[Review Essay] Animal Worlds after Uexküll: Ed Yong. *An Immense World: How Animal Senses Reveal the Hidden Realms Around Us*. New York: Random House, 2022. 449 pp.

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Ninety years after the publication of Jakob von Uexküll's *Streifzüge durch die Umwelten von Tieren und Menschen* (*A Foray into the Worlds of Animals and Humans*), in which the German-Estonian biologist developed the concept of the Umwelt to theorise about the perceptual or experiential worlds of animals, science writer Ed Yong has used the idea of Umwelten as a foundation for this well-designed, extensively researched, and vividly written book on animal senses – and on how they allow creatures of many different sorts to navigate their surrounding environments. Drawing on the multitude of studies on vertebrate as well as invertebrate animal species that postdate Uexküll's original account – studies from fields as diverse as sensory biology, behavioural ecology, neuroscience, animal communication, comparative physiology, and parasitology – Yong retunes the Umwelt concept in light of more recent work on the evolution, structure, and functions of animal senses. The author also uses a wider variety of case studies than those Uexküll originally considered, discussing animals ranging from (among many others) ants, scallops, and spiders to bats, moles, and manatees, not to mention domesticated species such as dogs and megafauna like elephants and whales. In the process, Yong provides a comprehensive overview of available hypotheses concerning these animals' modalities of experience, the more or less divergent perceptual worlds to which different creatures' sensory equipment gives them access. He thereby models how, by engaging in imaginative leaps restrained by a commitment to evidentiary support and interpretive humility, humans might breach the boundaries of their own Umwelt, or at least make speculative forays beyond its limits. Yet the author's account also raises broader questions about the 'hidden realms'

mentioned in the title. Relevant questions concern the ethical entailments of the Umwelt concept, not least when it comes to using animals in scientific research on other-than-human sensory capabilities; the experiences of individual animals vis-à-vis claims about the perceptual capacities of species or groups taken as aggregates; and, relatedly, the role of fictional discourse and the arts when it comes to understanding and engaging with animal worlds.

Noting how Uexküll's ideas influenced later work on embodied minds – that is, on the way physical embodiment shapes intelligent behaviour – Evan Thompson has characterised an Umwelt as 'a body-oriented world of perception and action' (59). It is, in other words, a way of describing the world as it presents itself to an animal given its specific organismic structure and corresponding sensorimotor capabilities (Thompson 59; see also Clark, 24-25). In accordance with this insight, much of Yong's book is devoted to detailing the physiological structures supporting the diverse sensory capacities and associated modes of world-creation and -navigation that have evolved across the animal kingdom. With the Introduction spelling out the Uexküllian inspiration for the study, while also taking stock of the difficulty of attempting to step inside other animals' Umwelten, Chapters 1-11 are organised by sensory modalities, from smell and taste to vision, touch, hearing (including echolocation), and the use of electric and magnetic fields. Each of these chapters features clusters of animals for whom the focal modality is a primary (though not an exclusive) means of building and inhabiting perceptual worlds. Chapter 12, returning to the idea of the non-exclusiveness of the senses, uses octopuses as a case study in how animals unite multiple perceptual channels for purposes of Umwelt creation. The final chapter reviews negative human impacts on more-than-human worlds, focusing specifically on light and noise pollution. Endnotes keyed to individual passages direct readers to a very full bibliography, with footnotes in the body of the text being used to define terms, clarify claims, or enrich the author's discussion with historical or other background. In general, although he does not shy away from offering technical details of the scientific studies on which he bases his account, thereby inviting readers to embark on further explorations of the animal worlds evoked over the course of the book, Yong writes in a lucid, accessible style throughout and avoids assuming prior knowledge of zoology, evolutionary theory, or related fields.

