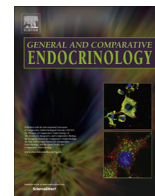




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## Review

# Role of olfaction in *Octopus vulgaris* reproduction



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## ABSTRACT

The olfactory system in any animal is the primary sensory system that responds to chemical stimuli emanating from a distant source. In aquatic animals "Odours" are molecules in solution that guide them to locate food, partners, nesting sites, and dangers to avoid. Fish, crustaceans and aquatic molluscs possess sensory systems that have anatomical similarities to the olfactory systems of land-based animals. Molluscs are a large group of aquatic and terrestrial animals that rely heavily on chemical communication with a generally dispersed sense of touch and chemical sensitivity. Cephalopods, the smallest class among extant marine molluscs, are predators with high visual capability and well developed vestibular, auditory, and tactile systems. Nevertheless they possess a well developed olfactory organ, but to date almost nothing is known about the mechanisms, functions and modulation of this chemosensory structure in octopods. Cephalopod brains are the largest of all invertebrate brains and across molluscs show the highest degree of centralization. The reproductive behaviour of *Octopus vulgaris* is under the control of a complex set of signal molecules such as neuropeptides, neurotransmitters and sex steroids that guide the behaviour from the level of individuals in evaluating mates, to stimulating or deterring copulation, to sperm-egg chemical signalling that promotes fertilization. These signals are intercepted by the olfactory organs and integrated in the olfactory lobes in the central nervous system. In this context we propose a model in which the olfactory organ and the olfactory lobe of *O. vulgaris* could represent the on-off switch between food intake and reproduction.

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## 1. Introduction

Olfaction is a vitally important sense for all animals, since how they perceive the environment and make proper behavioural choices are strictly related to their perceptive capabilities. Environmental odours guide animals to locate food, water, and nesting sites, as well as alerting them to avoid dangers. Odours emanating from other species, known as allelochemicals (Whittaker and Feeny, 1971), control prey localization, homing, symbiotic associations, territorial marking, predator deterrence and avoidance, metamorphosis and growth. Conspecific's odours are known as pheromones (Shorey, 1976). They can be recognition pheromones to indicate the identity of individuals, social status, social group, and place; as aggregation pheromones to mediate feeding, sex, and aggression; dispersion pheromones to maintain individual spacing and minimize predation; or reproductive pheromones to trigger courtship displays and postures (Ache and Young, 2005; Buck, 2000; Carbone et al., 2013; Eisthen and Polese, 2006).

The chemosensory systems are able to detect chemical stimulus emanating from a distant source. Terrestrial vertebrates and insects detect low concentrations of airborne, volatile chemical substances. Aquatic animals, while not encountering airborne (volatile odourants), possess sensory systems that are anatomically similar to the olfactory systems of land-based animals. "Odours" for these aquatic animals are sapid molecules in solution (Hay, 2009; Mollo et al., 2014). The species share striking similarities in the organization of the olfactory pathway, from the nature of the odorant and receptor proteins, to the organization of the olfactory central nervous system (CNS), through odour-guided behaviour and memory. These common features span a phylogenetically broad array of animals, implying that there is an effective solution to the problem of detecting and discriminating odours that remains a common challenge for all animals (Ache and Young, 2005; Eisthen and Polese, 2006; Laurent, 2002; Mollo et al., 2014; Smith, 2008).

Molluscs are a large and diverse group of aquatic and terrestrial animals that rely heavily on chemical communication. They have generally dispersed senses of touch and chemoreception. Excellent studies at behavioural, neural and biochemical levels on gastropods olfaction has been made and, among the aquatic species, *Aplysia*, *Tritonia* and *Lymnaea* are used as valuable model systems (Cummins and Degnan, 2010; Cummins and Wyeth, 2014).

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*Aplysia* represents an excellent model in terms of structure and function of olfactory organs in gastropods (Wertz et al., 2006), and the availability of central neuron transcriptomes (Moroz et al., 2006) as well as the genome enables detailed genetic analyses. *Aplysia* and other aquatic gastropods, most important, have no acoustic sense and their world is largely chemically guided so that water-soluble odorants mediate many physiological and behavioural events, leading to aggregation, habitat selection, defence and mating. Mate attraction and subsequent mating is stimulated by the release of conspecific water-borne sexual pheromones consisting of four small proteins named attractin, enticin, temptin and seductin (Cummins et al., 2004; Painter et al., 2004).

