ARTICLES

A New Model for Olfactory Imprinting in Salmon

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Olfactory imprinting is a specialized form of unconditioned learning in which olfactory information is acquired and then used in some specific behavioral context later in life. One of the hallmarks of olfactory imprinting is that it tends to be linked to a sensitive period of development. This prerequisite thus distinguishes olfactory imprinting from other types of odor learning in which only conditioned exposure to an odor stimulus is required for learning to occur. Most investigations designed to explore the mechanisms underlying olfactory imprinting have focused on mammalian species, concentrating on synaptic events at the level of the main and accessory olfactory bulbs.[1] Recent integrative studies with salmon[2,3] and rabbits,[4] however, provide compelling evidence that highly specific imprinted odor memories may also be retained in the periphery, i.e., at the level of the olfactory epithelium proper. These results suggest that populations of olfactory receptor neurons may be selectively tuned to respond to odor molecules present during a hormonally linked sensitive period. A potential key to the mechanism of how these peripheral odor memories become established draws on the unique ability of olfactory receptor neurons to turn over throughout an organism's life span.[5] How hormonal and environmental factors work together to influence olfactory neurogenesis is currently only sketchily understood,[6] but ultimately may provide important new insights not only for basic science but for salmon conservation as well.

KEY WORDS: salmon, olfactory imprinting, *Oncorhynchus kisutch,* memory formation

SALMON AS A MODEL SYSTEM FOR STUDYING PERIPHERAL OLFACTORY IMPRINTING

To the cellular neurobiologist who feels at home in a pair of hip waders, a coho salmon (*Oncorhynchus kisutch*) presents a tractable model species for examining mechanisms of olfactory imprinting and memory fundamental to other vertebrates. Even a child in grade school can appreciate that a fiery salmon leaping up massive waterfalls through grizzly bear-infested waters presents a certain olfactory charisma. But in the laboratory these animals also offer many useful advantages for studying basic mechanisms of olfaction. For starters they have an acute sense of smell. Indeed, almost every aspect of their lives is influenced to some degree by olfaction (including feeding, predator avoidance, reproduction, and migration) and the underlying endocrine factors that might influence their olfactory behaviors have been well worked out. Of great experimental value is their ability to imprint and home to controllable olfactory cues learned during a sensitive period of development called the parr-smolt transformation (smolting).[7] In coho salmon, smolting coincides with surges in plasma thyroid hormone levels that are believed to be important for olfactory imprinting, as well as many other physiological and behavioral changes that occur at that time.[8,9] Since plasma thyroid hormone levels are easily manipulated, it is possible to determine their effects on both specific neural structures and neurophysiological changes involved in imprinting.

As graduate students at the University of Washington, we began investigating this problem using a wide array of techniques ranging from fine-scale electrical recording of isolated olfactory receptor neurons and biochemistry to extensive field behavioral studies. Our aim was to explore the underlying mechanisms that produced a memory for the home stream. The picture that has emerged from this combined effort suggests that olfactory imprinting involves a tuning of olfactory receptor cells to specific stream odorants, and that this tuning is hormonally driven. A key element of this model is that a proliferation and selective survival of olfactory receptor neurons in the periphery drives olfactory imprinting in the brain, or specifically, in the olfactory bulbs where primary processing occurs. This novel approach to olfactory imprinting links olfactory neurogenesis to a well established, olfactory mediated behavior requiring both learning and memory. This paper reviews the conceptual framework that has lead us to this new model.

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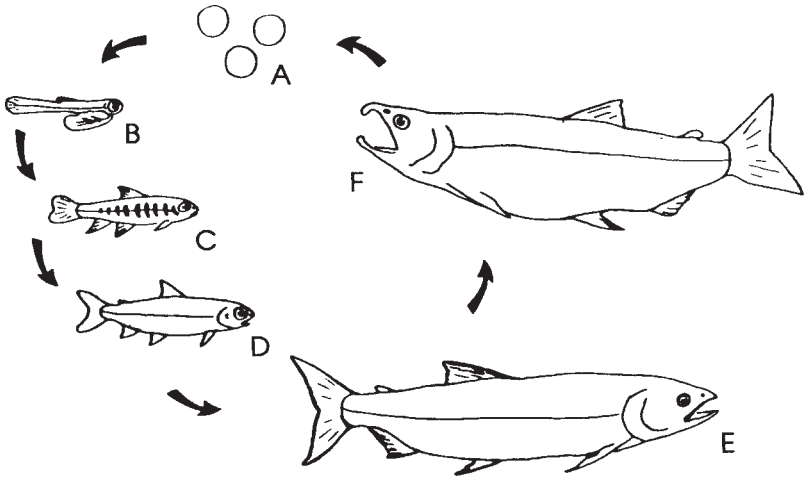

Figure 1. Life history of coho salmon. **A**: Eggs are laid each fall and hatch in freshwater streams. **B**: Hatchlings (alevins) reside in the gravel absorbing nutrients from their yolk sac. **C**: Parr continue to live and grow in freshwater streams until the following spring when they undergo the parr-smolt transformation which allows them to live in salt water. **D**: Smolts migrate downstream to begin life in the open ocean as sea-run salmon. **E**: Two to three years later, mature spawning salmon (**F**) return to their natal streams to spawn (From Nevitt and Moody, 1992).

