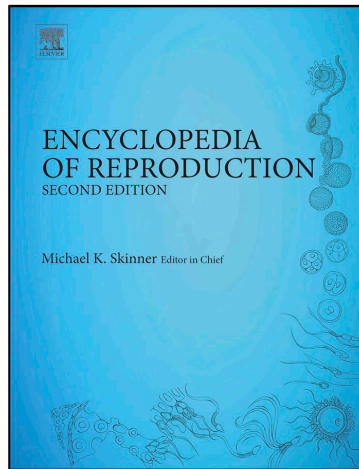


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SEASONAL REPRODUCTION

Photoperiodism in Fish

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Glossary

Circadian Clock A molecular machinery that functions on a 24 ± 4 h base (from the Greek *circa*: approximately, and *dian*: day).

Circannual Clock A molecular machinery that functions on a seasonal base.

Photoperiod Alternation of light (L) and darkness (D) during the 24 h cycle.

Abbreviations

BPG Brain-pituitary-gonads axis

D Darkness

DA Dopamine

E2 Estradiol 17β

FSH β Follicle-stimulating hormone subunit β

GnIH Gonadotropin inhibiting hormone

GnRH Gonadotropin releasing hormone

GSI Gonadosomatic index

HPT Hypothalamus

Kiss Kisspeptin

L Light

LH β Luteinizing hormone subunit β

MIS Maturation inducing steroid

NKb NKf, neurokinins b and f

POA Preoptic area

SCN Suprachiasmatic nuclei

T Testosterone

Introduction

In fish, reproduction displays cyclic variations at all levels of control: the seasonal information relayed to the circadian (biological) clocks, allows the production of rhythmic signals, which modulate the activity of the brain-pituitary-gonadal (BPG) axis, gonadal development and maturation, and finally courtship behavior and spawning (Cowan *et al.*, 2017; Falcón *et al.*, 2010a,b; Migaud *et al.*, 2010; Zohar *et al.*, 2010). Photoperiod, the main factor influencing the timing of fish reproduction, acts at different timescales from daily to once in a life (Juntti and Fernald, 2016). Photoperiod determines if daily or annual spawning occurs in the morning, afternoon or (most common situation) at night (Claydon *et al.*, 2014; Oliveira and Sánchez-Vázquez, 2010). In equatorial areas, it may occur throughout the year (Claydon *et al.*, 2014; Oliveira and Sánchez-Vázquez, 2010). Seasonal fish display a restricted spawning window, allowing partitioning between the energetic needs of reproduction and growth, and providing optimal conditions for offspring survival. Both functions are interconnected and rhythmic (Migaud *et al.*, 2010). Months of preparation precede, and a phase of arrest or recrudescence follows, the spawning window. Evidence for the presence of a circannual clock controlling fish reproduction has been obtained from studies in the trout (Duston and Bromage, 1991), catfish (Aggarwal *et al.*, 2014) and seabass (Prat *et al.*, 1999), which exhibit self-sustained circannual rhythms of spawning under constant conditions. The timing and duration of the spawning window is species-dependent (Oliveira and Sánchez-Vázquez, 2010). Spawning rhythms are synchronized by monsoons, tides and rainfalls in the tropics (Oliveira and

Sánchez-Vázquez, 2010). An extreme situation is observed in some salmon and eel species that reproduce only once in their life before dying (Juntti and Fernald, 2016).

In brief, the control of reproduction is highly dependent on a precise timing provided by the circadian system.

The Circadian System

Organization of the Circadian System

The circadian system is made of central clocks, of organs that provide input to the clocks and others that receive rhythmic input from the clocks. This system, which provides information on daily and calendar time to the rest of the organism, allows predicting and anticipating the cyclic variations in the environment. A single system controls a myriad of events (Fig. 1) (Ekström and Meissl, 2010; Falcón *et al.*, 2010a,b). Under constant conditions, the central clocks oscillate in a free running mode (24 ± 4 h). The underlying molecular mechanism involves the interaction of transcriptional activators and repressors that create two interlocking feedback loops, and virtually all fish cells possess such a machinery (Whitmore, 2010). Thus, multiple cellular clocks are present, organized in a network of more or less potent oscillatory units (Fig. 1). The 24 h light/dark (L/D) cycle is the main synchronizer of the clocks' activity, but other factors (temperature, food availability, water composition, social cues, rainfall, tides, and lunar cycles) may also provide input. Light is perceived through specific sensors, also located in different areas, including eyes, pineal gland, brain and skin (Baker *et al.*, 2015; Binder and McDonald, 2008; Chen *et al.*, 2014; Falcón *et al.*, 2010a,b).