The case is quite different in cephalopods, which represent the smallest class among marine molluscs and (excluding *Nautilus*) they are highly visual animals able to see under highly varying light conditions. Cephalopods have remarkable abilities to camouflage themselves on diverse substrates using visual cues alone (Zylinski and Johnsen, 2011). Foraging octopuses use visual cues to camouflage themselves and mimic fishes (Hanlon et al., 2010). They have low-frequency sensitivity and a lateral line (analogous to fishes) to hear and detect at long distance the presence of predator (Hanlon and Messenger, 1998).

Chemical signalling is another possible source of sensory input, which could work in combination with visual signals or alone to inform cephalopods of ecological factors, this is important especially for species that populate light-limited habitats (Nilsson et al., 2012).

In coleoid cephalopods there are three known chemical sensory epithelia: buccal lips (Emery, 1975), arm suckers (Graziadei and Gagne, 1976), and olfactory organs (Zemoff, 1869). The function of sensory epithelia in the buccal lips and arm suckers has been well studied and shows capabilities for both tactile and distance chemoreception (Hanlon and Messenger, 1998).

Within the cephalopods the *Octopus* brain is unique in possessing a chemo-tactile memory system that may have evolved in relation to its benthic life style (Hanlon and Messenger, 1998). Octopods use the arms to explore and detect tactile and chemosensory information functioning as “natural biosensors” (Di Cosmo, personal observation). These proprieties are conferred on the arms by their appendages, with the suckers supplied with receptor cells responsive to tactile and chemical stimuli.

Nevertheless cephalopods possess a well developed olfactory sense. Olfaction plays a role in mate choice of squid and cuttlefishes (Cummins et al., 2011; Gilly and Lucero, 1992; Lucero and Gilly, 1995; Lucero et al., 1992, 2000; Mobley et al., 2007; Piper and Lucero, 1999; Zatylny et al., 2000) and improves predation on crabs by cuttlefishes (Boal et al., 2000). *Nautilus* use olfaction for distant food odour detection and location, and perhaps for mate choice (Basil et al., 2000; Ruth et al., 2002).

Two control systems are involved in decoding the signals coming from the sense organs and in selecting an appropriate behaviour: the nervous and the endocrine systems (Hartenstein, 2006; La Font, 2000; Wells and Wells, 1959; Wells, 1962; Young, 1971). The reproductive behaviour of *Octopus vulgaris* is under the control of a complex set of internal and external molecules. Internal signal molecules such as sex steroids (Di Cosmo et al., 2001; De Lisa et al., 2012), neuropeptides (Di Cosmo and Di Cristo, 1998; Di Cristo et al., 2002a,b, 2005, 2009a) and neurotransmitters (Di Cosmo et al., 2004, 2006) guide the behaviour from the level of individuals in evaluating mates, to stimulating or deterring copulation, to sperm-egg chemical signalling that promotes fertilization (De Lisa et al., 2013). External chemical stimuli are, instead, detected by the olfactory organs and integrated in the olfactory lobes in the central nervous system. The olfactory organ results to play a key role in the development of the switch in behaviour from growth to reproduction (Polese et al., 2012, 2013; Di Cosmo

and Polese, 2014). In this context we propose a new integrative approach, that goes over the recent model proposed (Di Cristo, 2013) in which is not considered any environmental chemical involvement in the control of reproduction and that adds the olfactory organ of *O. vulgaris* to the already described olfactory lobe as the on-off switch between food intake and reproduction.

## 2. Olfaction in *O. vulgaris*

Traditionally the olfactory system in any animal is the primary sensory system that responds to chemical stimuli emanating from a distant source whereas other chemosensory systems generally require physical contact with the source for detection, and this sensory modality is called gustation.

Consequently, in aquatic environment, ecologically relevant odorants are those compounds that are easily dissolved in water, such as salts, sugars, amino acids, amines, peptides, proteins and functionalized hydrocarbons. Aquatic animals, including crustaceans and fish have a “gustatory systems” (e.g., leg detectors on lobsters and blue crabs, and barbels of catfish) that can detect chemicals dissolved in water as well without the requirement of physical contact with an object other than the chemicals themselves. These gustatory systems can respond to very low doses of those chemicals and evoke behaviours (Schmidt and Mellon, 2011; Caprio and Derby, 2008). In *O. vulgaris* the “gustatory systems” consists of receptors distributed on the suckers, considered the aquatic equivalent to taste (Wells, 1963; Graziadei and Gagne, 1973; Grasso and Basil, 2009), whereas chemoreception of water-born stimuli from a distant source seems to be detected by the olfactory organs (Anraku et al., 2005).