WHAT WE KNEW ABOUT THE MECHANISM OF SALMON IMPRINTING

Pacific salmon have long been recognized for their long distance homing migrations which bring them back to their natal spawning grounds to reproduce and so complete their dramatic life cycle (Fig.1). Numerous field and laboratory experiments have demonstrated an olfactory basis for this remarkable behavior: at a critical period of development, juvenile salmon imprint to the odorant signature of the home stream. Years later, mature adults use this olfactory memory to guide them home.[10] In a classic demonstration of olfactory imprinting,[11] Hasler and colleagues showed that salmon could be manipulated to return to an arbitrary stream scented with particular synthetic chemicals such as morpholine (MOR) or phenyl ethyl alcohol (PEA), provided that these fish were first briefly exposed to these odors during the parr-smolt transformation several years earlier. Without this priming, fish showed no behavioral response to either odorant.[7,11–13] This sensitive period, also referred to as "smolting", is a transitional phase somewhat analogous to amphibian metamorphosis.[8] Smolting is associated with surges in plasma thyroid hormones, and is characterized by a suite of physiological and behavioral changes that prepare young stream-dwelling salmon parr for life in the open ocean (Fig. 2). These changes include an increase in gill Na^+/K^+ ATPase activity, a silvering of the body, a shift in rheotactic orientation, and the ability to tolerate salt water.[9]

Since olfactory imprinting has been linked to smolting, it has been hypothesized that surges in thyroid hormones experienced during this time help to establish the imprinted olfactory memory.[7,14] Coho salmon fail to home to artificial odor-

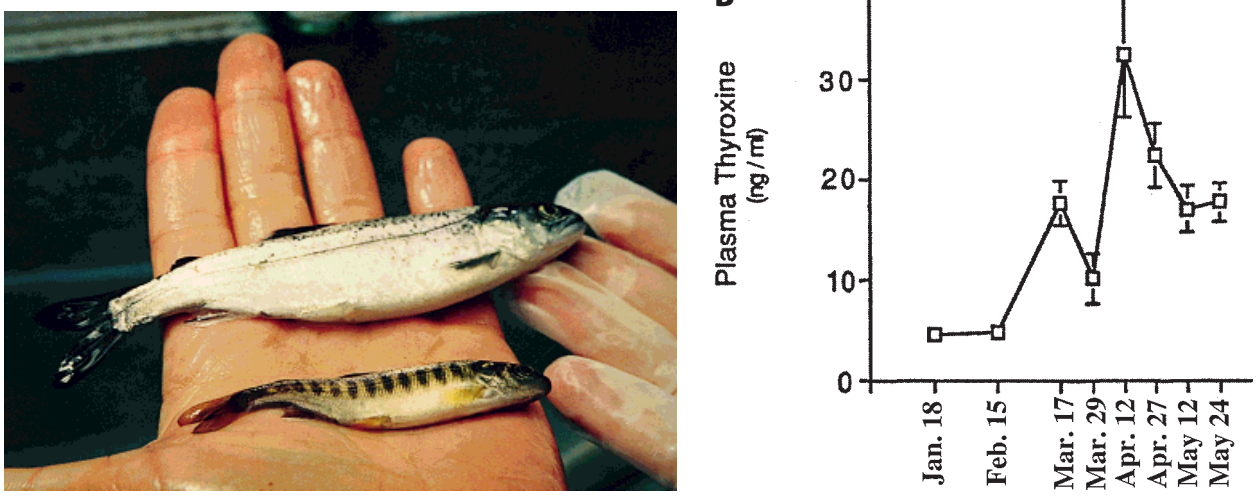

Figure 2. **A**: Coho salmon *(Oncorhynchus kisutch)* before and after the parr-smolt transformation. Parr-stage fish are characterized by smaller body size and vertical stripes (parr marks). In contrast, smolts (upper fish) are larger and highly silvered. **B**: Accompanying surge in plasma thyroid hormone levels across the parr-smolt transformation (Nevitt and Jarrard, unpublished data).