How do all these different multi-oscillatory units get in tune? One hypothesis assumes the existence of one or several "master oscillators" that provide imprinting on "slave oscillators". In this scheme, the pineal gland occupies a central position (Falcón *et al.*, 2010a,b). It is possible that this is by virtue of its rhythmic production of melatonin (Fig. 1).

The Pineal Gland and Melatonin

The pineal gland of fish contains functional photoreceptors, analogous to the retinal cones (Ekström and Meissl, 2010; Falcón *et al.*, 2010a,b). In most species, each pineal photoreceptor is a cellular circadian system by itself. At night, photoreceptors produce two kind of messages. One is an excitatory neurotransmitter, which stimulates the activity of second-order neurons (Ekström and Meissl, 2010). Light inhibits this release providing a highly sensitive indication on surrounding intensity. The neurons convey the nervous information to brain centers (Yáñez *et al.*, 2009) (Fig. 2). The other is melatonin produced from serotonin (Figs. 2 and 3) (Falcón *et al.*, 2010a,b). Light inhibits melatonin production, and the nocturnal rise is driven by intrinsic circadian clock machinery. Temperature controls the amplitude of the nocturnal surge in a species dependent manner (Figs. 2 and 3) (Falcón *et al.*, 2010a,b). It is worth mentioning that internal factors, including estradiol (E2), glucocorticoids, catecholamines, adenosine, GABA and melatonin itself, can also modulate this production (Falcón *et al.*, 2010a,b). Pineal melatonin is released into the blood and cerebrospinal fluid. The retina also produces melatonin however for autocrine/paracrine use only; it is catabolized *in situ*.

In some species, light perceived through the eyes contributes partially (seabass, cod) or totally (catfish, tilapia) to controlling pineal melatonin secretion (Bayarri *et al.*, 2003; Martínez-Chávez and Migaud, 2009), indicating a neural pathway connects the

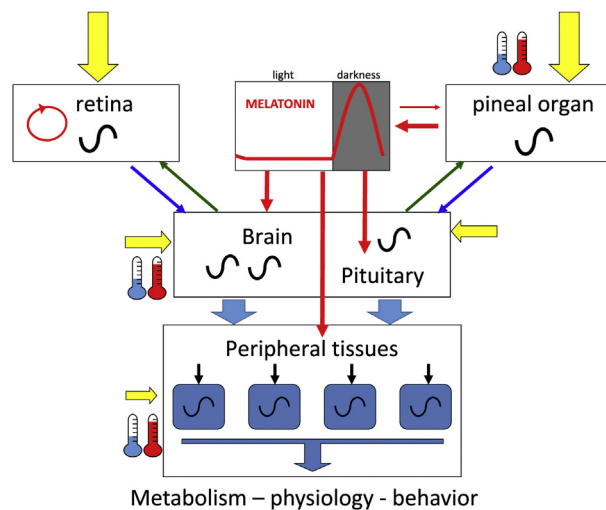


Fig. 1 Schematic view of the fish circadian system. In teleost fish the circadian system is made of more or less potent self-sustained units distributed in central and peripheral areas. The units are interconnected *via* nervous and/or hormonal pathways (arrows). They are directly and/or indirectly synchronized to the natural variations in photoperiod (yellow arrows) and temperature (thermometers) through photoreceptors and thermoreceptors located in the retina, pineal complex, deep diencephalon and skin. The pineal organ occupies a central position in the network through its rhythmic production of melatonin. Melatonin reaches multiple areas (red arrows), probably acting as a conductor/modulator of rhythms.