*O. vulgaris* is a predator with high visual capability as well as developed vestibular, auditory, and tactile systems. In some cases, octopuses are also prey for other marine animals, but it is not clear to what degree octopuses perceive danger by visual, tactile, auditory, and/or chemical cues, even though, given the presence of integrative sensory centres, it is reasonable to hypothesize that they use multimodal cues to perceive danger. Interestingly, for most part of their life, octopuses are solitary animals interacting with conspecifics just for reproductive purposes, therefore it is plausible to hypothesize that they use chemical compounds to find a partner. The anatomical descriptions of a putative olfactory organ in cephalopods first appeared in early literature (von Kölliker, 1844), followed by more recently demonstrations of their chemosensory capabilities and sensory mechanisms. To date, what is known about the olfactory organ in cephalopods comes from studies of *Nautilus* (Basil et al., 2000; Ruth et al., 2002) and decapods (Lucero and Gilly, 1995; Lucero et al., 1992, 2000; Mobley et al., 2007, 2008a,b; Piper and Lucero, 1999; Villanueva and Norman, 2008). In squid the olfactory organ is the site of a sensory epithelium resulted of ciliated supporting cells and different types of receptor cells that are bipolar neurons sending a dendritic stalk branch to the surface of the epithelium where sensory cilia are exposed to the marine environment. Each receptor neuron is connected to the ‘olfactory lobe’ and other areas of the brain with axon leads from their basal surface (Messenger, 1967, 1979). Recently Walderon et al. (2011) investigated the role of the olfaction in the distance chemoreception of conspecifics in *Octopus bimaculoides*, but almost nothing is known about the mechanisms, functions and modulation of the olfactory organ in octopods.

### 2.1. Olfactory organ of octopuses

In the mid 18th century Albert von Kölliker (1844) was attracted by a pair of dimples found on both sides of the head of both octopus and squid. These openings in the skin were thought

to be acoustic organs, but later it was suggested that they had a chemoreceptive function, perhaps analogous to the gastropod osphradium (Hancock, 1852; Chéron, 1866), although there was no experimental evidence in this regard. Watkinson (1909) made a seminal study on comparative morphology of olfactory organs in 23 species of coleoids suggesting that olfactory organs were analogous to nautiloid rhinophores. The morphology of the organs was described as a pit of sensory cells in *Octopus*, a flattened pad of cells in *Sepia*, and an elongate papilla in *Chiroteuthis*. Messenger (1967) described the innervation of olfactory organs with efferent nerve fibres coming from the olfactory and dorsal basal lobes of the brain in *Octopus*. Later on, in 1974, Woodhams and Messenger using electron microscopy techniques and Cajal staining, described, though not exhaustively, the olfactory organ of *O. vulgaris* as a small pocket, or dimple, in the skin, present on both sides of the head, ventral and posterior to the eye, and just anterior to the mantle cavity.

Optical microscopy using sagittal sections revealed a pseudo-stratified, columnar and ciliated epithelium. Below there were larger vacuolated cells, shaped as a ring. Electron microscopy revealed 3 cell types: one supporting cell type and two sensory cell types. More information about the olfactory epithelium has been gained in *Octopus joubini* by Emery (1976) who characterized six types of Olfactory Receptor Neurons (ORNs). Our recent study of olfactory organ from adult *O. vulgaris* (Polese et al., 2012; Di Cosmo and Polese, 2014) reveals a tiny white invagination that is difficult to recognise (Fig. 1). Light microscopy showed that the olfactory epithelium (OE) is organised as a bulging structure whose surface layer is composed of ORNs and sustentacular cells, below which is a layer of ring shaped cells that probably give turgor to the entire structure (Fig. 1).

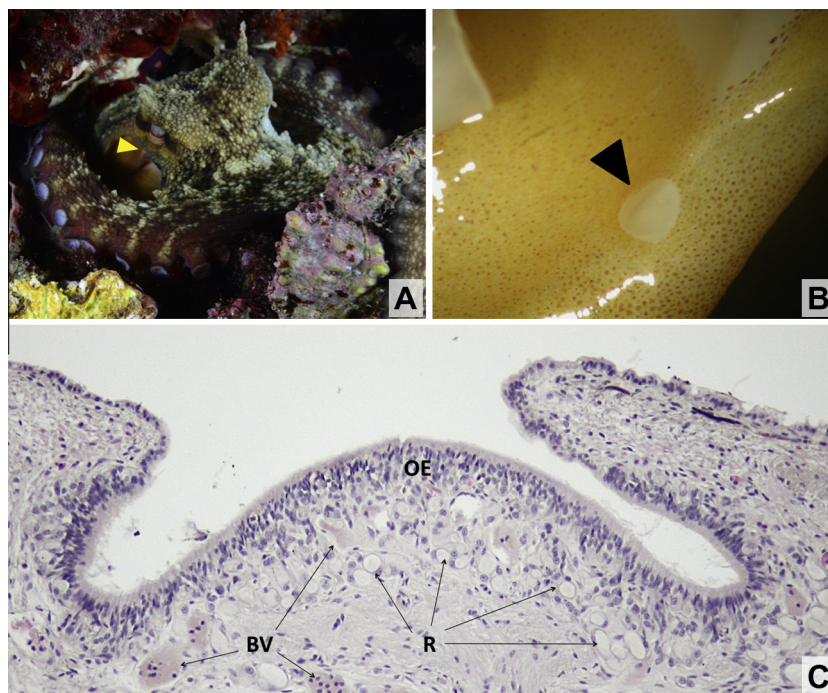
An understanding of the functional organization of neural pathways can be improved by immunocytochemical descriptions of its cellular components. Toward that end, we have used immunohistochemical techniques on *O. vulgaris*, and found immunoreactivity