Chapter 1 encompasses both the sense of smell and the sense of taste. The chapter opens with a comparison of dogs' and humans' capacity for smell, reporting what happens when Yong visits the research lab maintained by psychologist Alexandra Horowitz: 'As I look around, Finn [Horowitz's dog] smells around' (17). Here the author establishes a key theme that is further developed in many of the chapters: the pre-eminence of vision in the sensory worlds of *Homo sapiens*, and the need to recognise the bias that a heavy reliance on vision may introduce when humans attempt to imagine Umwelten organised around other sensory modalities – or for that matter, other-than-human ways of seeing. In the present instance, whereas humans 'can explore new scenes by subtly moving our heads and eyes', 'nostrils-first' explorers like Finn, though their movements may seem random and therefore aimless, are in fact following trails of scent; they will often examine 'vents, door cracks, and other places where moving air imports new odorants' (17). Furthermore, there is a temporal dimension of scents that must be taken into account. In contrast with light, smells linger even after their cause or originator has departed, and conversely they can also be used to predict future events, as with the smell of smoke from an approaching wildfire. For super-smellers like Finn, in addition to assessing the present, detecting the past, and divining the future, given that 'Animals are leaking sacks of chemicals, filling the air with great clouds of odorants', it is possible to use scents to read creatural biographies, by tracking their 'presence, identity, health, and recent meals' (21).

As these passages suggest, the author is a vivid describer of animals' exploratory behaviours. But what is more, he is a skilled explainer of the bodily structures that account for how, and why, animals come to rely on a particular sense modality in a given case. Thus, offering a capsule summary of the physiology of canine olfaction, Yong notes that humans have the same basic machinery, but with a key difference:

> [The neurons, odorant receptors, and other structures making up dogs' olfactory] hardware is packed off into a separate compartment, while ours is exposed to the main flow of air through our noses. This difference is crucial. It means that whenever we exhale, we purge the odorants from our noses, causing our experience of smell to strobe and flicker. Dogs, by contrast, get a smoother experience, because odorants that enter their noses tend to stay there, and are merely replenished by every sniff. (19)

Here emerges an expository pattern exemplified by the rest of chapter 1 and used throughout the book. The pattern involves oscillating between, on the one hand, a focus on imagining the experiential texture of animal worlds, often via insights gleaned from descriptions of observed behaviours, and, on the other hand, an emphasis on explaining the physiology, or biomechanics, giving rise to such textural detail. And there is a third element in this pattern: not only describing-imagining and explaining but also using evolutionary theory to contextualise the contrasting worlds available to different kinds of creatures – by grounding those worlds in different ecological niches and corresponding survival needs. As Yong puts it later in the book, 'The first step to understanding another animal's Umwelt is to understand what it uses its senses *for*' (61).

All three elements of the pattern are in play in chapter 1 as Yong discusses the role of pheromones in the animal kingdom, with a special focus on ants and elephants; cites evidence undermining the falsehood, influentially propounded by John James Audabon, that birds have no sense of smell; and notes that rattlesnake tongues, despite ingrained associations of tongues with taste, in fact serve an olfactory function, with each flick of the snake's tongue being the equivalent of a sniff. Thus, among clonal raider ants, all communication is via odorants known as pheromones, or chemical signals that carry standardised messages between members of the same species (30). Different categories of these signals explain different observed behaviours of the ants, from the lightweight chemicals that are easily aerosolised and can therefore summon large groups of workers, to the medium-weight pheromones that are slower to become airborne and can hence be used to mark trails, to the heaviest chemicals, known as cuticular hydrocarbons, that function as 'identity badges' used by ants 'to discern their own species from other kinds of ants, nestmates from other colonies, and queens from workers' (31). In turn, evolution provides an overarching context for these behavioural-pheromonal correlations. As a group of specialised wasps that evolved between 140 and 168 million years ago, ants shifted rapidly from a solitary to a highly social existence, acquiring, in the process, a large repertoire of odorant receptor genes. It therefore stands to reason that the insects' olfactory equipment, and their associated smell-driven worlds, took shape when ancestral ants began living in colonies for the first time and needed to be able to recognise their nestmates. Chapter 1 closes with a comparison of taste with

smell, the former of which is innate while the latter is 'sculpted through experience'. Across species, whereas smell involves extraordinarily complex processing routines on the part of the nervous system and can be put to indefinitely many uses, 'taste is almost always used to make binary decisions about food. Yes or no? Good or bad? Consume or spit?' (48). The general function of taste, if not the array of food preferences, thus marks a point of partial convergence among Umwelten.