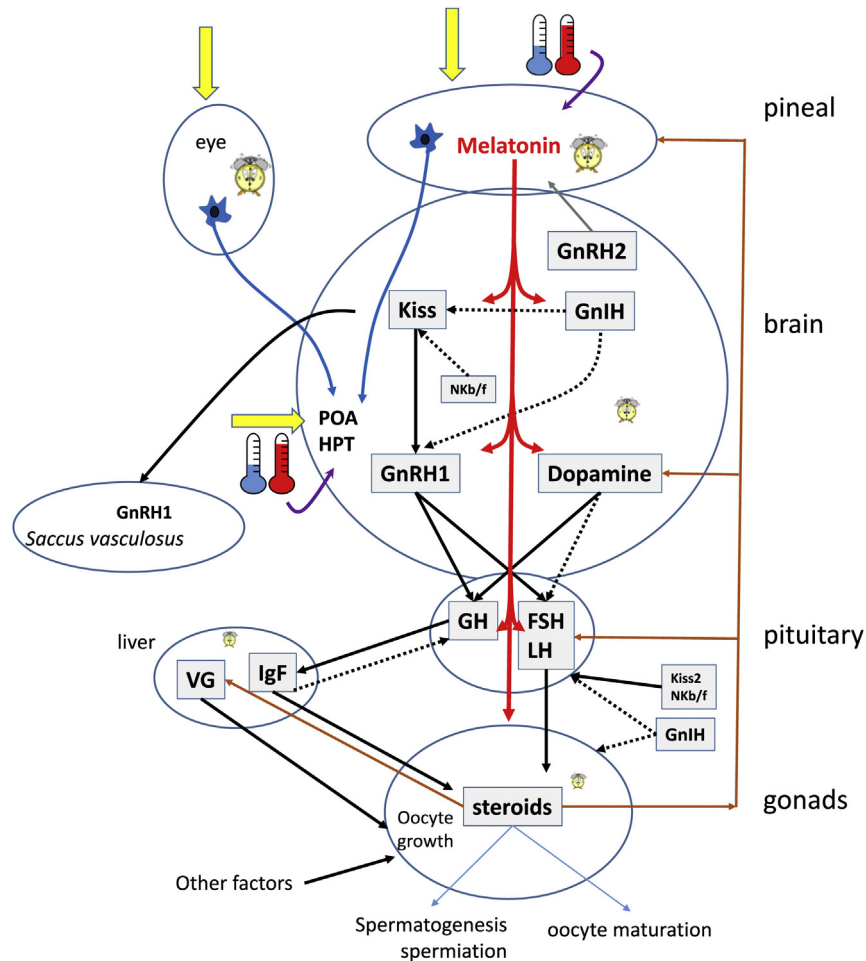


Fig. 2 Schematic view of the organization of the Brain/Pituitary/Gonads (BPG) axis in fish. The complex interactions at the different stages of the BPG axis are shown by the arrows (for details see text). Light and temperature inputs are shown by the yellow arrows and thermometers, respectively. Melatonin from the pineal gland (thick red arrows) acts at all levels of the axis. Neurons from the retina and pineal gland convey information to the hypothalamus (HPT) and preoptic area (POA). The sites of circadian clocks are shown by a clock. *DA*, dopamine; *FSH*, follicle-stimulating hormone; *GnIH*, gonadotropin inhibiting hormone; *GnRH*, gonadotropin releasing hormone; *IgF*, insulin like growth factor; *Kiss*, Kisspeptin; *LH*, luteinizing hormone; *Vg*, vitellogenin; *NKb*, *NKf*, neurokinins b and f.

retina to the pineal. Finally, no circadian clock controls melatonin secretion in Salmonid fish, where melatonin production is just an on/off response to the LD information (Falcón *et al.*, 2010a,b).

In all cases, the pattern of the melatonin oscillations reflects the daily variations in light and temperature. Its secretion rhythm provides robust and reliable information on daily and calendar times. Melatonin is now recognized as the hormonal time-keeper of the organism (Falcón *et al.*, 2010a,b; Migaud *et al.*, 2010).

Melatonin Receptors

Melatonin acts through three subtypes of specific transmembrane receptors (MT1, MT2 and Mel1c), which may be duplicated, and displaying a wide distribution in nervous and peripheral organs (Falcón *et al.*, 2010a). Virtually all brain areas express one or another subtype (Herrera-Perez *et al.*, 2010; Mazurais *et al.*, 1999). The receptors are particularly abundant in the thalamus, optic tectum and cerebellum, in areas that generally integrate light signals from the retina and/or pineal neurons. It is interesting that the suprachiasmatic nuclei (SCN) and preoptic area (POA), two thalamic neuroendocrine centers, also receive pineal and retinal nerve endings (Yáñez *et al.*, 2009).