ants experienced at early life stages when plasma thyroid hormone levels (T_3 and T_4) are comparatively low. However, artificially elevating T_4 to smolting levels stimulates precocial imprinting.[14] Similarly, it has been reported that Atlantic salmon (*Salmo salar*) have an optimal period for long-term olfactory learning which coincides with peak levels of thyroid activity,[15] though it has also been shown that olfactory imprinting in coho can occur in the absence of a dramatic plasma T_4 surge.[16] Since it has been established that T_4 is enzymatically converted extrathryoidally to the intracellularly active form T_3,[17,18] it is tempting to hypothesize that T_3 acts on the neural substrate for imprinting. Direct neural effects of these hormones have been widely documented in many vertebrates. For example, thyroid hormones (T_3 and T_4) promote cytoarchitectural changes, including increases in dendritic arborization of neurons,[19–22] synaptogenesis in the CNS,[23,24] increased functional expression of specific membrane receptors[25–28] and neurogenesis in peripheral olfactory systems of other vertebrates.[29–34]

Interestingly, although results from experimental manipulations point to smolting and the accompanying surge in thyroid hormone as the only sensitive period for imprinting, this paradigm is not borne out by natural movements patterns of young fish within river systems. Upon hatching, most species of juvenile salmon typically leave their incubation sites within weeks of hatching, often smolting miles from their place of birth. For example, it is well established that one of the most faithful homers, Sockeye salmon (*O. nerka*), typically spawn in streams, but migrate to nursery lakes where they eventually smolt one to two years later. Yet these fish return to spawn in their natal streams rather than in the lakes.[35,36,] Even species with a relatively "simple" life history pattern like coho salmon, that imprint as smolts when reared in the hatchery, demonstrate migration patterns in the wild that suggest they must imprint prior to smolting. For example, coho salmon often make extensive migrations downstream from their natal stream in the winter prior to their parr-smolt transformation,[37] yet home as adults to their natal site. The implication is that in natural situations, sensitive periods for imprinting may be more plastic than for fish reared in the relatively monotonous environment of the hatchery.

BEHAVIORAL STUDIES CONFIRM THE PARR-SMOLT TRANSFORMATION IS THE SENSITIVE PERIOD FOR IMPRINTING

In light of these discrepancies, our first experiments were designed to challenge the idea that the parr-smolt transformation was the only sensitive period for imprinting. Morphological and physiological evidence suggested that the salmonid olfactory system was functional as early as hatching,[38] and that soon after emergence, salmon were able to learn odors associated with specific habitats and odors from other fishes.[10,39] Furthermore, working at the University of British Columbia, Simon Courtenay[40] had demonstrated that juvenile coho salmon exposed to a synthetic odorant (morpholine) shortly after or even *before* hatching, were able to learn and retain a memory of this odorant over a year later. If these odor memories established early on were also used for homing, this finding would suggest that plasticity in neuronal development early on in the fish's life might play a role in learning the scent of the home stream.

Our first investigations examined the timing of olfactory imprinting by exposing juvenile coho salmon to either natural stream waters or to an artificial odorant (PEA) at three specific developmental stages (as alevin, parr and smolting fish). We chose this rosy smelling odor because Hasler had used it in his classic studies of salmon imprinting.[11] We then reared the fish to maturity and tested their behavioral responses. Our experiments involved presenting "homing" fish with natural choice experiments between tributaries scented with PEA and control streams. These experiments were conducted on the same site (Issaquah Creek, WA) where 40 years earlier Hasler and his student Warren Wisby had conducted their original experiments demonstrating that olfaction was required for homing.[41,42] In a second behavioral test, we also placed fish downstream of a divided spawning channel, scenting one side with PEA at concentrations (100 nM) used for imprinting. In these separate experiments, only salmon exposed to PEA specifically during the parr-smolt transformation demonstrated an increased behavioral attraction to this odorant as adults (Fig. 3).[42] We found no significant evidence that this species became imprinted to homing odors prior to this developmental stage. These experiments confirmed that the parr-smolt transformation was the sensitive period for imprinting at least in our hatchery-reared salmon. The challenge would be to come up with a physiological model that would elucidate both the patterns of homing noted for wild fish as well as the experimental data suggesting that the timing of imprinting was restricted to the parr-smolt transformation.

Once we had established that smolting was the sensitive period for imprinting for our hatchery-reared fish, the next part of our investigations aimed to tease apart some simple aspects of the underlying mechanisms contributing to this memory. At this time, most people working in the field believed that olfactory memories were born centrally, i.e., in the brain, but efforts to pinpoint neural correlates of imprinted memories in salmon were largely inconclusive. Results from independent studies had reported gross changes in electroencephalographic (EEG) activity in imprinted salmon in response to homestream waters.[43,44] Investigators attributed these electrical responses to odor-induced fluctuations in activity in the olfactory bulb, the primary processing center for incoming olfactory information, and speculated that some aspect of the imprinted memory must be stored there and later retrieved. Despite these initial findings, debate in the literature continued for years because these studies could not be reliably repeated.[44–50] Amidst the controversy that ensued, no testable model emerged that implicated a mechanism for how odor memories might be formed.

