Smelling to survive

Die Nase vorn

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Introduction

It's spring and the fields are freshly ploughed. There's a very special, pleasant smell in the air. If you've ever experienced such a moment, the smell signifies exactly this situation in your brain. Springtime, open soil, farmland. Maybe you're thrown back in time by a memory you didn't even know you had. Few sensory experiences are as good at recalling earlier experiences as olfactory ones (smell). It seems like the memories are simply lying in wait for the right odour to trigger them once again.

One of the most powerful examples in literature of the memory-unlocking ability of smell is found in the first of Marcel Proust's seven-volume masterpiece *In Search of Lost Time* (Original in French: *À la recherche du temps perdu*). It opens with the sweet smell of Madeleines, miniature sponge cakes, evoking involuntary memories of the author's childhood and adult life. But smell is not a sense that is unique to humans.

All organisms, with and without backbones, from insects to humans, use sensory systems to make sense of their environment and to communicate with each other. During the course of evolution, different species have become more or less dependent on a certain kind of information. Crickets and bats rely heavily on sound waves, dragonflies and humans often put their trust in sight, while moths, pigs and dogs are famous for their keen sense of smell.

As humans are indeed very visual beings, we tend to forget the other senses. Especially our own sense of smell. This is partly because we are less dependent on chemical information nowadays. But there is also something quite primitive about smell. Something we want to avoid. Just think about the lengths we go to in order to disguise our own, natural smells, to cover them with artificial odorants or to prevent them with deodorants. We may think we are less dependent on olfactory information than other species, but we aren't really. Many vital aspects of our lives depend heavily on smells. I will explore why and how in my chapter about the human sense of smell.

For other animals, an acute sense of smell is absolutely vital for survival and reproduction. Back in the 1800s, when the French entomologist Jean-Henri Fabre noticed how huge numbers of male moths were attracted to a caged female in his house, he assumed that odours were involved. We now know that he was on the right track. The male moth can follow the female scent, a trail close to homeopathic concentration given off by the female, making him probably the best smeller of them all.

When salmon returns to spawn in the same river branch where it was born, it uses smell to find its way. Without its sense of smell, it would be lost. So specific are the odours in the water that each river tributary has its own signature. Male dogs are as keen as moths, if not as sensitive, to find the bouquet of a female in heat. Even so, dogs are a thousand times more sensitive to smell than we humans. It's an ability that we've put to good use in many contexts, including for hunting and tracking, for locating earthquake victims and even for diagnosing cancer. For dogs, life is lived much more in a landscape of odours rather than visuals. As such, dogs "see" history as odours, not as visual impressions. Smells linger on and can tell them what happened — or who passed by — long after anyone saw it.

For a long time, birds were believed to have no or a very poor sense of smell. Today, we know otherwise. Vultures can pick up the scent of the distinct molecules emitted from a dead animal from far, far away. While sea birds, such as albatrosses, can smell their way to an ample supply of plankton, which in turn means good opportunities for fishing.

What's even more surprising perhaps is the fact that plants can smell and send odour messages to each other. They also use specific odours to manipulate friends and foes. When a plant is attacked, for instance by moth larvae, it changes its emission of volatiles. These molecules can have two different positive effects for the plant. They warn neighbours of the same species that an attack is going on, so that they can turn on their defence system before the herbivores get to them. The volatiles can also serve as a "call for help" by attracting enemies of the attackers. Your enemy's enemy is your friend, even in the plant world.

In another context, plants have evolved to attract the insects they are dependent on for pollination. Normally, this is a process that is a win-win for both players. Sometimes, however, the plant cheats the insects into doing the job without any payback whatsoever.

From all these examples, it's obvious that most organisms on earth are dependent on odour information to survive and reproduce. Being able to sense your chemical environment allows you to adapt to the surrounding conditions, find a resource or a mate and avoid different types of enemies, toxic substances and disease agents.

Before we can understand how smell works, we need to understand what smell really is. Both smell and taste consist of chemical information. The molecules in a water solution give us taste, while in air they give us smell. For something to smell it has to emit molecules light enough to take flight. A piece of sugar doesn't smell, as the molecules are too heavy to take off. While no one would mistake the molecules escaping from a lemon for anything else. The limonene and citral molecules fly easily towards our nose.

All emitted molecules however are not odours. Only when they can be detected by another organism do they contribute to the smell, for example, of a banana. The number of molecules emitted is impressive. A banana sends out hundreds of different molecules. Only a few of these are indeed odours detected by an insect or the human nose, while all the others are just volatile molecules.