The different melatonin receptor subtypes display daily variations (mRNA abundance, binding sites abundance or affinity for melatonin) (Bayarri *et al.*, 2010; Falcón *et al.*, 1996; Gaildrat *et al.*, 1998; Iigo *et al.*, 1994; Ikegami *et al.*, 2009) (Fig. 3). Binding sites abundance is generally higher during day than at night, but mRNA abundance may peak at different times of the LD cycle depending on the species and tissue investigated. These variations are maintained under constant, LL or DD, conditions in most but not all tissues, indicating a circadian clock control (Fig. 3) (Gaildrat *et al.*, 1998; Iigo *et al.*, 2003). Again, salmonid fish are

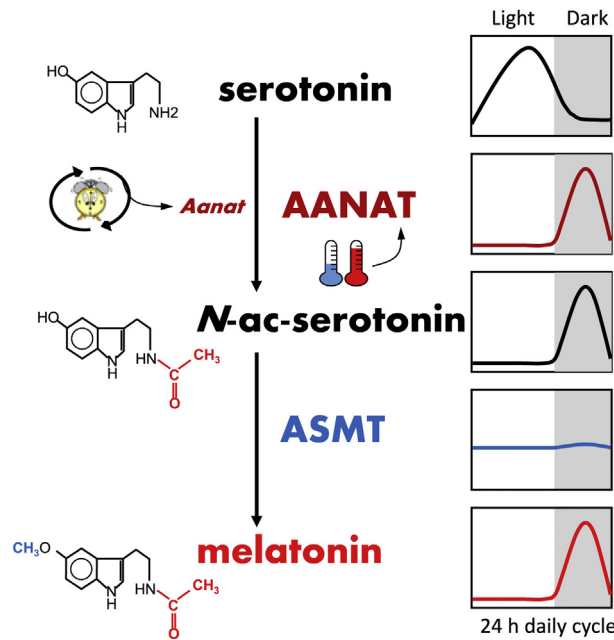


Fig. 3 Melatonin and its rhythmic biosynthesis from serotonin. Melatonin (*N*-acetyl-5-methoxytryptamine) is synthesized from serotonin in two steps: (1) The aralkylamine *N*-acetyltransferase (AANAT) catalyzes the conversion of serotonin into *N*-acetylserotonin (*N*-ac-serotonin); AANAT gene expression (*Aanat*) is controlled by intrinsic molecular clock machinery (clock); light inhibits AANAT protein abundance and activity while temperature controls amplitude of AANAT nocturnal activity (thermometers); (2) *N*-ac-serotonin is then methylated through the action of the acetylserotonin-*O*-methyltransferase (ASMT). The nocturnal surge in melatonin secretion results from the cyclic activity of AANAT. The duration of the nocturnal surge reflects the photoperiod, while its amplitude reflects the temperature. ASMT remains more or less constant throughout the light/dark cycle. The right panel shows the light/dark variations of each component during a 24 h cycle.

an exception: no rhythm is detected under LL or DD (Amano *et al.*, 2006). Seasonal variations in abundance of melatonin mRNA or binding sites have also been described in the pituitary (Falcón *et al.*, unpublished), hypothalamus and optic tectum (Bayarri *et al.*, 2010) of seabass maintained under LD and LL, indicating control by a circannual clock. Finally, tropical species with lunar-cycles synchronized melatonin profiles, also display lunar-dependent expression of their melatonin receptors (Park *et al.*, 2014). In brief, studies on the effects of melatonin must consider the daily, lunar and/or seasonal variations of the hormone as well as of its receptors, which varies from a species to another and from an organ to another.

