulphhydryl or tryptophanyl binding sites of the molecule, which would allow MeHg transfer to other tissues (Brouwer et al., 1982).

As mentioned previously, only one Hg concentration (i.e.  $1.25 \mu\text{g}\cdot\text{g}^{-1}$  dw) has been reported for the brain of one individual of the giant squid,

*Architeuthis dux*, to our knowledge (Bustamante et al., 2008). In the present study, the Hg concentrations were determined in the optic lobes, which is part of the nervous central system of cephalopods and are responsible for the highest level of coordinated function such as association, learning and visual analysis (Young, 1971). In this tissue, Hg concentrations ranged from 0.03 to 1.89  $\mu\text{g}\cdot\text{g}^{-1}$  dw among analysed individuals, which demonstrated that Hg accumulates in this area of the central nervous system. Values were comparable to, even slightly higher than, Hg concentrations reported in fish brains including 0.02 to 0.80  $\mu\text{g}\cdot\text{g}^{-1}$  dw in the golden grey mullet, *Liza aurata* (Pereira et al., 2014); 0.10 to 1.45  $\mu\text{g}\cdot\text{g}^{-1}$  dw in the bluefish, *Pomatomus saltatrix* (i.e. 0.02 to 0.29  $\mu\text{g}\cdot\text{g}^{-1}$  ww; Burger et al., 2013); and 0.10 to 1.60  $\mu\text{g}\cdot\text{g}^{-1}$  dw in the seabass, *Dicentrarchus labrax* (i.e. 0.02 to 0.32  $\mu\text{g}\cdot\text{g}^{-1}$  ww; Mieiro et al., 2011). In addition to the lack of information regarding contamination of the central nervous system of cephalopods, such as Hg concentrations in the brain, knowledge regarding Hg neurotoxicity in this Class is also incomplete.

Interestingly, Hg concentrations in the brain are strongly correlated with that of the muscles in different species investigated here, which indicates that Hg concentrations of the optic lobes are not regulated independently from Hg bioaccumulation throughout the organism. In addition,  $R^2$  values ranged from 0.66 to 0.98, depending on the group of species considered (see Fig. 2; Table 3), which indicates that Hg accumulation in the brain may be driven by the Hg concentrations in muscles in accordance with a defined brain/muscle ratio that is determined for each species. *L. vulgaris* and *I. coindetii* had a brain/muscle ratio of 0.35, *S. officinalis* and *T. eblanae* had a brain/muscle ratio of 0.50, and *E. cirrhosa* was the only species that displayed a ratio greater than 1 (about 1.3) as a result of higher Hg concentrations in the brain than the mantle (Fig. 2). A positive correlation between Hg concentrations in the brain and the muscles has been reported previously in eight species of catfish (*Brachyplatystoma filamentosum*; *B. platynemum*; *B. rousseauxii*; *B. vaillantii*; *Phractocephalus hemiliopterus*; *Pseudoplatystoma punctifer*; *P. tigrinum*; *Zungaro zungaro*) ( $R^2 = 0.917$ ;  $p < 0.0001$ ; Bastos et al., 2015). More importantly, the brain/muscle ratio never exceeded 0.6 when 21 fish species whose Hg concentrations in muscles ranged from 0.25 to 20.50  $\mu\text{g}\cdot\text{g}^{-1}$  dw were examined (i.e. 0.05 to 4.10  $\mu\text{g}\cdot\text{g}^{-1}$  ww; Bastos et al., 2015). Similarly, the brain/muscle Hg ratio (0.054/0.274  $\mu\text{g}\cdot\text{g}^{-1}$  ww) did not exceed 0.2 in yellow perch, *Perca flavescens* (Khadra et al., 2019). Furthermore, in the following species, ratios lower than one were determined, as follows: 0.43 for the semipalmated sandpiper, *Calidris pusilla* (Burger et al., 2014); 0.60 for the Atlantic puffin, *Fratercula arctica*; 0.68 for the common guillemot, *Uria aalge*; and 0.55 for the black-legged kittiwake, *Rissa tridactyla* (Fort et al., 2015). Thus, ratios observed for the squids and cuttlefish in our study are in accordance with previously reported data and suggest that Hg accumulation in the brain is limited compared to muscle tissue in cephalopods.