The beauty of working at the University of Washington's school of fisheries is that salmon are part of the culture there. Each fall runs of both Chinook

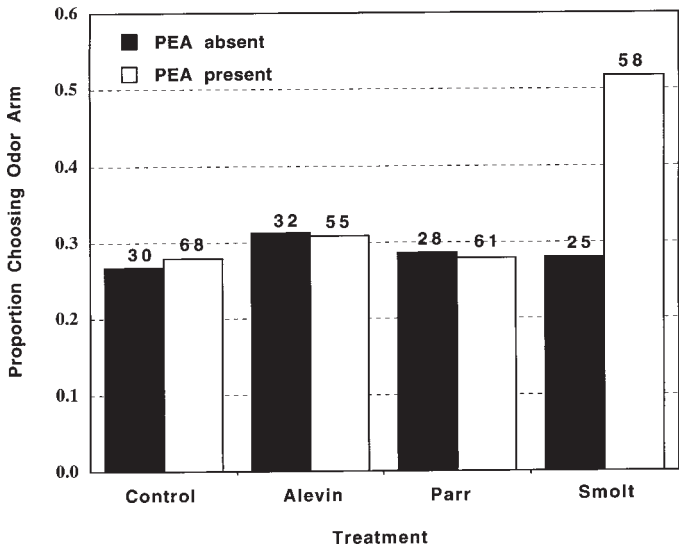

Figure 3. Behavioral responses of mature coho salmon to PEA in the Big Beef Creek divided spawning channel. Salmon were exposed to PEA at the developmental stage indicated or never experienced PEA (control). Open bars show the proportion of salmon choosing arm B before PEA was added. Shaded bars show the proportion of salmon choosing arm B in the presence of PEA metered into arm B. Numbers above bars indicate the total number of fish choosing either arm A or B (From Dittman et al., 1996).

(*O. tshawytscha*) and coho salmon home literally to the back door of the school where they provide a dramatically tangible inspiration for a person engaged in a problem like olfactory imprinting — something that a lab rat might not so easily inspire. We thought that a clue to understanding this problem might be in stepping back far enough to recognize what activity in the olfactory bulb might imply. This change of perspective naturally brought us a view of the nose where specialized cells called olfactory receptor neurons detect odorants. In salmon as in other fishes, olfactory receptor neurons are embedded in a mucous coated ciliated epithelium, which is folded like a flower into a rosette arrangement. The folding increases the surface area available for receptor cells to detect odors. Look four hundred times closer and olfactory receptor neurons resemble elongated bowling pins with cilia on the top end and a long axon streaming from the base. The cilia are enriched with receptors that bind odors, triggering a cascade of biochemical reactions that transduce this odor signal into an electrical response that is, in turn, transmitted centrally to the brain. In a mature salmon, axons arising from a 10 μm cell can be more than a centimeter long, terminating in the glomerular layer of the olfactory bulb of the brain. This new perspective gave us a fresh way to think about a mechanism: if the olfactory bulb did serve as a substrate for olfactory memory, then perhaps part of that substrate was in the olfactory receptor neurons themselves since these neurons contributed to some of that activity.

Our initial experiments were thus aimed at characterizing the electrical properties of ciliated olfactory receptor neurons isolated from coho salmon using a fine-scale electrical recording method called the patch clamp technique.[51,52] These efforts showed that ciliated olfactory receptor neurons isolated from salmon had broadly similar ionic conductances to olfactory receptor neurons that have been studied in other organisms. However, these results also showed significant variations in electrical properties linked to life-stage differences. In cells isolated from pre-smolts, a Ca^{2+}-dependent K^+ current dominated the outward current, whereas in cells isolated from smolted fish, a transient K^+ current became prominent (Fig. 4). We also identified and described consistent differences in the response characteristics of olfactory receptor neurons to internal dialysis with second messengers.[52] Together these data implied that olfactory receptor neurons were far from static detectors of odors in the environment, and this piqued our curiosity to examine the idea that the peripheral olfactory system might contribute to homestream learning.

The first step in this challenge was to hand rear ten thousand coho salmon through the parr-smolt transformation. Luckily we were already doing this in conjunction with our behavioral experiments discussed above — in fact these mechanistic studies were planned to complement our behavioral investigations. Rearing our own animals also gave us control over the olfactory environment that these fish experienced during their growth and development. Upon smolting, we exposed an experimental group of fish to PEA (100 nM) for ten days while a second, unexposed group served as controls. Fish were then coded by fin clipping and reared together in a common facility. The following fall and winter, we measured PEA responses in isolated ciliated olfactory receptor cells using patch clamp recording techniques in double-blind trials. We found that olfactory receptor cells isolated from PEA-imprinted fish were nearly twice as likely to respond to PEA compared to those isolated from naive fish of the same cohort (Fig. 5).[51] Furthermore, we found that cells from imprinted salmon showed a six-fold increase in responsiveness to PEA compared to cells from naive fish of the same cohort. Cells isolated from both PEA-imprinted and naive fish responded similarly to L-serine, a different odorant that salmon can smell, suggesting that the change in sensitivity was specific to the imprinted odorant.