Chapters 2 and 3 shift the focus to vision. There is, it turns out, a 'smorgasbord of eyes' across the animal kingdom, bringing with it 'a dizzying medley of visual Umwelten' (56-57). For one thing, animals have widely differing degrees of visual acuity. These differences can themselves be an obstacle to imagining perceptual worlds across species lines because humans, with their relatively sharp vision, may incorrectly assume that if they can see something, other creatures can as well (63). Certain animals, like scallops, the kind of molluscs known as chitons, fan worms, and giant clams, seem to have a type of distributed vision that involves 'seeing without scenes', as Yong puts it. Instead of experiencing a continuous, movie-like stream of images, at least some of these animals may use their eyes in a manner that is analogous to how humans use the sense of touch, as a kind of whole-body early-detection system that allows them to take defensive measures against potential threats (67-68). Other animals have visual fields that are structured differently from humans'. Thus, whereas for humans 'seeing is synonymous with facing, and exploration is achieved through gazing and turning' (70), birds' side-facing eyes mean that they don't have to turn to look at something. Similarly, given that the visual fields of many animals that live in flat habitats, including cows, rabbits, fiddler crabs, red kangaroos, and water striders, cover almost 360 degrees, they have a view of the entire horizon all at once. The killer fly (*Coenosia attenuata*), for its part, has ultrafast vision. Equipped with photoreceptors that send electrical signals to their brains far more rapidly than do the photoreceptors in human eyes, the flies' vision also updates so quickly that even our fastest actions must seem languid to them – meaning that 'An open palm, moving with lethal intent, would be easily dodged' (76). Still other animals can see in the darkness of the terrestrial night (the sweat bees of the Panamanian jungle) and the bathypelagic or midnight zone of deep-sea environments (the giant squid).

Building on the species-specific biomechanics and experience of visual worlds outlined in chapter 2, chapter 3 shifts to the question of how (and whether) different creatures' photoreceptors, neurons, and brains turn different wavelengths of reflected light into the sensation of colour. Yong distinguishes among monochromats (sloths, raccoons, sharks, whales, cephalopods like octopuses), whose retinas are not set up for colour vision; dichromats, who have two classes of photoreceptors with outputs tuned to different wavelengths that can therefore be compared, yielding the simplest form of colour vision (dogs, horses, early primates); trichromats, who have inherited an extra copy of a gene that allows for the perception of light at shorter wavelengths, adding reds and greens to the mix of blues and yellows visible to dichromats (the monkeys and apes of Africa, Asia, and Europe descended from the first primates, a group that includes humans); and tetrachomats, including hummingbirds and *Heliconius* butterflies, who can see not just a wider spectrum of colours than humans but wholly different dimensions of colour – potentially hundreds of millions of colours of which *Homo sapiens* may be able to see only around 1 percent. Relevant, in this last connection, is the research on ultraviolet ('beyond violet') light initiated in the 1880s by John Lubbock. Made up of wavelengths ranging from 10 to 400 nanometres, this light cannot be seen without UV-sensitive photoreceptors, which were initially thought to be rare among animals. It turns out, however, that humans are the exception when it comes ultraviolet vision, which is 'so ubiquitous that much of nature must look different to most other animals' (93-94). For instance, because of UV patterns in their feathers – patterns invisible to most humans – male and female blue tits look different from each other to the birds themselves, while reindeer use the UV-reflecting properties of snow to spot partially snow-covered mosses and lichens, which do not reflect light at this wavelength. The chapter concludes with an extended case study: the mantis shrimp, a species that has more classes of photoreceptors covering the ultraviolet spectrum than humans have photoreceptors in total (104-16).