Interestingly, the most contaminated species among the cephalopod species panel investigated was in *E. cirrhosa*, which had a brain/muscle Hg ratio of 1.3. This finding suggested that Hg brain-tropism is most significant in *E. cirrhosa*. To the best of our knowledge, a similar ratio has not been described in fish, except the blackchin tilapia, *Sarotherodon melanotheron*, which had a brain/muscle Hg ratio of 1.5 (Hg concentrations were of 1.25  $\mu\text{g}\cdot\text{g}^{-1}$  dw (i.e. 0.25  $\mu\text{g}\cdot\text{g}^{-1}$  ww) in the brain and 0.85  $\mu\text{g}\cdot\text{g}^{-1}$  dw (i.e. 0.17  $\mu\text{g}\cdot\text{g}^{-1}$  ww) in muscle (Coulbaly et al., 2012). Similarly for seabirds, the razorbill, *Alca torda*, had a Hg brain/muscle ratio close to 1 (i.e. 2.05 and 2.04  $\mu\text{g}\cdot\text{g}^{-1}$  dw, respectively). Finally, the highest ratios have been determined in humans, and have reached 3.6 (i.e. 0.090 and 0.025  $\mu\text{g}\cdot\text{g}^{-1}$  dw in the occipital cortex and in the abdominal muscles, respectively; Björkman et al., 2007). Despite these observations, no clear explanation has been provided to enhance our understanding of how Hg accumulation preferentially occurs in the brain versus muscles in these species.

In addition, our results revealed that Hg accumulation in the brain with respect to muscles does not depend on the contamination level.

In other words, the brain/muscle ratio did not increase as the range of Hg muscle concentrations measured for each species increased. Indeed, with the exception of two individuals that were highly contaminated ( $> 1.35 \mu\text{g}\cdot\text{g}^{-1}$  dw), mantle muscle Hg concentrations in *E. cirrhosa* specimens ranged from 0.24 to 0.57  $\mu\text{g}\cdot\text{g}^{-1}$  dw, which was similar to the range recorded in *S. officinalis* specimens (0.18–0.75  $\mu\text{g}\cdot\text{g}^{-1}$  dw). In fish, species reported as contaminated throughout a large range of Hg concentrations (e.g. from 0.25 to 20.50  $\mu\text{g}\cdot\text{g}^{-1}$  dw i.e. 0.05 to 4.10  $\mu\text{g}\cdot\text{g}^{-1}$  ww from Bastos et al., 2015) had low brain/muscle ratios that were similar to values determined for cephalopods, with the exception of *E. cirrhosa*. Consequently, Hg accumulation in the brain of the octopus may have a species-specific explanation. First, Hg concentrations in the musculature were measured in the mantle muscles to facilitate comparison between squids and cuttlefish. However, the majority of muscle mass in octopus species is found in their arms. Not surprisingly, Hg concentrations do not differ between both muscle types (Seixas et al., 2005). This finding indicates the brain/muscle ratio was likely not overestimated as a result of the analysis of mantle muscles in this study. Further, fostered Hg accumulation in the octopus brain may result from a more permeable tissue to metal intake. Cephalopods have linker junctions between glial cells, which form a blood-brain barrier (BBB) that surrounds the central nervous system (Abbott et al., 1992). Once in the bloodstream, transported MeHg is transferred across the BBB and is capable of reaching the brain thanks to its lipophilicity (Boening, 2000; Holmes et al., 2009). The BBB structure and function are known to vary among different taxa (O’Brown et al., 2018) and may have variable permeabilities with respect to Hg and/or MeHg (Aschner and Aschner, 1990). However, no findings have indicated that BBB structures differ among coleoid species that would explain the elevated Hg concentrations observed in the optic lobes of *E. cirrhosa*.

Alternatively, elevated levels of Hg accumulation in the brain that result from increased Hg exposure likely are a result of the tight binding between the metal and biochemical components of optic lobes. Despite of a lack of comparative data and knowledge, HR-XANES spectrometry analyses performed using optic lobes of *E. cirrhosa* revealed (1) that Hg was entirely methylated, as in the mantle muscle of *E. cirrhosa* (Mieiro et al., 2011), and (2) that MeHg is complexed to thiol groups. Importantly, Hg detoxification with selenium (Se) association can be excluded because no Hg bond signature to Se was observed via HR-XANES spectrometry in the tissues of *E. cirrhosa*. Thus, cysteine residues from peptides (e.g. glutathione) or proteins (e.g. metallothionein) are the most likely candidate ligands, since they are by far the most predominant biological thiols (Manceau et al., 2019). Nevertheless, it should be noted that it was not possible to determine whether another form of MeHg association occurred in other cephalopod species, since Hg concentrations in the brain of the other species assessed were too low to examine via XANES spectrometry.

## 5. Conclusions and perspectives

The present study provided information regarding the bioaccumulation and tissue distribution of Hg in five cephalopod species (*E. cirrhosa*, *S. officinalis*, *L. vulgaris*, *T. eblanae* and *I. coindetii*) from the Bay of Biscay and has provided new information regarding Hg concentrations and speciation of the digestive gland, muscles and central nervous system. Results showed that efficient Hg accumulation occurred in the optic lobes of cephalopods, which was strongly correlated with Hg concentrations measured in the mantle. The present study also pointed out inter-specific differences in Hg concentrations among the five studied species and the unique pattern of Hg bioaccumulation in the brain of *E. cirrhosa*.