To detect smells, all animals need some kind of detector system. To perform this task a specific part of the nervous system has to make contact with the environment and must be endowed with specific receptors to recognize relevant molecules. Our nose is actually the only place where our nervous system is in direct contact with the surroundings. The nerves hang out into the environment. Well, not quite, as they swim in a sea of snot inside your nose. But still, they are exposed to all kinds of pollutants and dust that enter the nose together with smells. Nerves can, however, neither see nor smell. They need to be equipped with some detectors, so-called receptors, to perform.

To see, humans need only three receptor types to register all visible light. All light consists of a waveform oscillating faster or slower, which gives the impression of different colours. When it comes to smelling, the situation is very different. Every type of odour molecule has a unique chemical property very different from all other molecules. That's why we don't have only three but around 400 olfactory receptors. Otherwise we wouldn't be able to smell the millions of different odours that we can distinguish between. Most receptors can detect a spectrum of different molecules. Their activation is similar to playing a piano. With 400 receptor keys to press, millions of odour melodies can be played.

Once the molecules of smell have been detected by the nerves in your nose, signals travel to a specific area of your brain where information is organized into little balls, glomeruli, of nervous tissue. Each glomerulus receives input from nerves carrying a specific receptor type. This means that the “melody” is translated into a three-dimensional map of activity. This map is read out by the next levels of neurons and in the end transferred to other areas in the brain, such as the hippocampus and the amygdala, where the significance of the odour is encoded and put into context. I will come back to the importance of these areas and the complete system.

Interestingly, the basic architecture of the olfactory system is very similar in most organisms studied (excluding plants). The peripheral nerves with receptors converge on little balls of nervous tissue and finally target specific brain areas. In animals as distinct as flies and humans we see the very same building blocks.

In more or less all animals, the sense of smell thus has a similar architecture even though it no doubt has different evolutionary origins. Convergent evolution has probably made it quite similar all the way from insects to humans. To smell, the nose of all organisms needs to be equipped with some kind of chemical detectors: neurons that are able to detect different kinds of molecules in the air (or for fish in the water). This detection and identification of molecules happens in olfactory receptors residing in the membrane of the smell nerves, the olfactory sensory neurons.

The receptors consist of proteins traversing the membrane of the neuron seven times and thereby forming pockets and folds, where the smell molecules can fit like keys in a lock. When a key fits, it unlocks a cascade of neurochemical events called a transduction cascade, which in the end causes the neuron to react electrically. This signal can then travel via the neuron’s axon to the first olfactory station of the brain.

But before we move into the brain, let’s look at the microenvironment around the olfactory sensory neurons. In the noses of all mammals, birds and other land-living vertebrates, the neurons hang out straight into the air. This is the only place on our body where neurons are actually directly exposed to the environment. The nose has therefore been equipped with a protective mucus layer surrounding the exposed neurons. In insects and other arthropods, the neurons have been encased into small hairs on the antennae and the palps (the insect noses). Each little hair also contains mucus. This mucus has about the same composition as seawater but with a lot of proteins added, making it thick and less prone to evaporate. These proteins also help in dissolving fatty molecules in the nose’s ocean water.

From antennae and the nose, the olfactory sensory neurons project their axons to the olfactory bulb (vertebrates) or the antennal lobe (arthropods) of the brain. In all the animals described here, these primary olfactory brain centres have a more or less similar architecture. The axons of the nose neurons find their way to little balls of nervous tissue called glomeruli. Each olfactory sensory neuron type, expressing a specific type of olfactory receptor, target one little glomerulus of the bulb/lobe. This means that when neurons in the nose or the antennae are activated, a map of activity will be painted over the glomeruli. In insects we typically find 50-500 glomeruli, while a mouse, for example, has around 2,000 and a human even more.

Within the olfactory bulb or antennal lobe some information processing is going on thanks to widespread local neurons shuffling information from one little ball to the other, allowing the input from different types of odours to affect each other. In the end, the processed message leaves the lobe/bulb via neurons targeting higher brain areas involved in perception, memory, decision-making or other cognitive processes.

What about all the odour messages flowing between and within species? Well, there is special terminology for all these semiochemicals. You will find these repeated in many of the chapters, but let’s take a quick look at them here first.

An odour that is sending a message between individuals of the same species is called a ***pheromone***. A typical example is when a female dog in heat sends out an odour message that calls on every male dog in the vicinity and the message is: “Come mate with me!” You will see many examples of pheromones in the coming chapters.