The Reproduction System

During the breeding season, levels of androgens rise in males, and those of estrogens and/or progestins rise in females, allowing gonad maturation and spawning behavior (Juntti and Fernald, 2016). This is under the control of the brain-pituitary-gonads (BPG) axis (Fig. 3). One main component of the BPG axis is the hypothalamic gonadotropin-releasing-hormone (GnRH), which stimulates the synthesis and release of gonadotropins: follicle-stimulating hormone (FSH β) and luteinizing hormone (LH β), which in turn regulate steroidogenesis. Sex steroids are necessary for gametogenesis, and final gamete maturation (Zohar *et al.*, 2010). Sex steroids in turn exert diverse positive/negative feedback effects on tissues throughout the body (Fig. 3) with the cumulative effect of preparing multiple tissues for reproduction (Juntti and Fernald, 2016).

In distant teleost (perciforms), three isoforms of *Gnrh* exist: the hypophysiotropic *Gnrh1* in the pre-optic area/hypothalamus, *Gnrh2* in the midbrain tegmentum, and *Gnrh3* in the terminal nerve/ventral telencephalon (Powell *et al.*, 1994; Gothilf *et al.*, 1996). In early teleost (salmonids and cyprinids) only *Gnrh2* and *Gnrh3* isoforms have been identified; *Gnrh3* is believed to assume the non-redundant roles of *Gnrh1* (Zohar *et al.*, 2010). GnRH stimulation of gonadotropins secretion may be opposed by dopamine (DA) inhibition in some, but not all, teleost fish (Dufour *et al.*, 2010). Both the GnRH hypophysiotropic and DA inhibitory neurons are located in the preoptic area (POA) (Dufour *et al.*, 2010; Zohar *et al.*, 2010).

Other neuropeptides are involved in the control of reproduction acting upstream or downstream GnRH1/3 and DA; amongst the most significant are the gonadotropin inhibiting hormone (GnIH), Kisspeptins (Kiss1, Kiss2) and Neurokinins (NKb and NKf) (Paullada-Salmerón *et al.*, 2016; Zohar *et al.*, 2010) (Fig. 2).

1. GnIH, which belongs to the RFamide peptide family, has been reported to either inhibit (Paullada-Salmerón *et al.*, 2016; Spicer *et al.*, 2017) or stimulate (Biran *et al.*, 2014) gonadotropins. The time of year and experimental procedure used might explain these discrepancies. GnIH peptides interact functionally with GnRH neurons (Peng *et al.*, 2016; Spicer *et al.*, 2017), and reduce

- GnRH1 mRNA levels (Paullada-Salmerón *et al.*, 2016). An inverse relationship characterizes GnIH and GnRH mRNA abundance during the reproductive cycle of the carp (Peng *et al.*, 2016). In this species, three GnIH receptor subtypes are detected at all stages of the BPG axis, which also display seasonal variations in mRNA abundance. In the zebrafish, LPXRFamide antagonizes the Kiss2 activation of Kiss receptors (Spicer *et al.*, 2017).
- Kiss1 and Kiss2 genes are expressed, respectively, in the *habenula*/medio-basal hypothalamus, and hypothalamus (Alvarado *et al.*, 2016). In the striped-bass and seabass, Kiss2 acts on the hypothalamus (targeting GnRH neurons) and the pituitary, in a stage- and sex-dependent manner (Alvarado *et al.*, 2016; Zmora *et al.*, 2014, 2015). This results in the upregulation of GnRH1, FSH β and LH β expressions and secretion for the latter two corresponding peptides. Kiss and Kiss receptors are also present in the gonads but their roles remain enigmatic.
 - NKb and NKf stimulate FSH β and LH β levels in the tilapia, zebrafish and goldfish pituitaries as well as *fsH* and *lh* mRNA and LH β release in the striped-bass (Zmora *et al.*, 2017). It also inhibits *kiss2* expression and stimulate *Gnrh* expression (Zmora *et al.*, 2017).

Melatonin and Reproduction: A Rhythmic Adventure

Virtually all components of the BPG axis display daily and annual variations (Cowan *et al.*, 2017). How these variations are linked to those of the environmental cues remains largely unknown (Juntti and Fernald, 2016). As a time-keeper of the organism, melatonin has drawn attention. Early studies have shown that photoperiod manipulation, together with pinealectomy or melatonin administration, could induce pro- or anti-gonadal effects or have no effect at all in fish (Falcón *et al.*, 2010a). A confusing picture thus arose, which most certainly results from the use of different species and sex, at different reproductive states and seasons, with different doses and ways of melatonin administration. Although the modalities of action are not always well understood, evidence points in favor of a role of melatonin in fish, provided by studies on the localization of melatonin receptors and the reported effects of the hormone at multiple levels of the BPG axis.