The collection of data regarding Hg concentrations and speciation in this specific tissue is essential for evaluating Hg exposure risk in cephalopods, which are characterised by the presence of centralised nervous systems, their high cognitive capabilities, and their sophisticated behaviour. While many studies have demonstrated that MeHg impairs motor function, senses, communication (e.g. Basu et al., 2005; Zahir et al.,

2005; Puga et al., 2016), and induces oxidative stress responses (Mieiro et al., 2011), no information has been reported regarding Hg neurotoxicity in cephalopods to date. Since Hg concentrations of some *E. cirrhosa* specimens (i.e. 1.9  $\mu\text{g}\cdot\text{g}^{-1}$  dw) were 3 times above the neurotoxic threshold found for the white seabream, *D. sargus* (Pereira et al., 2016), further research will be needed to investigate how unique features of species may explain the high Hg levels recorded in octopodidae, and more generally, how Hg contamination in cephalopods may affect their functional brain plasticity, behaviour and fitness (Liscovitch-Brauer et al., 2017; Di Cosmo et al., 2018).

### CRedit authorship contribution statement

**Antoine Minet:** Formal analysis, Writing - original draft. **Alain Manceau:** Methodology, Investigation, Writing - original draft. **Anaïs Valada-Mennuni:** Investigation, Writing - original draft. **Maud Brault-Favrou:** Investigation. **Carine Churlaud:** Investigation. **Jérôme Fort:** Conceptualization. **Thành Nguyen:** Investigation. **Jérôme Spitz:** Resources, Writing - review & editing. **Paco Bustamante:** Methodology, Writing - original draft, Supervision. **Thomas Lacoue-Labarthe:** Conceptualization, Methodology, Writing - original draft, Supervision.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgments

This work is a contribution to the MERCy project funded by the *Ministère de la Transition Ecologique et Solidaire et de la Fondation pour la Recherche sur la Biodiversité*. The *Région Nouvelle Aquitaine* is acknowledged for its support to the PhD grant of AM through the EXPO project. We are grateful for the use of the facilities of the Plateforme Analyses Élémentaires of the LIENSs laboratory and to IFREMER for allowing the sampling during the EVHOE cruises (2016–2017). Thanks are due to the CPER (Contrat de Projet Etat-Région) and the FEDER (Fonds Européen de Développement Régional) for funding the AMA of the LIENSs laboratory. The Institut Universitaire de France (IUF) is acknowledged for its support to PB as a Senior Member. This work benefitted from the French GDR “Aquatic Ecotoxicology” framework which aims at fostering stimulating scientific discussions and collaborations for more integrative approaches. The spectroscopic work was supported by the EcoX project funded by the Equipex initiative of the Agence Nationale pour la Recherche (ANR) under grant ANR-10-EQPX-27-01.

### References

Abbott, N.J., Lane, N.J., Bundgaard, M., 1992. A fibre matrix model for the restricting junction of the blood-brain barrier in a cephalopod mollusc: implications for capillary and epithelial permeability. *J. Neurocytol.* 21, 304–311.

Adams, D.H., Sonne, C., Basu, N., Dietz, R., Nam, D.H., Leifsson, P.S., Jensen, A.L., 2010. Mercury contamination in spotted seatrout, *Cynoscion nebulosus*: an assessment of liver, kidney, blood, and nervous system health. *Sci. Total Environ.* 408 (23), 5808–5816.

Arai, T., Amalina, R., Bachok, Z., 2016. Species-specific liver moisture content of coral reef fishes in the Malaysian South China Sea. *Trop. Ecol.* 57 (3), 613–618.

Aschner, M., Aschner, J.L., 1990. Mercury neurotoxicity: mechanisms of blood-brain barrier transport. *Neurosci. Biobehav. Rev.* 14, 169–176.

Bastos, W.R., Dórea, J.G., Bernardi, J.V.E., Lauthartte, L.C., Mussu, M.H., Hauser, M., Dória, C.R.C., Malm, O., 2015. Mercury in muscle and brain of catfish from the Madeira river, Amazon, Brazil. *Ecotoxicol. Environ. Saf.* 118, 90–97.

Basu, N., Stamler, C.J., Loua, K.M., Chana, H.M., 2005. An interspecies comparison of mercury inhibition on muscarinic acetylcholine receptor binding in the cerebral cortex and cerebellum. *Toxicol. Appl. Pharmacol.* 205, 71–76.