against the following peptides, GnRH, FMRFamide, APGWamide and NPY (Fig. 2) (Di Cosmo and Polese, 2014) known to be involved in reproduction and energy balance (Di Cosmo and Polese, 2013, 2014; Di Cristo et al., 2002a,b, 2005, 2009a,b; Minakata et al., 2009). In the olfactory epithelium, whilst FMRFamide, APGWamide and NPY immunoreactivities are localized in both ORNs and fibres, GnRH immunoreactivity (-ir) is confined only to the fibres that reach the olfactory epithelium giving rise to a neural net (Fig. 2). Extending the observations to the CNS lobes, it appears that these GnRH-ir fibres, found in the mucosa, belong, indeed, to the neurons located in the posterior olfactory lobules (Di Cosmo and Di Cristo, 1998). This suggests a modulatory role of the olfactory lobules on the activity of the olfactory receptor neurons.

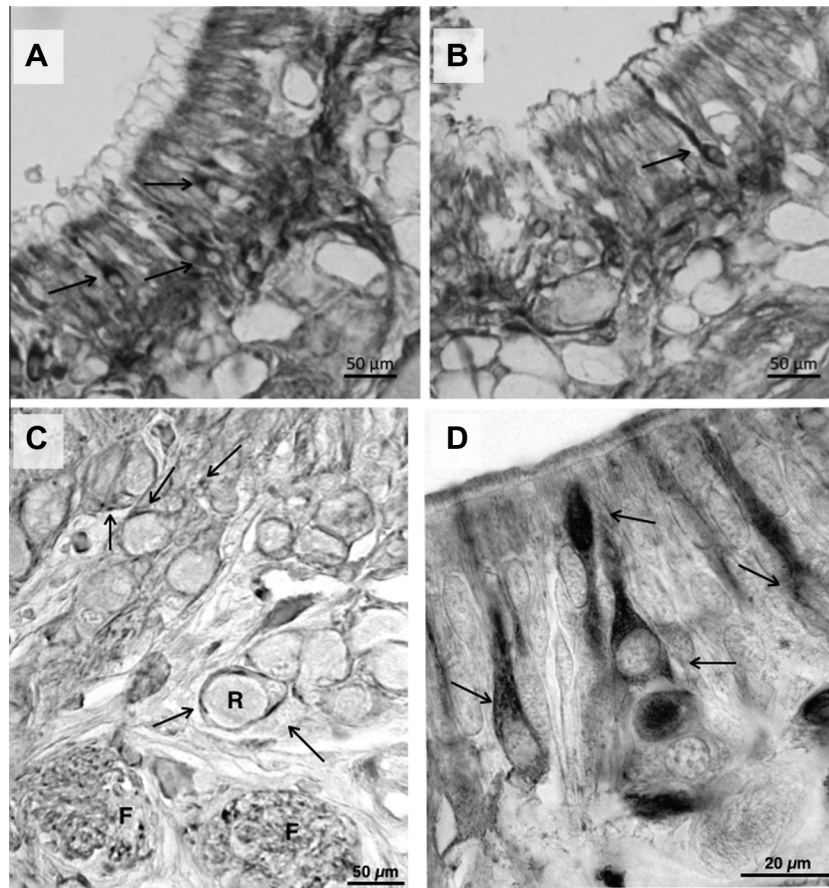
## 2.2. Olfactory lobe

Anatomically, as well described by Young (1971), the olfactory lobe in *O. vulgaris* is located on the optic tract close to the optic gland. It is organized into three lobules: anterior, middle, and posterior. These three lobules are interconnected to each other and they also receive fibres, through the olfactory nerve, from the olfactory organ. The majority of olfactory nerve fibres enter the posterior and middle lobules and cross the cell layer reaching the neuropil of the posterior olfactory lobe.