The results of these experiments suggested to us that some component of the homestream memory was encoded in the peripheral olfactory receptor cells themselves. In characterizing the electrical properties of isolated olfactory receptor neurons, we had noted differences associated with the timing of cell harvesting with respect to the

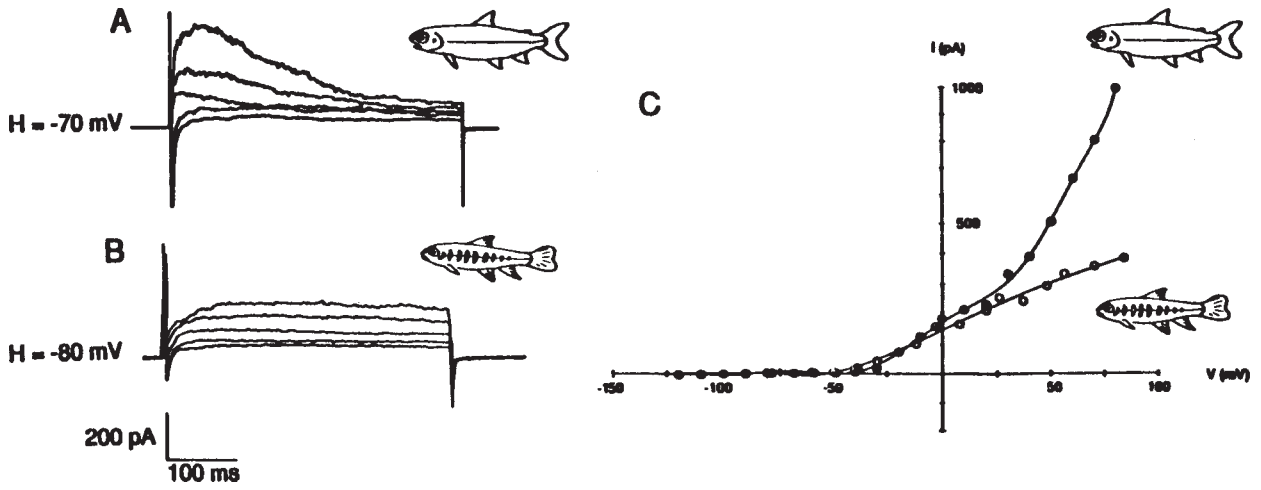

Figure 4. Outward currents: life-stage differences. Families of current traces recorded from cells isolated from a parr (**A**) and a smolt (**B**). External Sr^{2+} was used to block the Ca^{2+}-activated K^+ current. Steps are to –23, –12, +8, +26 and +56 mV and to –20, –10, +20, +40 and +60 mV respectively. (**C**): The corresponding peak current-voltage relationship for the families of current traces in A (○) and B (●). (From Nevitt and Moody, 1992).