Benoit, J.M., Gilmour, C.C., Heyes, A., Mason, R.P., Miller, C.L., 2002. Geochemical and Biological Controls over Methylmercury Production and Degradation in Aquatic Ecosystems. In: Cai, Y., Braids, O.C. (Eds.), *Biogeochemistry of Environmentally Important Trace Elements*. ACS Publications, pp. 262–297.

Berntssen, M.H.G., Aatland, A., Handy, R.D., 2003. Chronic dietary mercury exposure causes oxidative stress, brain lesions, and altered behaviour in Atlantic salmon (*Salmo salar*) parr. *Aquat. Toxicol.* 65, 55–72.

Berntssen, M.H.G., Hylland, K., Julshamn, K., Lundbye, A.K., Waagbø, R., 2004. Maximum limits of organic and inorganic mercury in fish feed. *Aquac. Nutr.* 10, 83–97.

Björkman, L., Lundekvam, B.F., Lægred, T., Bertelsen, B.I., Morild, I., Lilleng, P., Lind, B., Palm, B., Vahter, M., 2007. Mercury in human brain, blood, muscle and toenails in relation to exposure: an autopsy study. *Environ. Health* 6, 30.

Bloom, N.S., 1992. On the chemical form of mercury in edible fish and marine invertebrate tissue. *Can. J. Fish. Aquat. Sci.* 49, 1010–1017.

Boening, D.W., 2000. Ecological effects, transport, and fate of mercury: a general review. *Chemosphere* 40 (12), 1335–1351.

Boucaud-Camou, E., Yim, M., 1980. Fine structure and function of the digestive cell of *Sepia officinalis* (Mollusca: Cephalopoda). *J. Zool.* 191, 89–105.

Boucher-Rodoni, R., Boucaud-Camou, E., Mangold, K., 1987. Feeding and digestion. In: Boyle, P.R. (Ed.), *Cephalopod Life Cycle*. Academic Press, London, pp. 85–108.

Bourdineaud, J.P., Gonzalez-Rey, M., Rovezzi, M., Gatzel, P., Nagy, K.L., Manceau, A., 2019. Divalent mercury from dissolved organic matter is bioavailable to fish and accumulates as dithiolate and tetrathiolate complex. *Environ. Sci. Technol.* 53, 4880–4981.

Brambilla, G., Abete, M.C., Binato, G., Chiaravalle, E., Cossu, M., Dellatte, E., Miniero, R., Orletti, R., Piras, P., Roncarati, A., Ubaldi, A., Chessa, G., 2013. Mercury occurrence in Italian seafood from the Mediterranean Sea and possible intake scenarios of the Italian coastal population. *Regul. Toxicol. Pharmacol.* 65, 269–277.

Brouwer, M., Bonaventura, C., Bonaventura, J., 1982. Heavy metal ion interactions with *Callinectes sapidus* hemocyanin: structural and functional changes induced by a variety of heavy metal ions. *Biochemistry* 21 (10), 2538–2547.

Brouwer, M., Bonaventura, C., Bonaventura, J., 1983. Metal ion interactions with *Limulus polyphemus* and *Callinectes sapidus* hemocyanins: stoichiometry and structural and functional consequences of calcium(II), cadmium(II), zinc(II), and mercury(II) binding. *American Chemical Society, Biochemistry* 22 (20), 4723–4730.

Burger, J., Jeitner, C., Donio, M., Pittfield, T., Gochfeld, M., 2013. Mercury and selenium levels, and selenium:mercury molar ratios of brain, muscle and other tissues in bluefish (*Pomatomus saltatrix*) from New Jersey, USA. *Sci. Total Environ.* 443, 278–286.

Burger, J., Gochfeld, M., Niles, L., Dey, A., Jeitner, C., Pittfield, T., Tspoura, N., 2014. Metals in tissues of migrant semipalmated sandpipers (*Calidris pusilla*) from Delaware Bay, New Jersey. *Environ. Res.* 133, 362–370.

Burnham, K.P., Anderson, D.R., 2002. *Model Selection and Multimodel Inference: A practical information-theoretic approach* (2nd Ed.). Springer-Verlag, New York, USA.

Bustamante, P., Caurant, F., Fowler, S.W., Miramand, P., 1998. Cephalopods as a vector for the transfer of cadmium to top marine predators in the north-east Atlantic Ocean. *Sci. Total Environ.* 220, 71–80.

Bustamante, P., Teyszié, J.-L., Fowler, S.W., Cotret, O., Danis, B., Miramand, P., Warnau, M., 2002. Biokinetics of zinc and cadmium accumulation and depuration at different stages in the life cycle of the cuttlefish *Sepia officinalis*. *Mar. Ecol. Prog. Ser.* 231, 167–177.