The remaining semiochemicals send messages between species. They are typically divided into categories depending on who benefits from them, the sender or the receiver. If the receiver benefits, they are called ***kairomones***. A typical example would be the odour given off by a prey animal, for example a mouse, and picked up by a predator, often a cat.

If the smells benefit the sender, they are called ***allomones***. Any kind of lure would fall into this category, but it would also include a defence mechanism, such as a skunk sending out a stinky spray to fend off an enemy.

Finally, an odour message can also benefit both parties. In this case, it is called a ***synomone***. The classic example here is the smell of insect pollinated flowers, where both the flower gets pollinated and the insect receives a reward in the form of nectar and pollen.

All the information we as humans have gathered on how the sense of smell works, which molecules are involved and which types of behaviours are displayed in response to these, allows us to design different strategies to assist us in different ways. Today, electronic noses play an important role in disease diagnosis, security checks and surveillance of environmental pollution. No one can avoid the huge industry involved in inventing new and alluring odours for us to apply over our bodies. When the pig breeder wants to inseminate the sow, he buys synthetic boar pheromone to get her in the mood. Insects of many different kinds are managed using pheromones and plant odours.

In this book, I will use different examples from the world around us to describe the fascinating world of smells. An understanding of our own olfactory system, its function and its architecture, provides an important basis before we venture out into all other systems. In a number of chapters I will tell captivating stories emerging from my own and my colleagues’ research. The stories will cover different animals but will also look at how plant smell affects our environment. I will begin by exploring how climate change might affect the ecology of smell — and will end with an overview of how humans make use of all our knowledge on smell and odour-guided behaviours to our own benefit.

Chapter 1 | Smelling in the Anthropocene

If you were walking down the road 1,000 years ago your sensory experience would probably be quite different to the one you have today. Looking around you in 1021, you would see no cars, airplanes or ships. Maybe not even a proper road in the modern sense of the word. Undoubtedly, the world would be a whole lot quieter, almost silent perhaps. These are our impressions from sound and vision, but what about from our sense of smell?

There are so many levels to the sense of smell. Do we and our environment smell different(ly) today compared to a millennium ago? Or even 100 years ago? How exactly have the scents in our surroundings changed over the years? How have we humans contributed to this changing smellscape — the complex landscape of odours and aromas around us? Have our own smells and perception of odours changed along the way? How have our activities affected our capacity to smell? What actions are to blame for bringing about such changes in both humans and animals?

Well, for a start, in 1021 you couldn't expect to get a whiff of a car exhaust or a stink from the local water treatment plant. You would not be exposed to synthetic odours either: perfumes, deodorants or that new car smell, for example. Even natural odours might have been different.

Ever since humans started colonizing Earth's every corner, we have found ways to change, manipulate and exploit our environment. To name just a few: we have cut down forests, planted crops, exterminated both plants and animals and industrialized the world. This new geological epoch, where the world has been changed dramatically through human activities, is often referred to as the Anthropocene.[1]

A clear definition of the exact time span of this period is still disputed. Suggestions for its starting point range from the onset of the agricultural revolution, around 10,000-15,000 years ago, to just after World War II, a period defined by nuclear tests, the post-1950 Great Acceleration and the accompanying dramatic socioeconomic and climate changes.

Whichever scale we choose, it's clear that humans have had immense impact on this planet in general, but also on every breath we and other animals take. As well as on the very molecules contained in each of those sniffs.

Our changing smellscape

Let's consider natural smells first, and how they might have changed. A thousand years ago, nature was still quite unaffected by humans. Many species of plants and animals coinhabited fields and forests. Flowers were abundant. Pine and spruce were mixed with many species of deciduous trees. The keyword was diversity. As time went by, humans cut and burnt down forests and transformed flowering meadows into farm fields. All these changes allowed the great spread and multiplication of the human race. At the same time, they altered the smellscape around us profoundly.

Instead of diverse, mixed-species forests, we got large-scale, single-species tree cultivations. In the same way, smells were simplified. Take for instance the scent of a modern spruce forest compared to an old mixed stand. If you get the chance, try making the comparison yourself the next time you're out there in the woods.

In parallel, the same simplification has been underway in the fields. What were once great mixes of species have become huge monocultures. The US prairie turned into never-ending corn and wheat fields. European meadows have gone the same way. When contemplating the so-called natural odours around us, the smellscape has, already, gone through a pronounced change. How so?