Functional differences among the lobules of the OL are suggested from differential distributions of peptidergic neurons in these brain regions. FMRFamide is widely distributed in all three lobules, whereas GnRH and APGWa are mainly localized in the posterior lobules neurons and send their fibres to the optic glands (Di Cosmo and Di Cristo, 1998; Di Cristo et al., 2005). This finding suggested a multipetidergic control of the reproduction through the modulation of the optic gland activity (Di Cosmo and Polese, 2014; Di Cristo, 2013). Other peptides were found in OL neurons: NPY (Suzuki et al., 2002), Galanin (Suzuki et al., 2000), and Corticotropin-Releasing Factor (CRF) (Suzuki et al., 2003), known to play a



**Fig. 1.** Olfactory organ of *Octopus vulgaris*: (A) *O. vulgaris* in wild, arrowhead indicates the olfactory organ; (B) ventral view of *O. vulgaris* mantle edge, arrowhead indicates the olfactory pit; (C) sagittal section of the olfactory organ (OE: olfactory epithelium; R: ring shape cells; BV: blood vessels).



**Fig. 2.** Immunoreactivity of peptides in the *Octopus vulgaris* olfactory epithelium: (A) APGWamide immunoreactive OSNs; (B) FMRFamide immunoreactive OSN; (C) GnrH immunoreactive fibres (F) passing through the olfactory nerve and reach the ring shaped cells (R); (D) NPY immunoreactive OSNs. Arrows indicate peptides immunoreactivity.

key role in the energy allocation choice between metabolism and reproduction. Recently, De Lisa et al. (2012) found also oestrogen receptor (ER) expression in the OL neurons.

### 3. Neuroendocrine control of reproductive behaviour in *O. vulgaris*

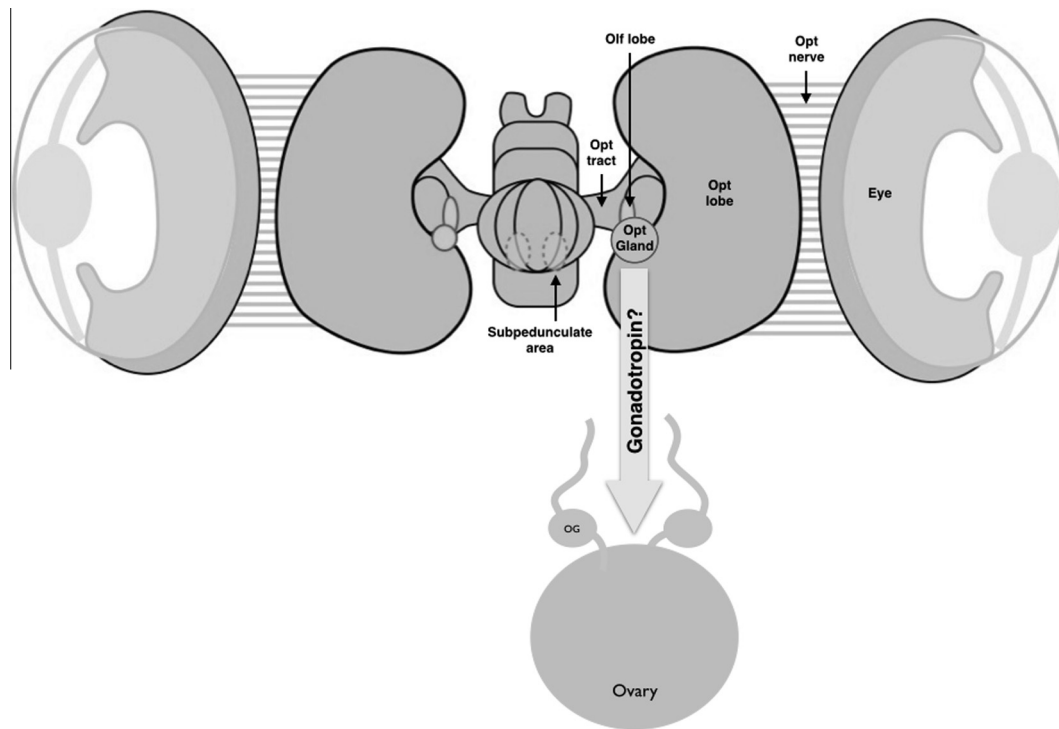
Communication within animals without nervous systems (e.g., sponges and placozoans) and even protists require a wide array of bioactive factors, which are in some cases identical to the neurotransmitters, hormones, and other neuroactive substances found in highly derived taxa (Robitzki et al., 1989; Schuchert, 1993). Therefore it appears that cell communication through secreted, diffusible signals is phylogenetically older than neural transmission (Carr et al., 1989). The cross-talk between these two internal communication systems involved in decoding signals coming from environment through sensory organs – the nervous and endocrine systems –, regulates various mechanisms and physiological processes such as reproduction. Environmental stimuli such as temperature, photoperiod, partners and food availability are perceived by sensory organs, and they deliver this information to specific areas of the CNS. These areas receive and integrate the information to generate internal responses that affect endocrine glands (from neuroendocrine cells to non-neural endocrine glands) inducing gonad growth and maturation, egg laying and sexual behaviour. *O. vulgaris* females reproduce only once and die just after their eggs hatch. After finding a suitable den they do not eat and spend their whole time caring for the eggs, cleaning them