Bustamante, P., Lahaye, V., Durnez, C., Churlaud, C., Caurant, F., 2006. Total and organic Hg concentrations in cephalopods from the North East Atlantic waters: influence of geographical origin and feeding ecology. *Sci. Total Environ.* 368, 585–596.

Bustamante, P., González, A.F., Rocha, F., Miramand, P., Guerra, A., 2008. Metal and metalloid concentrations in the giant squid *Architeuthis dux* from Iberian waters. *Mar. Environ. Res.* 66 (2), 278–287.

Chabenat, A., Bellanger, C., Jozet-Alves, C., Knigge, T., 2019. Hidden in the sand: alteration of burying behaviour in shore crabs and cuttlefish by antidepressant exposure. *Ecotoxicol. Environ. Saf.* 186, 109738.

Chételat, J., Ackerman, J.T., Eagles-Smith, C.A., Hebert, C.E., 2020. Methylmercury exposure in wildlife: a review of the ecological and physiological processes affecting contaminant concentrations and their interpretation. *Sci. Total Environ.* 711, 135117.

Chouvelon, T., Warnau, M., Churlaud, C., Bustamante, P., 2009. Hg concentrations and related risk assessment in coral reef crustaceans, molluscs and fish from New Caledonia. *Environ. Pollut.* 157, 331–340.

Chouvelon, T., Spitz, J., Cherel, Y., Caurant, F., Sirmel, R., Mèndez-Fernandez, P., Bustamante, P., 2011. Species and ontogenic differences in  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values and Hg and Cd concentrations of cephalopods. *Mar. Ecol. Prog. Ser.* 433, 107–120.

Chouvelon, T., Cresson, P., Bouchoucha, M., Brach-Papa, C., Bustamante, P., Crochet, S., Marco-Miralles, F., Thomas, B., Knoerya, J., 2018. Oligotrophy as a major driver of mercury bioaccumulation in medium-to high-trophic level consumers: a marine ecosystem-comparative study. *Environ. Pollut.* 233, 844–854.

Clark, M.R., 1996. Cephalopods as prey. 3. Cetaceans. *Philos. Trans. R. Soc. Lond., B* 351, 1053–1065.

Coelho, M., Domingues, P., Balguerías, E., Fernandez, M., Andrade, J.P., 1997. A comparative study of the diet of *Loligo vulgaris* (Lamarck, 1799) (Mollusca: Cephalopoda) from the south coast of Portugal and the Saharan Bank (central-East Atlantic). *Fish. Res.* 29, 245–255.

Coulibaly, S., Atse, B.C., Koffi, K.M., Sylla, S., Konan, K.J., Kouassi, N.J., 2012. Seasonal accumulations of some heavy metal in water, sediment and tissues of black-chinned tilapia *Sarotherodon melanotheron* from Biétri Bay in Ebrié Lagoon, Ivory Coast. *Bull. Environ. Contam. Toxicol.* 88, 571–576.

Di Cosmo, A., Maselli, V., Polese, G., 2018. Octopus vulgaris: An Alternative in Evolution. In: Kloc, M., Kubiak, J.Z. (Eds.), *Marine Organisms as Model Systems in Biology and Medicine* 65. Springer, pp. 585–598.

Dorneles, P.R., Lailson-Brito, J., Aguiar dos Santos, R., Silva da Costa, P.A., Malma, O., Azevedo, A.F., Torres, J.P.M., 2007. Cephalopods and cetaceans as indicators of offshore bioavailability of cadmium off Central South Brazil Bight. *Environ. Pollut.* 148 (1), 352–359.

Driscoll, C.T., Mason, R.P., Man Chan, H., Jacob, D.J., Pirrone, N., 2013. Mercury as a global pollutant: sources, pathways, and effects. *Environ. Sci. Technol.* 47 (10), 4967–4983.