The Pituitary

The fish pituitary expresses melatonin binding-sites as well as MT1, MT2 and/or Mel1c mRNA receptors (Chai *et al.*, 2013; Gaildrat and Falcón, 2000; Ikegami *et al.*, 2009). And, cyclic-AMP from cultured pituitaries varies after melatonin challenge in pike and trout (Falcón *et al.*, 2010a). In the sea bass, MT2 mRNA abundance displays seasonal variations in an inverse relationship with the FSH β and LH β mRNA annual variations and reproductive status (Falcón *et al.*, unpublished). This agrees with the idea that melatonin inhibits gonadotropins as first demonstrated in the Atlantic croaker (Khan and Thomas, 1996). Other *in vivo* studies later confirmed an inhibitory impact of melatonin on GnRH, LH β or FSH β mRNA (pituitary), or protein abundance (pituitary or plasma) in the eel (Dufour *et al.*, 2010), Pacific salmon (Amano *et al.*, 2004) and Mediterranean seabass (Alvarado *et al.*, 2015). A clear-cut mechanism of action is however difficult to highlight because of differences in the experimental protocols and species studied. Thus, in masu salmon, melatonin administration inhibited permanently (FSH β), while inhibition of LH β and GnRH was transient (Amano *et al.*, 2004). In contrast, melatonin implants impacted neither the annual rhythm of pituitary gonadotropins mRNA abundance, nor plasma levels of FSH in the Mediterranean seabass, while the February peak of plasma LH β was slightly decreased (Alvarado *et al.*, 2015). This contrasts with *in vitro* studies showing inhibition of gonadotropins mRNA abundance by melatonin or melatonin analogs (Falcón *et al.*, unpublished). The differences might result from a combination of factors, including fish strains and experimental conditions (e.g., *in vitro* the possible interactions with other brain factors are disrupted). In euryhaline fish, water salinity might also be of importance. In the Mediterranean seabass, the annual variations in gonadotropins mRNA abundance (Alvarado *et al.*, 2015) was not affected by water salinity in marked contrast with all other pituitary hormones (Falcón *et al.*, unpublished). However, the *in vitro* response to melatonin was dramatically modified by previous adaptation to sea or fresh water. The time of the year at which the experiments are done is also of importance.

The Brain (POA/Hypothalamus)

Melatonin injected into the 3rd ventricle of the Atlantic croaker inhibited LH β release by the pituitary glands (Khan and Thomas, 1996). This, and the identification of melatonin receptors in various brain areas, including the POA and hypothalamus (Falcón *et al.*, 2010a; Migaud *et al.*, 2010), paved the way to studies dealing with the effects of melatonin on the different regulators of the pituitary function, including kisspeptins, GnRH, GnIH, and DA. In female zebrafish, *in vivo* melatonin treatment elevated *kiss1*, *kiss2* and *gnrh3* gene expression in the brain and LH β in the pituitary (Camevali *et al.*, 2011). The effect on GnRH was probably indirect. Indeed (1) in the seabass, where GnRH1 and GnRH3 display LD variations and respond to melatonin, melatonin receptors co-localize with Kiss1/Kiss2, not GnRH (Alvarado *et al.*, 2015; Servili *et al.*, 2013); and (2) in the orange-spotted grouper, LD variations in the expression of MT1 melatonin receptors, *kiss2* and *gnrh1*, are consistent with the idea that melatonin regulates day/night variations of *gnrh1* expression through Kiss2; a decrease in MT1 receptors expression would increase the expression of *gnrh1* by upregulating *kiss2* expression (Chai *et al.*, 2013).