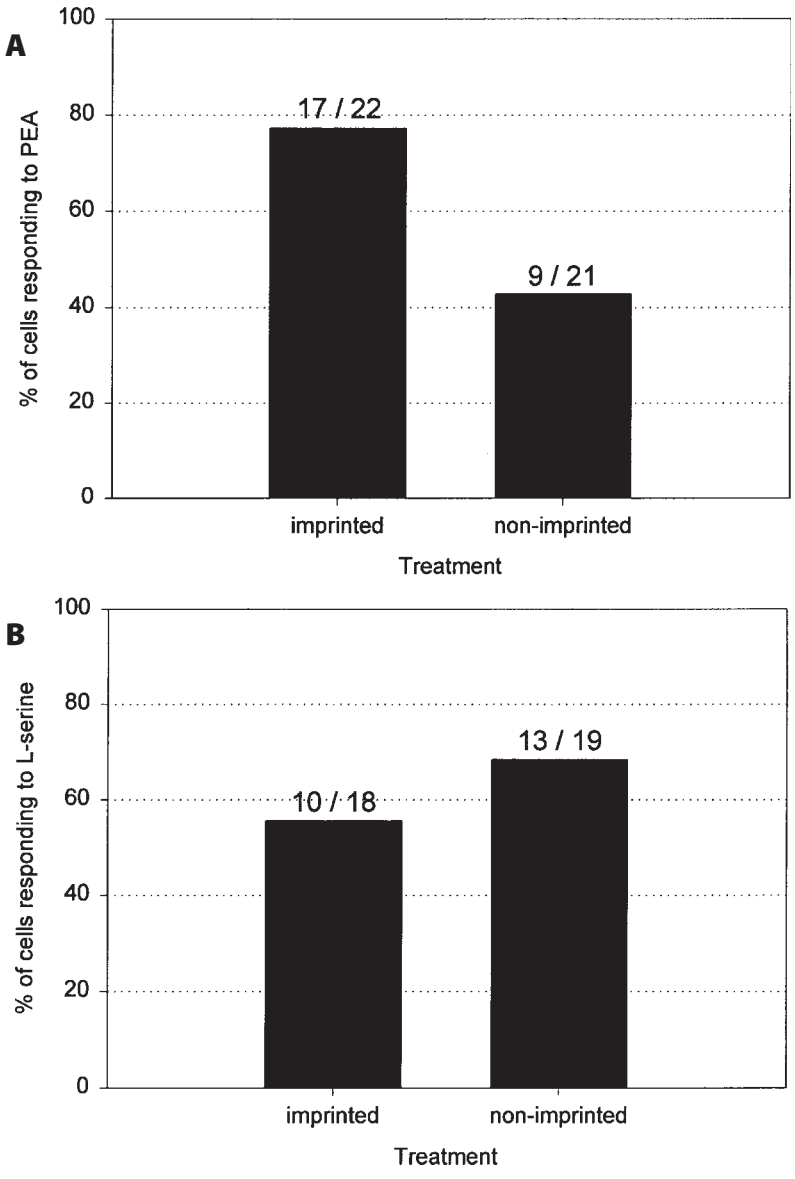

Figure 5. Responses of isolated olfactory receptor neurons to PEA and L-serine. **A**: Cells isolated from PEA-imprinted and PEA-naive fish were scored as positive or null responders to PEA in (10^{-6}–10^{-8} M) in double-blind trials. Percentages of cells responding to PEA were significantly different between the two groups of cells (17/22 PEA-imprinted; 9/21 naive; $P<0.05$ G-test). **B**: Percentages of cells responding to a second odorant, L-serine (10^{-5}–10^{-8} M), were not significantly different between the two groups (10/18 PEA-imprinted, 13/19 naive; $P>0.05$, G-test).

salmon life cycle. These preliminary results had suggested to us that second messengers like cyclic GMP might play a role in modulating odor induced electrical excitability of these neurons,[52–54] but that this effect was linked to the fish's developmental state. At the same time, we had initiated studies examining whether odorant activation affected cAMP signaling in the cilia of salmon olfactory receptor cells as had been suggested for other vertebrates.[55,56] Our early results suggested that the imprinting odorant PEA had little effect on coho salmon olfactory adenylyl cyclase. [3,57] However, our findings implied that cGMP might play a role in olfactory signaling. This result led us to hypothesize that imprinted odors might have different effects on guanylyl cyclase activity, and provided a different mechanism through which to explore our hypothesis that peripheral imprinting contributed to homestream learning.

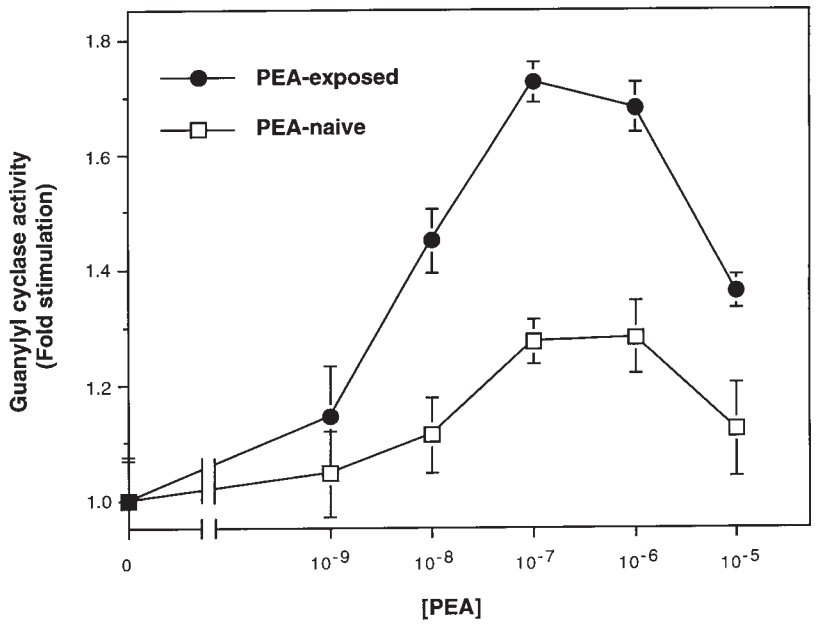

Figure 6. Sensitivity of guanylyl cyclase to PEA in olfactory cilia isolated from PEA-exposed and PEA-naive salmon. Cilia were prepared from 10 PEA-exposed or PEA-naive salmon. (Dittman, unpublished data).