The disruptive role of CO2

When we drive or fly or operate our industries, we emit many substances that also tend to affect the climate and the molecules carried in the atmosphere. One of the most publicized changes associated with the Anthropocene is an increased level of environmental CO_2, which contributes to the greenhouse effect, the dramatic shift in world temperatures, increased acidity of our oceans and the overall destabilization of our climate.[2]

Although CO_2 is a rather non-reactive compound with no direct chemical impact on odours in the atmosphere, ambient CO_2 can modify plant emission of volatile compounds. This happens through physiological changes within the plant. Carbon dioxide can increase a plants' photosynthetic activity, by reducing water consumption and by changing the chemical composition of the plant tissues.[3] Variations in CO_2 levels can also affect the ability of insects to locate their hosts. Moths track CO_2 bursts at flower openings to locate their nectar sources. Impaired flower targeting in elevated CO_2 therefore impacts both pollination and pest infestation.[4]

Elevated backgrounds of CO_2 reduce the ability of a mosquito to locate a blood host, as CO_2 is one of the major olfactory cues used by mosquitoes in host detection (see Chapter 9).[5] This might be considered a benefit from a human perspective, but there are downsides.

From an evolutionary perspective, the rate of mosquito speciation has been shown to increase dramatically during periods of elevated levels of atmospheric CO_2.[6] This increased speciation rate may have been driven by the reduction in the CO_2 host signal quality, which has led to other, more specific, smells to function as potential isolating mechanisms between new species. As such, the projected rise in atmospheric CO_2 from anthropogenic activity has important implications for human health, and potentially pollination efficiency, arising from changing insect abundance and distribution.

On land, the outlook is grim. At sea, it's just as bad. CO_2 dissolves in the oceans, forming carbonic acid, which makes the water more acidic.[7] Studies have also shown that acidic water disturbs the sense of smell in marine organisms. Whether they use this sense to detect and avoid predators, to locate food or to track down a mate, a lower ocean pH is likely to disrupt marine life considerably and make these tasks more difficult.[8] It's not yet known whether the marine ecosystem and the food web can adapt to these changing conditions.

Gases galore and shifts in temperatures

Unlike CO_2, ozone and NOx can directly affect odour blend composition due to their oxidative power. Recently, both pollutants have increased in the atmosphere, and are expected to increase even further.[9] With increasing amounts of these pollutants, the odour blends insects use to locate food, hosts or oviposition sites are ever more likely to change. While each of these aspects has individual effects, interactions among them will also result in other effects, too.

NOx gases are produced whenever we burn different kinds of fuels. They are health hazards per se, but they also cause acid rain and smog. Nitrous oxide, known as laughing gas, also adds to global warming. Methane is produced in many natural processes, including the frequently cited cow farts and burps. But now it is also being released from the thawing tundra, ecologically the coldest of all the biomes, further adding to record high temperatures.

Ozone in the upper atmosphere forms a natural protective layer around the Earth, shielding us from sun radiation. At ground level, however, it is the main constituent of smog. It’s formed when sunlight interacts with different types of emissions from human activities.

On top of all these different gases, we pile on many types of herbicides, fungicides and insecticides to control problematic weeds, fungi and insects. These chemicals have been shown to affect olfaction. And finally, human activities tend to release metal ions that can have a direct impact on the olfactory senses.

Shifting air and sea temperatures are key features of the Anthropocene. Will they influence the way we smell the world? While increased ambient temperature could directly affect odour composition, as the amount of each compound in a blend is a function of its volatility, it could also indirectly upset the physiological response of both the emitter and the receiver.

The insect world

In recent years, considerable attention has been raised by studies revealing that we are losing our insects. In some areas of Germany, for instance, insect biomass has decreased by more than half.[10] Such a dramatic change in our biotic environment has some pretty severe consequences for humans. Bee populations are dwindling, which means that fruit trees are not pollinated, and no honey is produced. Bumblebees are also negatively affected, as are several other beneficial insects.

What’s more, as insects form the staple food for many of our birds, these creatures are also suffering from a food shortage. Could this decrease in insect numbers be caused by gas and pollutant effects on olfaction and odours? This seems, at least partly, to be a possibility. In several studies of different systems, it has been shown that the gases we emit cause smells to change.

Let’s take insect pollination as an example. Over millions of years, co-evolution has fine-tuned the interaction between flower and insect for the benefit of both (well, most of the time — see Chapter 13). Flowers have a visual appearance that insects use for more long-distance orientation, while floral bouquets guide the insects on their final approach. When all of this works out, the plant gets pollinated and the insect gets rewarded in the form of nectar and pollen. Still, we’re talking about a vulnerable system. We were able to show just how vulnerable by removing the most intimate smell interaction between flower and insect (see Chapter 7 on moths for more details of this research).