and aerating them. For the last month of her life a mother octopus does not leave her den except to defend her eggs from predators. The last thing a mother octopus does for her young when they are ready to hatch is to blow them through her siphon and disperse them. Even if several works were performed to explain the factors and the structures underlying such anorexic behaviour (O'Dor et al., 1984; O'Dor and Wells, 1978; Wells and Clarke, 1996; Wells et al., 1983; Wells and Wells, 1959), the molecules and the detailed neural pathways involved are still unknown. *O. vulgaris* has a third order neuroendocrine regulator system (La Font, 2000) comparable to the vertebrates HPG axis (Hypothalamus, Pituitary, Gonad). What are the chemical messengers involved in the cross talk between nervous and endocrine systems? They can be divided into three main categories considering their chemical properties and mode of action: neurotransmitters, neuromodulators and hormones. To date, the chemical messengers known to play a role in the control of reproduction in *O. vulgaris* are summarized in Table 1.

Until now, the control of reproduction in *O. vulgaris* was based on the Wells and Wells (1959) study that assigned a main role to darkness as the inducer of gonad maturation in female *O. vulgaris* as shown in Fig. 3. After experimentally cutting the optic tract and optic nerves, they observed enlargement of the optic gland (a neuroendocrine gland) resulting in hypertrophy of the ovary and subsequently maturation. What is released from the optic gland that induces gonad maturation in *O. vulgaris* is still unknown, is it a gonadotropin? What are the other factors, if any, involved in the control of octopus reproduction? Le Gall et al. (1988) found FMRFamide in the optic gland nerve in *Sepia officinalis* suggesting

**Table 1**  
Chemical messengers involved in *O. vulgaris* reproduction.

Chemical messengers	Source	Function	References
FMRF amide	Olfactory lobe, reproductive tract	Inhibits optic gland maturation	Di Cosmo and Di Cristo (1998), Di Cristo et al. (2005) and Di Cosmo and Polese (2013)
GnRH	Olfactory lobe, reproductive tract	Stimulates optic gland and oviduct muscle	Di Cosmo and Di Cristo (1998), Di Cristo et al. (2005) and Di Cosmo and Polese (2013)
APGW amide	Olfactory lobe	Controls of male reproductive behaviour and ejaculation	Di Cosmo and Polese (2013)
NPY	Olfactory lobe	Regulation of optic gland activity	Suzuki et al. (2002)
CRF	Olfactory lobe	Regulation of optic gland activity	Suzuki et al. (2003)
Galanin	Olfactory lobe	Regulation of optic gland activity	Suzuki et al. (2000)
Serotonin	Olfactory lobe	Regulation of optic gland activity	Suzuki et al. (2000)
NMDA	Nervous system	Increases GnRH mRNA level in the olfactory lobe	De Lisa et al. (2012)
17 $\beta$ -estradiol and its receptors	Nervous System, olfactory lobe, reproductive system	Increase GnRH and 17 $\beta$ -estradiol receptor mRNA level in the olfactory lobe	De Lisa et al. (2012), Di Cosmo et al. (2002) and Di Cosmo et al. (2001)
Progesterone and its receptors	Nervous system, reproductive system	Stimulation of gametogenesis and vitellogenesis	Di Cosmo et al. (2001), Di Cristo et al. (2008) and Di Cristo et al. (2010)
Testosterone and its receptors	Nervous system, reproductive system	Stimulation of spermatogenesis	Di Cosmo et al. (2001) and Di Cristo et al. (2010)



**Fig. 3.** Anatomical diagram of Wells and Wells (1959) *O. vulgaris* sexual maturation model. Cutting the optic tract or making surgical lesions in the subpedunculate lobe resulted in an enlargement of the optic gland and subsequently hypertrophy of the gonads. Similar results were obtained by cutting the optic nerve or removing the optic lobes.