As with smell and taste, Yong makes use of evolutionary theory to contextualise these visual ways of worldmaking. DNA analyses suggest that colour vision first arose some 500 million years during the Cambrian explosion of animal types, when the ancestors of modern animals developed neural mechanisms needed to identify predators in the shallow water near

shorelines where they evolved. In such environments, monochromats would have had trouble detecting shapes against the fluctuating illumination caused by the waves and ripples focusing solar rays in complex patterns. By contrast, colour vision helps animals compare objects across different conditions and thereby 'stabilize [their] view of a world where light dances and flickers' (88). Along the same lines, scientists have argued that trichromats would have had a distinct evolutionary advantage over animals with mono- and dichromatic vision when it comes to identifying red, orange, and yellow fruit against the green foliage of rainforests, and for that matter the most nutritious rainforest leaves. The converse evolutionary argument can also be made. Because eyes, like all sensory systems, require significant resources to build and maintain, if their cost outweighs their usefulness for a given creature, they may very well disappear. As a result, 'In underground realms, in caves, and in other dark corners of the Earth where vision cannot earn its worth, eyes are often lost' (78).

The next four chapters concern feeling and touch, with chapter 4 discussing 'The Unwanted Sense', or animals' capacity to feel pain, chapter 5 sensitivity to heat, chapter 6 the physiological hardware and neural software of touch, and chapter 7 the sensory worlds bound up with surface vibrations, which constitute a sort of bridge between touch and sound, the topic of both chapter 8 and chapter 9. I return to the issue of pain below, focusing for now on some of the more striking details from the other chapters just mentioned.

As Yong notes in chapter 5, all living things are in search of a 'Goldilocks zone' where the temperature is neither too cold nor too hot, with animals' nervous systems being designed to help them find that zone by sensing and responding to temperature. The author describes a number of 'extremophiles', or creatures that thrive at extreme temperature limits. The Saharan silver ant, for example, forages in temperatures approaching 130 degrees Fahrenheit, whereas the lifelong habitat for ice worms is glacial ice. Yong cautions readers not to project discomfort onto such creatures, by assuming that humans' sensory limits apply to them as well. The temperature-inflected sensory worlds of animals in everyday environments are also worth taking into account, because they, too, diverge from what might be assumed to be a cross-species benchmark or norm. An experiment involving fruit flies showed that the insects can use minute differences in temperature to make extraordinarily rapid decisions about direction of

movement, and that they execute mid-air U-turns when hitting the edge of a hot air mass. Yong comments: 'I suddenly reconsider the movements of every fly I've ever seen. Their paths, which always seemed so random and chaotic, now take on an air of purpose, as if the insect is threading its way through an obstacle course of hot and cold that I can't perceive, don't care about, and oafishly wade through' (140-41).

Chapter 6 begins with an account of the sensitivity of sea otters' paws, grounding the biomechanics of touch, for this as well as other species, in a brain region called the somatosensory cortex. As Yong notes, 'Different sections of [this region] receive inputs from different parts of the body, and the relative size of these sections can hint at an animal's major tactile organs' (157). In humans, sections linked to the hands, lips, and genitals are largest, whereas for other species it may be whiskers (mice), bills (platypuses), or even teeth (naked mole-rats). Case studies discussed in this chapter include the star-nosed mole, with 'a nose that works like a hand and scans like an eye' (165); duck species, including mallards and shovelers, that use mechanoreceptors in their bills to find food in murky or muddy water; and birds and insects equipped with a sensing capacity that has been termed remote touch, which enables them to detect objects and gauge textures beyond the physical range of their bills or stingers. Some mammals, including mice and rats, sweep their whiskers back and forth as they move (an action known as 'whisking') in parallel with the way humans sweep their eyes over a scene, while pinnipeds such as seals can use their whiskers to track the hydrodynamic wakes of fish. Other species that rely heavily on the mechanical sense of touch, in contrast with the chemical senses of smell and taste, include fish equipped with neuromasts, part of a system of sensors (known as 'the lateral line') that allows them to detect obstacles distorting the 'flow field' around their bodies; crocodilians whose bumpy sensors on the edges of their jaws enable them to detect movements and vibrations in water; and tiger wandering spiders, whose legs are covered in hundreds of thousands of tiny hairs that can pick up on air disturbances caused by approaching flies.