Our next set of experiments examined guanylyl cyclase activity in the presence of PEA in olfactory cilia isolated from PEA-imprinted and non-imprinted salmon — members of the same cohort on which both behavioral and electrophysiological experiments had been performed. Because behavioral sensitivity to imprinted odorants had been linked to maturational state in other studies, we conducted experiments using cilia isolated eight months prior to maturation and also periodically during the period of final maturation and spawning. We found that stimulation of guanylyl cyclase activity by PEA was significantly greater in olfactory cilia isolated from PEA-imprinted salmon compared with PEA-naive fish only at the time of the homing migration, 2 years after PEA exposure (Fig. 6).[3] These results suggested that sensitization olfactory guanylyl cyclase may play an important role in olfactory imprinting.

Taken together our results suggested to us that exposing salmon smolts to nanomolar concentrations of PEA for as little as 10 days could be correlated with dramatic and measurable changes in their peripheral sensitivity to odors even years later. But how could we reconcile this data into a workable model, particularly since olfactory receptor neurons were thought to turnover throughout the fish's life? Since this sensitive period for odor exposure was linked to surges in plasma thyroid hormone levels, we guessed that the changes in peripheral sensitivity we had discovered might also involve a hormonally driven modulation in the expression of particular olfactory receptor proteins,[6,58,59] or populations of receptor neurons that expressed these proteins. Either idea was consistent with differences in outward current components in olfactory receptor cells isolated before and after smolting that we had reported. Moreover, other reports were indicating that the olfactory epithelium of smolting salmon (*O. masou*) was enriched in thyroid hormone receptors compared with epithelium from parr.[60] This data offered further support to a model invoking thyroid hormone as a modulator in this system. At the same time, additional discoveries of odorant-induced peripheral plasticity in rabbits[4] and olfactory-deficient strains of mice[61] using electro-olfactogram (EOG) recording techniques suggested that our results might have broader implications for environmentally-induced plasticity in the olfactory epithelium in vertebrates.

Other clues came from scattered studies investigating changes in olfactory neuroanatomy across the parr-smolt transformation. Unpublished work with Atlantic salmon (*Salmo salar*) suggested a quadrupling of olfactory receptor cell number, as well as specific changes in the relative composition of the olfactory bulb neuropil during this transition.[62] Similar studies with Chinook salmon later confirmed these findings.[63] These data implied that populations of olfactory receptor neurons were proliferating specifically during the parr-smolt transformation, though detailed studies relating hormones to proliferation had not been done. More precise anatomical studies showed the primary olfactory projection patterns in the glomerular layer of the olfactory bulb for a salmonid (Rainbow trout: *O. mykiss)*. Working at the University of Michigan, David Riddle and Bruce Oakley had recently identified nine distinct terminal olfactory receptor cell projection fields ranging in size from 1% to 35% of the glomerular layer where olfactory receptor neurons form synapses in the brain, but the functional relevance of this segregation was unclear.[64]

A WORKING MODEL OF OLFACTORY IMPRINTING

Based on our own data and the information available to us from other studies we formally proposed a new model for olfactory imprinting in salmon.[2,3,65] Our model suggests that:

1) During sensitive periods for imprinting, thyroid hormones (T_3 and T_4) promote a nonspecific proliferation of olfactory receptor neurons that are sensitive to a wide variety of odors.
2) Receptor cells that are most active (i.e., responsive to the odorants present in the environment) survive, while others die. Selective survival may involve competition for synaptic targets.
3) This punctuated proliferation and selective survival of olfactory receptor cells triggers a reorganization of glomerular structures within the bulb.

After publishing our first paper suggesting our new model for olfactory imprinting,[2] we were pleasantly surprised to receive a letter from Robin Hudson at the Institut fur Medizinische Psychologie in Munich, Germany. Hudson also studied olfactory imprinting, but in a different species altogether: the European rabbit (*Oryctolagus cuniculus*). Hudson and co-workers[4] had observed that if pregnant mothers were fed aromatic juniper berries (part of the their diet in nature), then at weaning time, their pups preferred to eat juniper, even if they were reared by a foster mother fed standard laboratory rabbit chow. Moreover, this learning event was accompanied by a dramatic proliferation of olfactory receptor cells that occurred post-natally when pups were suckling. Her results also showed an enhanced sensitivity of the pup's peripheral olfactory system to juniper, but only if the mother had eaten juniper while pregnant. The implication was that the young pups' noses were tuned to be super-sensitive to odors that were associated with the food that their mother ate, and that this tuning was reflected in neural proliferation and changes in sensitivity in the peripheral olfactory system. Working independently, in parallel and on phylogenetically different systems, we had come up with nearly identical models for peripheral olfactory imprinting.

IMPLICATIONS OF THE MODEL

This model suggests that populations of olfactory receptor neurons may be selectively tuned to respond to odor molecules present during a hormonally linked sensitive period. The evidence we have reviewed suggests that salmon imprint to homestream odors at the parr-smolt transformation when thyroid hormones surge, but more subtle peaks occur much earlier in development, particularly at hatching when fish emerge from their natal gravel.[66–68] Detailed electrophysioloical investigations suggest that hatchlings (alevins) respond to a variety of odors.[38] If the olfactory system is competent to respond to thyroid hormone at these early stages, then changes in levels of this hormone may well contribute to olfactory imprinting.