In the eel, melatonin implants did not affect *gnRH* mRNA abundance, while decreasing *fsH β* and *lh β* mRNA and steroids plasma levels (Dufour *et al.*, 2010). In this species, melatonin stimulates DA synthesis in brain areas known to innervate the pituitary. Such a mechanism might also operate in other species where melatonin/DA interactions have been detected. Melatonin administration

lowers DA levels in the brain and/or pituitary of rainbow trout (Hernandez-Rauda *et al.*, 2000), three-spot wrasse (Takemura *et al.*, 2010) and carp during the spawning period (Popek *et al.*, 2010a), while it increases DA release from brain explants of sapphire devil (Badruzzaman *et al.*, 2013). In the latter two species, DA and melatonin rhythms appear inversely correlated (Badruzzaman *et al.*, 2013; Popek *et al.*, 2010b).

Interactions of melatonin with GnIH have been demonstrated in two fish species, the cinnamon clownfish (Nikaido *et al.*, 2010) and zebrafish (Yumnamcha *et al.*, 2017). In the former, GnIH and MT1 melatonin receptors co-localize in the hypothalamus. In the latter melatonin induces a dose-dependent decrease in *gnih* transcription *in vitro*.

The Gonads

Melatonin binding sites or receptors have been identified in the gonads of teleost fish (Chai *et al.*, 2013; Chatteraj *et al.*, 2009a,b; Ikegami *et al.*, 2009; Molina-Borja *et al.*, 1994). The receptors display daily and annual variations in an inverse relationship with serum melatonin levels (Chatteraj *et al.*, 2009). Steroids and corresponding receptors also display daily and annual variations in association with the reproductive cycle. Photoperiod and temperature synchronize these variations (Zohar and Billard, 1984), which might involve a circannual clock because testosterone (T) and E2 rhythms are maintained under constant conditions in the killifish (Shimizu, 2003). The levels of T, 11-ketotestosterone, E2, and 17 α ,20 β -dihydroxy-4-pregnen-3-one (also known as maturation inducing steroid or MIS), rise during the breeding season (Juntti and Fernald, 2016). It is the increases in FSH β and LH β levels that promote steroidogenesis in the gonads. Sexual steroids contribute then to the process of gonadal maturation and spawning.

Melatonin mediates, at least in part, the effects of photoperiod on gonadal steroids. *In vivo* melatonin administration (1) mimics the effects of short days on GSI, gonadotropins and T, without affecting spermiation of masu salmon (Amano *et al.*, 2000); and (2) advanced testicular maturation during the preparatory phase, but was inhibitory during the pre-spawning and spawning phases, and ineffective during the post-spawning phase in the Indian carp (Bhattacharya *et al.*, 2007). *In vitro* studies support evidence of such complex and direct effects of melatonin on the gonads: (1) steroidogenesis in cultured trout ovarian follicles was stimulated by melatonin at early stages of development and became inhibitory at later stages, with a bimodal dose-dependent effect at maximum follicular growth (Leatherland and Lin, 2001); (2) in carps, pre-incubation of oocytes with melatonin prior to addition of MIS resulted in an accelerated rate of germinal vesical breakdown (Chatteraj *et al.*, 2008); (3) in the zebrafish melatonin increased the expression of two membrane progesterone receptor isoforms (*mpr α* and *mpr β*) (Carnevali *et al.*, 2011).

A permanent communication between the brain/pituitary complex and the gonads allows the activity of the different components of the BPG axis to be synchronized at all stages of the life cycle (Zohar *et al.*, 2010). Thus, steroids released by the gonads exert a feed-back control at different levels of the brain-pituitary axis. They also feed-back on the liver where they control VTG production (Specker and Sullivan, 1994). In the brain, the two major points of gonadal feedback regulation are the pituitary and the DA neurons of the POA. Steroids also modulate *gnRH* expression and content but the effects are mediated through Kiss neurons (Alvarado *et al.*, 2016; Zohar *et al.*, 2010). The pineal gland is also a target: *in vitro* (1) trout pineal cells express a E2 receptors, which mediate complex effects on melatonin secretion (Falcón *et al.*, 2010a,b); and (2) in the catfish E2 and T inhibit one enzyme of the melatonin pathway and hence melatonin synthesis (Yanthan and Gupta, 2007).