- Duhamel, E., Pawlowski, L., Garren, F., 2017. EVHOE 2017 cruise. RV Thalassa, <https://doi.org/10.17600/17002300>.
- Eagles-Smith, C.A., Silbergeld, E.K., Basu, N., Bustamante, P., Diaz-Barriga, F., Hopkins, W.A., Kidd, K.A., Nyland, J.F., 2018. Modulators of mercury risk to wildlife and humans in the context of rapid global change. *Ambio* 47 (2), 170–197.
- Farina, M., Rocha, J.B.T., Aschner, M., 2011. Mechanisms of methylmercury-induced neurotoxicity: evidence from experimental studies. *Life Sci.* 89 (15–16), 555–563.
- Fort, J., Lacoue-Labarthe, T., Nguyen, H.L., Boué, A., Spitz, J., Bustamante, P., 2015. Mercury in wintering seabirds, an aggravating factor to winter wrecks? *Sci. Total Environ.* 527–528, 448–454.
- Gentès, S., Maury-Brachet, R., Feng, C., Pedrero, Z., Tessier, E., Legeay, A., Mesmer-Dudons, N., Baudrimont, M., Maurice, L., Amouroux, D., Gonzalez, P., 2015. Specific effects of dietary Methylmercury and inorganic mercury in Zebrafish (*Danio rerio*) determined by genetic, histological, and metallothionein responses. *Environ. Sci. Technol.* 49 (21), 12984–12993.
- Hammerschmidt, C.R., Fitzgerald, W.F., 2004. Geochemical controls on the production and distribution of methylmercury in near-shore marine sediments. *Environ. Sci. Technol.* 38 (5), 1487–1495.
- Hanlon, R.T., Messenger, J.B., 2018. *Cephalopod Behaviour*. Cambridge University Press, Cambridge.
- Holmes, P., James, K.A.F., Levy, L.S., 2009. Is low-level environmental mercury exposure of concern to human health? *Sci. Total Environ.* 408 (2), 171–182.
- Jackson, G.D., Bustamante, P., Cherel, Y., Fulton, E.A., Grist, E.P.M., Jackson, C.H., Nichols, P.D., Pethybridge, H., Phillips, K., Ward, R.D., Xavier, J.C., 2007. Applying new tools to cephalopod trophic dynamics and ecology: perspectives from the Southern Ocean Cephalopod Workshop, February 2–3, 2006. *Rev. Fish Biol. Fisher.* 17, 79–99.
- Khadra, M., Planas, D., Brodeur, P., Amyota, M., 2019. Mercury and selenium distribution in fish tissues and early life stages of Yellow Perch (*Perca flavescens*). *Environ. Polluti.* 254: Part A, 112963.
- Kojadinovic, J., Jackson, C.H., Cherel, Y., Jackson, G.D., Bustamante, P., 2011. Multi-elemental concentrations in the tissues of the oceanic squid *Todarodes filippovae* from Tasmania and the southern Indian Ocean. *Ecotoxicol. Environ. Saf.* 74 (5), 1238–1249.
- Lacoue-Labarthe, T., Warnau, M., Oberhansli, F., Teysseie, J.L., Bustamante, P., 2009. Bioaccumulation of inorganic Hg by the juvenile cuttlefish *Sepia officinalis* exposed to <sup>203</sup>Hg radiolabelled seawater and food. *Aquat. Biol.* 6, 91–98.
- Lacoue-Labarthe, T., Le Pabic, C., Bustamante, P., 2016. Ecotoxicology of early-life stages in the common cuttlefish *Sepia officinalis*: review and perspectives. *Vie Milieu* 66 (1), 65–79.
- Léauté J.-P., Pawlowski L., Garren F (2016). EVHOE 2016 cruise, RV Thalassa, doi:10.17600/16002900.
- Lemos Bisi, T., Lepoint, G., De Freitas, Azevedo A., Renato Dorneles, P., Flach, L., Das, K., Malm, O., Lailson-Brito, J., 2012. Trophic relationships and mercury biomagnification in Brazilian tropical coastal food webs. *Ecol. Indic.* 18, 291–302.
- Lischka, A., Lacoue-Labarthe, T., Hoving, H.J.T., JavidPour, J., Merten, V., Churlaud, C., Bustamante, P., 2018. High cadmium and mercury concentrations in the tissues of the orange-back flying squid, *Sthenoteuthis pteropus*, from the tropical Eastern Atlantic. *Ecotoxicol. Environ. Saf.* 163C, 323–330.
- Liscovitch-Brauer, N., Alon, S., Porath, H.T., Elstein, B., Unger, R., Ziv, T., Admon, A., Levanon, E.Y., Rosenthal, J.J.C., Eisenberg, E., 2017. Trade-off between transcriptome plasticity and genome evolution in cephalopods. *Cell Press* 169 (2), 191–202.
- López-Berenguer, G., Peñalver, J., Martínez-López, E., 2020. A critical review about neurotoxic effects in marine mammals of mercury and other trace elements. *Chemosphere* 246, 125688.