One of the strengths of this model is that it bridges a gap between results implicating the parr-smolt transformation as the only sensitive period for imprinting and observations of migratory patterns of wild runs that suggest that the timing of imprinting is more flexible. We think that hatchery-reared salmon experience sensitive periods for imprinting predominantly during developmentally controlled times when thyroid hormone surges, or just after release from hatcheries when their environment is rapidly changing.[39] In hatchery rearing facilities, water quality, temperature, flow rate and diet are all carefully controlled, and housing methods typically eliminate territorial and other behaviors that juvenile salmon would naturally be expressing during their early life history. In contrast, wild salmon may experience a greater plasticity in imprinting because the thyroid-endocrine axis is influenced by the environment that a young fish experiences.[39] Under more natural conditions, patterns of movement within the river system brings a young wild fish in contact with a myriad of enrichment including different water sources, temperatures and flow rates, and any of these factors can stimulate thyroid hormone production.[69–73] Our model thus does not restrict learning to the parr-smolt transformation, but links imprinting events with increases in thyroid hormone. The basic idea is that when thyroid hormone surges and is converted to T_3, neural proliferation and pruning follow, in a sense tuning the fish's peripheral olfactory system to the river system that it has experienced throughout its early life (Fig. 7).

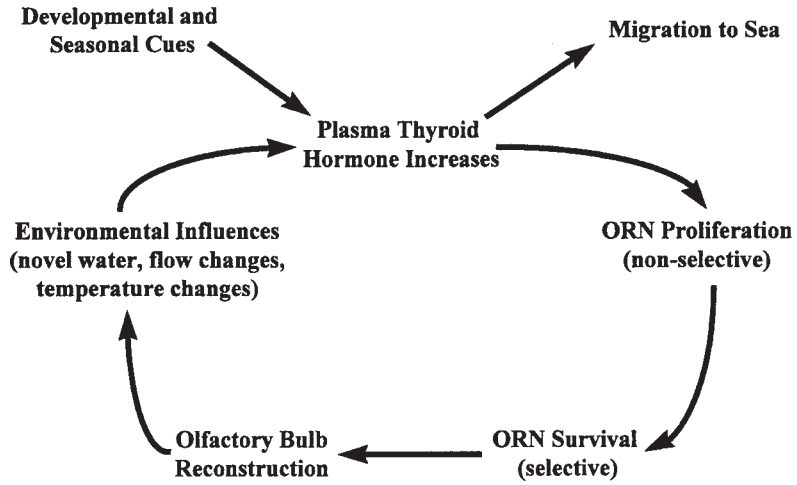

Figure 7. Olfactory plasticity may be driven by surges in thyroid hormone. This hypothetical model illustrates a possible scenario for incorporating environmental influences on early neural development into our model of olfactory imprinting. (ORN indicates olfactory receptor neuron).

This model also carries with it important considerations for conservation of wild salmon runs, particularly with respect to influences imposed by hatchery rearing. Outside of Alaska, Pacific salmon populations have been declining in both number and diversity for the past 100 years despite multi-million dollar investments in hatcheries to ensure their survival.[74,75] These declines can be attributed to a number of factors including habitat destruction, over-fishing, dams, agricultural practices and, indeed, even hatcheries themselves.[74,75] Hatchery-reared fish often demonstrate inappropriate behaviors when released in the wild (e.g. increased aggression in feeding, impaired mating behavior, increased levels of straying). Thus, hatchery practices can have profound ecological and genetic consequences on the hatchery population as well as the wild populations with which they may interact.[74–78] Our growing understanding of the potential for plasticity in imprinting helps us to appreciate that an adult spawning salmon is not simply the product of a genetic stock, but is shaped by the environment in which it is reared. The neural blueprint that is modified through development translates early experience into behaviors expressed later in life — behaviors that may influence the reproductive success of the individual as well as the population. Conservation efforts that ignore this basic tenant may well produce bodies, but do nothing to preserve the reproductive integrity of a salmon run over the long term if plasticity in the neural and subsequent behavioral development of the animal is not appreciated.

The model we present offers a framework for investigating olfactory imprinting in salmon and possibly other systems as well. The mechanisms involved are bound to be more complex than this simple model suggests, but our aim is to offer a conceptual outlook for future investigation, linking olfactory experience during a sensitive period of development to functional reorganization of the olfactory bulb.[79] Artificial odors serve as a useful tool for investigating mechanisms of olfactory imprinting, but they do not simulate the natural environment. Instead, they simplify the system so that we can study its components. And in fact, however unrealistic to the natural experiences of wild salmon in natural river systems, the combination of hatchery rearing and controlled enrichment using artificial odorants has lead to substantial improvements in our understanding of the underlying mechanisms contributing to olfactory imprinting.

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