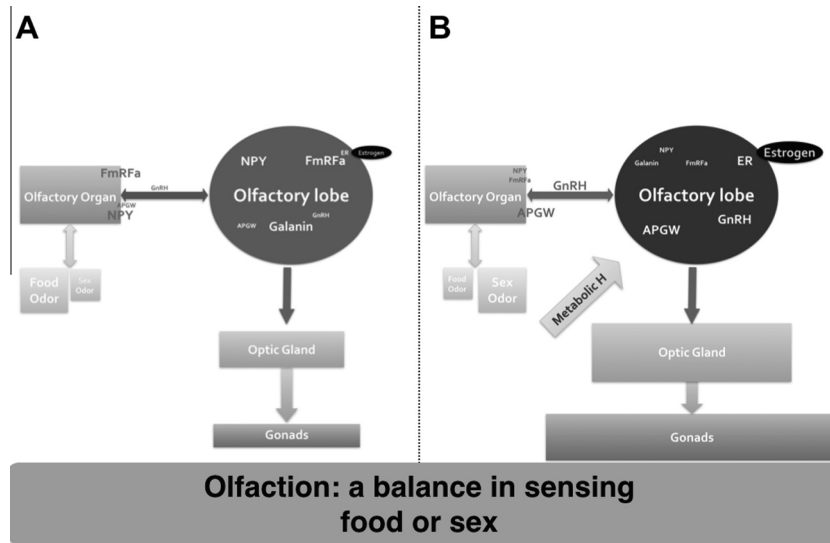
inhibitory control of the optic gland activity. The findings of several neuropeptides, neurotransmitters and hormones in the nervous lobes controlling reproduction (Table 1) provide new insights to the Wells and Wells' model (Fig. 3).

Our group has found a peptidergic linkages between the olfactory lobe and optic gland, which may represent a control or modulatory system. Besides the finding of FMRFamide in the subpedunculate area and in the OL, we localized cGnRH-I isoform in neurons of the posterior olfactory lobule, close to the optic gland, that send fibres to the chief cells of the optic gland (Di Cristo et al., 2002a) (Table 1).

These data allow us to hypothesize multipetidergic control of the optic gland activity, not only in an inhibitory way (FMRFamide), but also excitatory (GnRH). Another peptide, APGWamide,

known to work as a common neurotransmitter/neuromodulator peptide found in many species of molluscs and often related to sex organ growth or reproductive behaviour (Di Cosmo and Polese, 2013), was localized in the same olfactory lobule in which we had previously localized the GnRH neurons (Table 1). Thus APGWamide is strictly linked to and associated with those systems and lobes that directly process both nearby and distant chemical signals (Table 1). Finally, other peptides, NPY, Galanin, CRF, were found in the same nervous areas (Table 1). All these three peptides are known to play a key role in the balance between metabolism and reproduction (Crown et al., 2007; de Jong-Brink et al., 2001).

At peripheral level in the fusiform ganglia, which directly innervate the male and female gonads, we discovered the presence of FMRFamide and GnRH neurons that, interestingly, send fibres to



**Fig. 4.** Control of reproduction based on chemical cues. The olfactory lobe acts as a switch between growth and reproduction. In addition the olfactory lobe modulates the olfactory organ to be more sensitive to food or sex odours via the molecular players identified: (A) FMRFamide, NPY, Galanin inhibit reproduction and stimulate food intake; (B) GnRH, APGWamide, ER, and NMDA stimulate reproduction inhibiting sensitiveness to food odours.