If floral scent disappears, no pollination takes place and no nectar is removed. Because of the delicate nature of this system, however, the smell doesn’t need to disappear entirely to disrupt communication. It might only need to change. And this is what we see happening after pollution with gases, particularly with ozone.

The ozone effect

Ozone has a very strong oxidizing effect. This means that it causes chemical reactions in other molecules. In my lab we carried out an experiment where we let tobacco sphingid moths fly towards a specific flower in the wind tunnel. First, we replicated current conditions found in nature, and the moths easily located the flower and both pollination and nectar feeding took place. Then, we placed the flower under elevated ozone levels and observed the moth behaviour again. The insect was clearly disoriented and failed to locate the flower. When we analysed the molecules emitted by the flower it turned out that several of them had changed to something else with a very different smell.

Exposure to an ozone level that already exists during warm days in some parts of the world had a disruptive effect directly on the pollination services provided by the insect. We continued our experiments to see if some plasticity in the insect system could ameliorate the effects of the ozone and this was indeed what we found.

If a moth was provided with the “new” floral scent along with strong visual guidance, a single experience of the new smell together with a nectar reward was enough for the moth to learn to fly towards the ozonated smell and use it for future feeding.[11] As Ian Malcolm says in *Jurassic Park*: “Life finds a way.”

Most examples, however, reveal detrimental effects of high ozone levels on the pollination services of bees, bumblebees, moths and others. The same also holds true for other gases, such as diesel exhaust.[12] It is therefore clear that we should do our utmost to limit the emissions of these gases and preferably decrease them substantially.

In another study, my colleague Geraldine Wright investigated the effects of “modern” pesticides on bee pollinators. Neonicotinoids are the most used insecticides in the world and are less harmful to birds and mammals than the old carbamates and organophosphates. Lower levels were also supposed to be less harmful to the beneficial bees. However, when Geraldine looked at olfactory learning in honeybees that had been exposed only to very low concentrations of neonicotinoids it was clear that they were severely affected.[13] Again, the olfactory communication and underlying abilities were impeded by human interventions.

The role of temperature fluctuations

Temperature also affects the life of insects. A higher temperature will make all smell molecules evaporate a lot faster and everything might smell a bit more. As insects have no thermo-regulation — they lack the ability to maintain a stable body temperature — their physiological functions are often finely tuned to the ambient temperatures of their habitat. Their sense of smell is no exception. A desert-living beetle might have an optimal function at 40°C, while my own recordings from smell neurons in the antenna of winter moths show that these have a temperature optimum of around 10°C. When you reach 20°C the system hardly functions anymore. This means that an ever-increasing temperature caused by climate change will have a direct effect on the sense of smell of insects and probably in many other “cold-blooded” animals, too.

A rise in temperature also allows insects to invade new areas of the world. Even though the spread of the insects is not directly connected to olfaction, it is clear that several notorious odour-guided insects are experiencing a boom. In Chapter 9 you will read about the malaria mosquito. This is only one of many species spreading diseases over the world. Right now, we see them invading new areas, including Europe and North America. More recently, the mosquito-borne Zika virus has spread into southern USA from South and Central America, thanks to the spread of *Aedes* mosquitoes. Other diseases, such as West Nile virus and chikungunya, are also on the spread as new areas open up for the vector mosquitoes.[14]

In Chapter 10 you will learn about the smell life of bark beetles. Only a decade ago these beetles produced one generation of offspring, which meant that each female could produce 60 beetles in a year. Now, we have up to three generations in central Europe, which means that a single female can see 3,000 beetle offspring going into hibernation after killing a large number of spruce trees.

Insect research ahead

Clearly, more research is needed to investigate what is going on. In an attempt to understand exactly how the Anthropocene is influencing the smell life of insects I initiated the Max Planck Center next Generation Insect Chemical Ecology (nGICE for short) to focus specifically on this area. It involves linking and teaming up experts in this broad field across three different institutions: my own Department of Evolutionary Neuroethology at the Max Planck Institute for Chemical Ecology in Germany, the Swedish University of Agricultural Sciences and The Pheromone Group at the Department of Biology at Lund University, also in Sweden.