- Manceau, A., Enescu, M., Simionovici, A., Lanson, M., Gonzalez-Rey, M., Rovezzi, M., Tucoulou, R., Glatzel, P., Nagy, K.L., Bourdineaud, J.P., 2016. Chemical forms of mercury in human hair reveal sources of exposure. *Environ. Sci. Technol.* 50, 10721–10729.
- Manceau, A., Bustamante, P., Haouz, A., Bourdineaud, J.P., Gonzalez-Rey, M., Geertsen, V., Barruet, E., Rovezzi, M., Glatzel, P., Pin, S., 2019. Mercury(II) binding to metallothionein in *Mytilus edulis* revealed by high energy-resolution XANES spectroscopy. *Chem. Eur. J.* 25, 997–1009.
- Manso, M., Carvalho, M.L., Nunes, M.L., 2007. Characterization of essential and toxic elements in cephalopod tissues by EDXRF and AAS. *X-Ray Spectrom.* 36, 413–418.
- Martin, J.H., Flegal, A.R., 1975. High copper concentrations in squid livers in association with elevated levels of silver, cadmium and zinc. *Mar. Biol.* 30, 51–55.
- Mason, R.P., Benoit, J.M., 2003. Organomercury compounds in the environment. In: Craig, P.J. (Ed.), *Organometallic Compounds in the Environment*. Wiley, New York, pp. 57–99.
- Maz-Courrau, A., López-Vera, C., Galván-Magaña, F., Escobar-Sánchez, O., Rosiles-Martínez, R., Sanjuán-Muñoz, A., 2012. Bioaccumulation and biomagnification of total mercury in four exploited shark species in the Baja California Peninsula, Mexico. *Bull. Environ. Contam. Toxicol.* 88, 129–134.
- Mieiro, C.L., Pereira, M.E., Duarte, A.C., Pacheco, M., 2011. Brain as a critical target of mercury in environmentally exposed fish (*Dicentrarchus labrax*)—bioaccumulation and oxidative stress profiles. *Aquat. Toxicol.* 103 (3–4), 233–240.
- Mieiro, C.L., Coelho, J.P., Pacheco, M., Duarte, A.C., Pereira, M.E., 2012. Evaluation of species-specific dissimilarities in two marine fish species: mercury accumulation as a function of metal levels in consumed prey. *Arch. Environ. Contam. Toxicol.* 63 (1), 125–136.
- Miramand, P., Bentley, D., 1992. Concentration and distribution of heavy metals in two cephalopods *Eledone cirrhosa* and *Sepia officinalis*, from the French coast of the English Channel. *Mar. Biol.* 114, 407–414.
- O'Brien, C.E., Roubmedakis, K., Winkelmann, I.E., 2018. The current state of cephalopod science and perspectives on the most critical challenges ahead from three early-career researchers. *Front. Physiol.* 9, 700.
- O'Brown, N.M., Pfau, S.J., Gu, C., 2018. Bridging barriers: a comparative look at the blood-brain barrier across organisms. *Genes Dev.* 32 (7–8), 466–478.
- Penicaud, V., Lacoue-Labarthe, T., Bustamante, P., 2017. Metal bioaccumulation and detoxification processes in cephalopods: a review. *Environ. Res.* 155, 123–133.
- Pereira, P., Raimundo, J., Vale, C., Kadara, E., 2009. Metal concentrations in digestive gland and mantle of *Sepia officinalis* from two coastal lagoons of Portugal. *Sci. Total Environ.* 407 (3), 1080–1088.
- Pereira, P., Raimundo, J., Araújo, O., Canário, J., Almeida, A., Pacheco, M., 2014. Fish eyes and brain as primary targets for mercury accumulation – a new insight on environmental risk assessment. *Sci. Total Environ.* 494–495, 290–298.
- Pereira, P., Puga, S., Cardoso, V., Pinto-Ribeiro, F., Raimundo, J., Barata, M., Pousão-Ferreira, P., Pacheco, M., Almeida, A., 2016. Inorganic mercury accumulation in brain following waterborne exposure elicits a deficit on the number of brain cells and impairs swimming behavior in fish (white seabream—*Diplodus sargus*). *Aquat. Toxicol.* 170, 400–412.
- Pierce, G.J., Boyle, P.R., Hastie, L.C., Santos, M.B., 1994. Diets of squid *Loligo forbesi* and *Loligo vulgaris* in the Northeast Atlantic. *Fish. Res.* 21, 149–163.
- Puga, S., Pereira, P., Pinto-Ribeiro, F., O'Driscoll, N.J., Mann, E., Barata, M., Pousão-Ferreira, P., Canário, J., Almeida, A., Pacheco, M., 2016. Unveiling the neurotoxicity of methylmercury in fish (*Diplodus sargus*) through a regional morphometric analysis of brain and swimming behavior assessment. *Aquat. Toxicol.* 180, 320–333.
- R Core Team, 2017. R: A Language and Environment for Statistical Computing R Foundation for Statistical Computing, Vienna, Austria (2017).