Surface vibrations have been largely ignored up this point, even by scientists who study animal senses. Yet one investigator, who has compiled a library of amplified recordings created by attaching microphones to the base of plants inhabited by insects, estimates that some 200,000

insect species communicate through such vibrations. Sand scorpions and spiders, for their part, use surface vibrations to capture prey, with the orb web of the *Nephila* spider, for example, functioning as what Yong describes as a surveillance system and the Japanese orb-weaver *Oclonoba sybotides* even 'outsourc[ing] the decision about which prey to attack to its web' (208). But it is not just insects who use surface vibrations for world-building purposes. So too do moles and elephants, as may have other elephant-like creatures who once roamed the planet in large numbers, before being (mostly) wiped out by the ancestors of current-day humans.

Chapter 8, 'All Ears: Sound', begins with a comparison of hearing and touch as mechanical senses. Both senses detect movements in the outside world by using receptors that send electrical signals when they're bent, pressed, or deflected. In touch, such movements occur when fingertips, paws, bills, or whiskers are pressed against or slid across a surface; in hearing, the movements occur 'when sound waves reach the ear and deflect small hair cells within it' (214). Yong's first case study is the barn owl, the structure of whose ear mirrors that of the human ear. But whereas humans' outer ears are small, fleshy flaps, all of the feathers covering the owl's 'facial disk' act like a radar dish that collects incoming sound waves and funnels them toward the bird's ear holes, which are extraordinarily large. The owl's eardrum and cochlea are also disproportionately large, and because their ears are uniquely asymmetric, the owl can use the resulting differences in timing and loudness of incoming sounds to work out, more accurately than most land-dwelling animals, the position of the sounds' source. More generally, hearing can provide information about more or less distant events; it can also operate in the darkness and through opaque barriers (unlike sight), does not require a surface (unlike vibrational sense), and functions at the speed of sound (in contrast with the slower diffusion of molecules in the case of smell).

Titled 'A Silent World Shouts Back', chapter 9 continues the author's discussion of sound. More precisely, the chapter considers echolocation, which Yong describes in his Introduction as animals' most impressive use of the sense of hearing. The author begins with a profile of a bat named Zipper, who is a member of one the two groups of animals that have 'biological sonar', the other group being toothed whales like dolphins, orcas, and sperm whales. Donald Griffin, who coined the term echolocation, showed that bats exploit their biosonar both

to navigate and to hunt. Thus, when the bat opens her mouth and emits a stream of short, ultrasonic pulses from her mouth, she listens for the returning echoes to detect and locate objects around her; this is a skill that the animals evolved to find insects at night, when vision is of limited use. Drawing on studies that postdate Griffin's ground-breaking research, the author identifies 10 challenges that the animals must overcome to accomplish this feat – from analysing the time gaps between calls and echoes at multiple frequencies to coping with interference caused by cluttered environments. Although Yong echoes the philosopher Thomas Nagel in admitting that, for all that has been learned about echolocation, it may ultimately prove impossible to know what it is like to be a bat (254), his own rich survey of the opportunities and challenges afforded by bat sonar provides evidence to the contrary. His discussion can be viewed as a proof-of-concept demonstration of how to use the study of animal sensation to undergird the exploration, without anthropocentric arrogance, of other-than-human Umwelten.