the circular muscle layers of the reproductive ducts, suggesting an involvement of these two neuropeptides in motor coordination, egg-laying, and spermatophore transport (Di Cosmo and Polese, 2013; Di Cristo et al., 2002b). Extending our research at the peripheral level, we recently identified and characterized a chemoattractant peptide isolated from mature eggs of octopus females: Octo-Sap (octopus–sperm attracting peptide) (De Lisa et al., 2013). This bioactive peptide is able to increase sperm motility and induce chemotaxis by changing the octopus spermatozoa swimming behaviour in a dose-dependent manner. There are other chemical messengers that contribute to this scenario. Using the physiological range of  $17\beta$ -oestradiol concentrations, as determined by our previous studies on sex steroid hormone fluctuations during the annual reproductive cycle (Table 1), we observed a concentration-dependent increase of Oct-ER (octopus oestradiol receptor) mRNA levels in the olfactory lobes of *O. vulgaris* CNS, demonstrating that Oct-ER mRNA expression was up-regulated by  $17\beta$ -oestradiol. Moreover, the stimulation of the olfactory lobes with  $17\beta$ -oestradiol increased the Oct-GnRH mRNA confirming the existence of a strong coupling between  $17\beta$ -oestradiol and the transcriptional activity of Oct-GnRH neurons. The discovery of the role played by  $17\beta$ -oestradiol in the modulation of the transcriptional activity of both Oct-GnRH and Oct-ER genes in the olfactory lobes is in agreement with the existence of an axis 'area subpedunculate-olfactory lobe-optic gland' responsible for the reproductive behaviour of *O. vulgaris*, in which the activity of Oct-GnRH neurons is not only under the control of glutamatergic neurons (Di Cristo et al., 2009a), but also is regulated by  $17\beta$ -oestradiol (De Lisa et al., 2012).

### 3.1. The key role of olfactory lobe and olfactory organ: the scent of sex vs. food odour

In the Wells and Wells' model light plays a crucial role in gonad maturation (Fig. 3). They demonstrated the inhibitory action of the light on the optic gland activity. Using surgical lesion of optic nerves or optic tract or subpedunculate area, they were able to induce gonad maturation in *O. vulgaris* females. Their model proposes a simple mechanism where light switches reproduction on or off. In the wild, this kind of effect could be related to the life history of *O. vulgaris* females, which leave shallow and brighter

waters for deeper and darker waters for spawning. All the data previously reported strongly suggest a different and integrative regulation of *O. vulgaris* reproductive behaviour involving another nervous structure, the olfactory lobe in which the multipetidergic control exerted by GnRH, FMRFamide, APGWamide, NPY, and Galanin play an important role in the regulation of the optic gland activity (Fig. 4). Given that this lobe is also the site on which converges olfactory information coming from the olfactory organ, which in turn is under the same peptidergic control, it could suggest a modulation of the chemical perception resulting more sensitive to food odours, during the energy storage period, with a consequential switch off for reproduction. Conversely, when the female is in the reproductive period the OL could modulate the olfactory organ to be more sensitive to sex odours resulting in a switch on for reproduction. A similar modulation of olfaction could be responsible for the food avoidance of the female during maternal care with a switch off for food intake (Fig. 4). Interesting examples of a link between hormones and olfaction have been described in: shore crab, where female ecdysteroids level are linked with feeding (Hayden et al., 2007); blue crab, where proctolin plays a role in modulation of courtship behaviour (Wood et al., 1996); mosquito, where females drink a blood meal, which prepares them for reproduction, and factors in the blood then regulate the olfactory system's sensitivity to odours (Rinker et al., 2013); axolotl, where NPY and GnRH modulate activity in the olfactory epithelium in response to changing of physiological states and sensory cues (Mousley et al., 2006).

## 4. Conclusion

The perception of the environment by *O. vulgaris* has been always attributed to its visual and chemo-tactile capabilities, but little information is available on its olfactory function. Chemical cues determine feeding choices, selection of mates and habitats, competitive interactions and transfer of energy within and among ecosystems. In *O. vulgaris* the organ dedicated to the perception of water borne stimuli coming from a distance is the olfactory organ. In this review we have assigned a central role to both the olfactory organ and the OL in the chemical perception and integration of odour signals that allow the animal to balance their energy allocation between growth vs. reproduction (Fig. 4). Octopuses during

the long non-reproductive adulthood, dedicate major attention in prey choice to improve the quality of sperm and eggs and exploration across the sea bottom. In contrast during the short reproductive period, *O. vulgaris* spends its time on multiple mating and maternal care behaviours. In this review we have proposed a model in which the OL is the main control centre of the reproductive behaviour of *O. vulgaris* female.

To date many questions remain still open. Future work on *O. vulgaris* olfaction must also consider how animals acquire the odours detected by the olfactory organ and what kind of odour the olfactory organ perceives. The OL acting as control centre may be target organ for metabolic hormones such as leptin like and insulin like peptides, and olfactory organ could exert regulatory action on the OL via epigenetic effects of nutrients and pheromones on gene expression (Kohl, 2013; Elekonich and Robinson, 2000). The knowledge of the nature of the factor released by the optic gland could shed light on the role played by this gland in the reproduction: is it a gonadotropin or a trophic factor? Intriguingly, even though the mechanisms and molecules regulating reproduction are the same in both male and female, O'Dor and Wells (1978) observed mature sperms in young *O. vulgaris* males independently from optic gland hypertrophy.

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