Our common goal is to uncover how climate change, greenhouse gases and air pollution influence and impact the chemical communication between insects. We want to understand how insects adapt to these changes in their environment. Our aim is to contribute to solving global problems in the context of climate crisis, global nutrition and combating diseases.[15]

Smelling plastic

In 1907, in New York, Leo Baekeland, a Belgian chemist, invented Bakelite, the first plastic made from synthetic components. Since then, the production of plastic has taken on enormous proportions. We have now reached a world output of an estimated 360 million tonnes per year. Why does this matter to olfaction?

As we will see in Chapter 4, birds use their sense of smell for several reasons. For pelagic birds, one important feature of their noses is the ability to smell dimethyl sulfide (DMS). This is a compound emitted by crushed phytoplankton, often when consumed by zooplankton. For birds, the presence of this sulphur gas is therefore a telltale sign that plenty of food is around.

Unfortunately, relying on this molecule to find food also creates a problem in this plastic age. When plastic has been floating in the water for a couple of months it starts to release DMS — deceiving nature into believing it is edible in the process.[16] The UN Environment programme states that we pour around eight million tons of plastic into the oceans of the world each year[17] — quite possibly adding up to a total of over five trillion macro and micro pieces of plastic (and counting…), there's plenty around to confuse sea life. Birds mistakenly eat the plastic, which clogs their digestive systems and ultimately kills them. This is the reason why an estimated one million seabirds die each year — because their stomachs are full of our plastic debris.

Not only the birds have developed the capability to use DMS to find food in the ocean. Both seals and whales (see Chapter 5) are very likely to use the same strategy, exposing themselves to the very same plastic dangers. In one study of baby turtles, 100 per cent of these tiny creatures had plastic in their stomachs.[18] Our immense production of plastics for many single-use-and-throw-away purposes has created such severe environmental repercussions.

In the Great Pacific Garbage Patch (one of five “garbage patches” identified in our oceans), currents and winds accumulate our discarded debris (including plastic and discarded fishing gear) into an area roughly twice the size of Texas — or three times the size of France if you prefer a European scale.[19] Its surface is largely covered by microplastics. These microplastics, studies suggest, may already outnumber zooplankton — and have definitely already made their way down to the Mariana Trench, the deepest spot in our oceans.[20] You can imagine what this trend is doing to birds and other sea-living creatures attracted by the smell.

A sea change in smell

Of course, on top of the airborne smell of DMS that affects birds and animals, there is also manmade chemical pollution spreading through our waterways, oceans, lakes and rivers. Fish, crustaceans and other aquatic creatures are living in a soup of manmade molecules, where some are devastating for them and their ecological system.

Just as in our own system for smelling, fish olfactory sensory neurons are directly exposed, in their case to the surrounding water and everything dissolved in it. Take copper. Studies have shown that increased copper concentration has a direct detrimental effect on the function of fish smell neurons, and likewise on shore crabs and crayfish. Chronic exposure to elevated levels of copper disrupts normal, odour-directed behaviour involved in mating and foraging.[21]

When we protect our crops, we spray pesticides of different kinds that sooner or later find their way to water streams. Most of us with gardens will have at some time or other used glyphosate-based herbicides against weeds. This compound, when tested in concentrations occurring in nature, prevented fish from finding food and directly affected the function of the nose in Coho Salmon.[22] Many other chemicals affect fish behaviour directly. As salmonid fishes of different kinds are extremely important economically, the effect of pesticides has been investigated in depth for many more of these. Both sexual behaviour and homing (see Chapter 5) have been shown to be influenced by a host of the industrial chemicals we use in agriculture and forestry. Interestingly, behaviour was also influenced by cypermethrin, which is used to protect salmons from copepod salmon lice in the fish breeding industry.

Another good example is 4-nonylphenol (4-NP), which is used as a ubiquitous surfactant both in industry and in sewage treatment plants. Today, this chemical is found in more or less every body of water over the globe. When scientists exposed social fish species to 4-NP concentrations equal to that found in nature, the effects were quite drastic. The fish stopped responding to pheromones mediating schooling and instead displayed opposite behaviours. The 4-NP pollution evidently has a direct effect on behaviour vital to both predator avoidance and feeding.[23]

Looking at all the numerous chemicals we produce and the different ways they add to nature’s natural chemical diversity, it’s clear that fish and other water animals suffer heavily from them. One way is through the direct and indirect effects on their olfactory life. Sometimes the pollutants just seem to destroy the ability to smell, sometimes they affect smell-directed behaviour indirectly, for instance via the hormonal pathways.

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Chapter 1 | Smelling in the Anthropocene

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