Next come two chapters focusing on sensory capacities that even the most intrepid Umwelt explorers are likely to have trouble imagining from the inside: namely, animals' ability to perceive the electric and magnetic fields that do not feature, so far as is known, in humans' sensory worlds. Chapter 10, 'Living Batteries', begins with an account of electric fish; the discussion encompasses electric eels as well as two groups of what are known as weakly electric fish – namely, the elephantfishes (mormyroids) of Africa and the knifefishes (gymnotiforms) of South America. Such fish use electric fields not to incapacitate prey, like the eels, but rather to sense the world around them and communicate with one another. Exploiting a perceptual resource for which the Ukrainian-born zoologist Hans Lissman and a colleague coined the term *active electrolocation* in 1958, weakly electric fish rely on sensory cells called electroreceptors to calculate the position, size, shape, and distances of objects in their environment. There is evidence suggesting that this electric sense evolved from the lateral line, by virtue of which fish use fields of water to detect objects around them. But electrolocation affords superior capacities for predation, given that stillness, concealment, and silence do not mask animals who enter electric fields. Other research has revealed, among species ranging from sharks and sawfish to

catfish and salamanders, a sense termed *passive electroreception*. Animals with this sensory capacity do not generate their own electric fields to locate objects in their environment but rather passively detect the electric fields of prey animals, for example.

Chapter 11, 'They Know the Way', turns from electric fields to the magnetic field that curves around the planet, due to the churning movement of molten iron and nickel inside the solid iron sphere at the planet's core (301). As Yong notes, this geomagnetic field is a reliable guide for travellers, unaffected by weather and unchanged by the seasons or, for that matter, the setting of the sun. Whereas humans must use compasses to pick up on the field, other animals, including sea turtles, spiny lobsters, songbirds, and others, are able to detect the field without any assistive technology, using a sensory capacity known as magnetoreception. Reviewing findings from studies of animals as diverse as bogong moths in Australia, monarch butterflies in North America, European robins, and sea turtles, the author notes that a leading hypothesis about how magnetoreception works now focuses on a group of molecules called *cryptochromes*. These molecules, which are found in songbirds' eyes as well as their brains, trigger radical pair reactions that are influenced, in turn, by magnetic fields (312-13). However, in describing the sometimes heated debates among different groups of researchers in this area, Yong wonders whether the radical-pair explanation has gained traction because it aligns magnetoreception with vision – a sense that plays such a crucial role in human Umwelten. In other words, it may be that, both in this specific case and more generally, 'The boundaries of our own Umwelten corral our ability to understand the Umwelten of others' (319).

The way that even migrating animals who can detect magnetic fields typically rely on other capacities such as vision and touch more than magnetoreception, which they use as a kind of backup sense, points ahead to the topic of chapter 12. As indicated by its Uexküll-inspired title, 'Every Window at Once: Uniting the Senses', this chapter focuses on the multisensory methods that animals exploit to build their perceptual worlds. Uexküll compared an animal's body to a house 'with many sensory windows overlooking an outlying garden' (322). With his previous chapters having, in effect, looked through those windows one by one, the author turns now to the whole-body constitution of animal Umwelten, or how the form of an animal's entire body shapes its overall sensory world. As Yong stresses, no animal uses one sense to the

exclusion of all others, and besides being complementary, particular sensory capacities can also combine. Mosquitoes, for example, respond to both temperatures and smells, while ants' worlds might be imaginable as ones that humans could access if they had noses in their fingertips (324). Yong cites neuroscientist Michael Hendricks' theory that sentience arises from the contrast between exafferance and reafferance, or signals that are other-produced versus signals that are self-produced. Because animals navigate the world by distinguishing between these two kinds of signals, they must make sense of themselves in order to make sense of their environments, meaning that 'an animal's Umwelt is the product not just of its sense organs but of its entire nervous system acting in concert' (328). The author uses the case study of octopuses to stage a whole-body approach to animal worldmaking, starting with the animals' eyes, moving to their arms and suckers, and then addressing their other sensory organs. Octopuses have separate nervous systems associated with each of their arms; only about one-third of their neurons are located in the animal's head, with the brain mostly letting the arms have their own way while providing occasional top-down guidance. Accordingly, an octopus likely has two distinct Umwelten, with the arms living in a world of taste and touch and the head dominated by vision. Uexküll's house-with-windows metaphor must therefore be adapted to accommodate this dual experiential world, which Yong likens to two semidetached houses connected by a small door. More generally, the author writes, 'To stand any chance of knowing what it is like to be another animal, we need to know almost everything about that other animal', including 'its senses, its nervous system and the rest of its body, its needs and its environment, its evolutionary past and its ecological present' – all the while approaching this work humbly and 'recognizing how easily our intuitions can lead us astray' (334).