Thyroid Hormones and the *Saccus Vasculosus*

Thyroid hormones, triiodothyronine (T3) and thyroxine (T4), control energy metabolism and growth, and regulate development and differentiation of tissues. The hypothalamic thyrotropin-releasing hormone (TRH) produced by cells in the POA stimulates the production of pituitary thyroid-stimulating-hormone (TSH β). In turn TSH stimulates the production of T4 and T3 by the thyroid follicles, but most of the T3 present in the circulation is obtained *via* the conversion of T4 to T3 by deiodinases (DIO) (Swapna and Senthilkumaran, 2007). Evidence linking thyroid hormones and reproduction is extensively documented elsewhere (Duarte-Guterman *et al.*, 2014; Flood *et al.*, 2013; Swapna and Senthilkumaran, 2007) and annual variations in T3/T4 production have been correlated with seasonal reproduction in several fish species (Cowan *et al.*, 2017). TSH and DIO have also been identified in the coronet cells of the SV of masu salmon where abundance of *tsh β* mRNA, *dio2* mRNA and/or the corresponding proteins display light dependent changes *in vivo* and *in vitro* (Nakane and Yoshimura, 2014). Coronet cells also express photopigment genes. Finally, removal of the SV abolished the short-photoperiod induced testicular growth in the fish. In the SV of the Atlantic salmon, both Kiss receptors and GnRH3 transcripts were detected in another cell type than the coronet cells, perhaps the cerebrospinal fluid contacting cells, albeit at lower levels than in the brain (Chi *et al.*, 2017). In addition, transcripts variations mirrored those in the brain in fish maintained under different photoperiodic conditions. Together, these data suggest that the SV contributes to regulating photoperiodic fish reproduction.

Photoperiodism in Fish Farming

The photoperiod control of gametogenesis, reproductive seasonality, and the subsequent interactions between reproduction and growth, have been implemented in broodstock management and performance optimization in commercial fish farming (Migaud

et al., 2010). Manipulated photoperiod and temperature regimes are routinely used in commercial broodstock operations to phase-shift the spawning season and obtain eggs all year round (Migaud *et al.*, 2010; Zohar *et al.*, 1995). Additionally, when fish in production systems enter gametogenesis and reproductive development, growth rate is significantly diminished due to a shift in utilization of energy sources toward gonadal growth instead of somatic growth (Good and Davidson, 2016; Taranger *et al.*, 2010). This represents a major obstacle in commercial aquaculture, as many species start gametogenesis before reaching market size. Long photoperiods have been implemented to prevent precocious sexual maturation in large-scale commercial systems, such as floating netpens or land-based tanks, in which submerged or overhead lights are used to extend the duration of the daylight hours (Porter *et al.*, 1999).

Conclusions

The control of reproduction involves a complex network of actors as summarized in Fig. 3. Most of the network components display daily and annual variations so that reproduction events occur at the right time of the day and year. Photoperiod and temperature are the two main external synchronizers of the system that act through sensors located in different organs and tissues. The pineal gland is one of them. Evidence accumulates indicating that melatonin, its hormonal output, plays a major role in transducing photoperiodism to reproduction, acting at different levels of the network (Fig. 3). Melatonin might be considered a harmonizer or conductor of a concert of rhythms. No generalized model on the effects and roles of melatonin can be drawn; perhaps “several models” exist among the ~30,000 fish species listed. Differences between species have been highlighted and too few have been thoroughly investigated. Also, studies need to be exhaustive, considering sex and age of the fish investigated, time of day and year, water salinity and composition, etc. Indeed, melatonin appears to have multiple and sometimes complex effects on the reproductive system as well as on other neuroendocrine regulations more or less related to reproduction. To date such studies are lacking and attempts targeted mainly aquaculture fish, which do not necessarily behave and function like the wild counterparts. The necessary comparative studies will not only contribute to our understanding of fish biology and evolution, they should also help implementing conservation policies. This is indispensable in light of the ever-increasing anthropogenic pressures that fish are facing. The negative effects of intensive fisheries, physical and chemical pollution, reduction of wild natural spaces and global climate change (ocean acidification, temperature rise) are more than additive and put survival of species into challenge. A better knowledge of fish physiology and behavior will also allow a better management of fisheries policies and benefit the aquaculture industries. The large variability in regulatory systems, sensitivities and responses observed mean that species-specific regimes should be implemented in commercial settings to improve and standardize husbandry practices (e.g., use of light quality and intensity, temperature, etc.) in fish indoors and outdoors aquaculture.

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