- Renzone, A., Zino, F., Franchi, E., 1998. Mercury levels along the food chain and risk for exposed populations. *Environ. Res.* 77 (2), 68–72.
- Rjeibi, M., Metian, M., Hajji, T., Guyot, T., Ben Chaouacha-Chekir, R., Bustamante, P., 2014. Interspecific and geographical variations of trace metal concentrations in cephalopods from Tunisian waters. *Environ. Monit. Assess.* 186 (6), 3767–3783.
- Rjeibi, M., Metian, M., Hajji, T., Guyot, T., Ben Chaouacha-Chekir, R., Bustamante, P., 2015. Seasonal survey of contaminants (Cd and Hg) and micronutrients (Cu and Zn) in edible tissues of cephalopods from Tunisia: assessment of risk and nutritional benefits. *J. Food Sci.* 80 (1), 199–206.
- Rouleau, C., Borg-Nezack, K., Gottofrey, J., Tjälve, H., 1999. Accumulation of waterborne mercury(II) in specific areas of fish brain. *Environ. Sci. Technol.* 33 (19), 3384–3389.
- Rovezzi, M., Lapras, C., Manceau, A., Glatzel, P., Verbeni, R., 2017. High energy-resolution x-ray spectroscopy at ultra-high dilution with spherically bent crystal analyzers of 0.5 m radius. *Rev. Sci. Instrum.* 88, 013108.
- Scheuhammer, A.M., Meyer, M.W., Sandheinrich, M.B., Murray, M.W., 2007. Effects of environmental methylmercury on the health of wild birds, mammals, and fish. *Ambio* 36, 12–18.
- Seco, J., Xavier, J.C., Brierley, A., Bustamante, P., Coelho, J.P., Gregory, S., Fielding, S., Pardal, M.A., Pereira, B., Stowasser, G., Tarling, G.A., Pereira, M.E., 2020. Mercury levels in Southern Ocean Squid: variability over the last decade. *Chemosphere* 239C, 124785.
- Seixas, S., Bustamante, P., Pierce, G., 2005. Accumulation of mercury in the tissues of the common octopus *Octopus vulgaris* (L.) in two localities on the Portuguese coast. *Sci. Total Environ.* 340, 113–122.
- Shigeno, S., Andrews, P.L.R., Ponte, G., Fiorito, G., 2018. Cephalopod brains: an overview of current knowledge to facilitate comparison with vertebrates. *Front. Physiol.* 9, 952.
- Spitz, J., Mourocq, E., Shoen, V., Ridoux, V., 2010. Proximate composition and energy content of forage species from the Bay of Biscay: high or low quality food? *ICES J. Mar. Sci.* 67, 909–915.
- Storelli, M.M., Storelli, A., Giacomini-Stuffler, R., Marcotrigiano, G.O., 2005. Mercury speciation in the muscle of two commercially important fish, hake (*Merluccius merluccius*) and striped mullet (*Mullus barbatus*) from the Mediterranean Sea: estimated weekly intake. *Food Chem.* 89, 295–300.
- Storelli, M.M., Garofalo, R., Giungato, D., Giacomini-Stuffler, R., 2010. Intake of essential and non-essential elements from consumption of octopus, cuttlefish and squid. *Food Addit. Contam.: Part B* 3 (1), 14–18.
- Sun, R., Yuan, J., Sonke, J.E., Zhang, Y., Zhang, T., Zheng, W., Chen, S., Meng, M., Chen, J., Liu, Y., Peng, X., Liu, C., 2020. Methylmercury produced in upper oceans accumulates in deep Mariana Trench fauna. *Nat. Commun.* 11, 3389.
- Suppes, C., Tiemeier, O., Deyoe, C., 1967. Seasonal Variations of Fat, Protein, and Moisture in Channel Catfish. *Trans. Kans. Acad. Sci.* (1903-) 70 (3).
- Syversen, T., Kaur, P., 2012. The toxicology of mercury and its compounds. *J. Trace Elem. Med. Biol.* 26 (4), 215–226.
- Van der Velden, S., Dempson, J.B., Evans, M.S., Muir, D.C.G., Power, M., 2013. Basal mercury concentrations and biomagnification rates in freshwater and marine food webs: effects on Arctic charr (*Salvelinus alpinus*) from eastern Canada. *Sci. Total Environ.* 444, 531–542.
- Villar, E., Cabrol, L., Heimbürger-Boavida, L.E., 2020. Widespread microbial mercury methylation genes in the global ocean. *Environ. Microbiol. Rep.* 12 (3), 277–287.
- Weiner, J., Suchanek, T., 2008. Basis for ecotoxicological concern in aquatic ecosystems contaminated by historical mercury mining. *Ecol. Appl.* 18 (8) Supplement: A3–A11.
- Young, J.Z., 1971. *The Anatomy of the Nervous System of Octopus vulgaris*. Clarendon press, Oxford.
- Zahir, F., Shamim, J.R., Haq, S.K., Khan, R.H., 2005. Low dose mercury toxicity and human health. *Environ. Toxicol. Pharmacol.* 20 (2), 351–360.