The final chapter, 'Save the Quiet, Preserve the Dark: Threatened Sensescapes', begins by noting that among the many deleterious impacts of human activity on animal worlds, including anthropogenic climate change, ocean acidification, and loss of biodiversity across the globe, sensory pollution has not received the attention it deserves. As Yong puts it, 'Instead of stepping into the Umwelten of other animals, we have forced them to live in ours by barraging them with stimuli of our own making' (336). The chapter focuses on light and noise pollution. Artificial light harms – disorients, entraps, disrupts the behavioural regimes of – species as

diverse as bats, songbirds, sea turtles, and pollinating insects, while noisy environments likewise degrade animals' habitats and shrink their perceptual worlds, both on land and in the sea. For example, because giant whales can live for a century and more, there may be individuals who have personally experienced the onset of noisy underwater environments in which they can hear only about a tenth as far as they could previously. Yong comments here on a general paradox: just as humans started to develop the conceptual and technological tools needed to come closer to understanding what it is like to be another animal, 'we have made it harder than ever for other animals to be' (346).

The concluding chapter, then, emphasises humans' obligations to other animals, calling for a recognition of the inherent value of creatural worlds. In Yong's account, this recognition translates into a duty to respect and preserve the full variety of Umwelten – to avoid encroaching on species' right to thrive through the free exercise of their sensory capacities. This explicitly anti-anthropocentric emphasis, however, conflicts with other strands of the author's discourse. For one thing, it runs counter to Yong's claim, in the closing pages, that only humans are capable of knowing (or caring about) what other animals may be sensing (352). Uexküll assumed otherwise in developing a method for training guide dogs that was premised on dogs' ability to imagine the perceptual worlds of humans with visual impairments (see Magnus). Likewise, in describing how *Argyrodes* spiders mask their own vibrations by timing their movements to coincide with those of the *Nephila* spiders into whose webs they 'hack' (206), Yong himself presents a case in which one species of nonhuman animal imagines, and exploits, the perceptual world of another. But there is also, throughout the book, a disturbing tendency to minimize the way scientific inquiry itself can diminish or even destroy other-than-human Umwelten – through the very research on which the author draws to argue against humans' colonisation of sensory worlds. Thus, Yong uses a neutral or even joking tone in describing how some creatures are sacrificed in studies of animal senses. Having previously characterised the sophisticated visual worlds of killer flies as well as fruit flies' ability to compute infinitesimal differences of temperature, Yong reports that he 'almost' feels sorry for the flies used as food for the spiders in the lab of an expert researcher, whose statement 'I hate flies' (205) the author quotes without comment. Similarly, in the chapter on echolocation, Yong reports how bat

researchers 'whoop and cheer like excited sports fans' as they observe a bat 'catching moth after moth' (244) – and this despite the author's earlier discussion of moths' impressive ultrasonic hearing and his later description of bogong moths' magnetoreceptive capacities.

Other research summarised by Yong turns on acts of predation that are likewise engineered by human investigators, rather than merely being observed in the wild. Scurrying mice are sacrificed to measure owls' range of hearing, the eggs of red-eyed tree frogs are placed in cages with cat-eyed snakes to test the frog embryos' perception of surface vibrations, and the brains of cockroaches are removed to gauge the sensitivity of the stinger with which emerald jewel wasps parasitize their prey. As these examples suggest, the experimental designs of animal researchers not only encroach on but also, in some cases, extinguish creatural worlds. These investigators rely on asymmetries of power to map neuronal activity in nonhuman brains; encage marine animals ranging from scallops and shrimp to seals and octopuses; confine insects to enclosures parts of which are heated to lethal temperatures; use surgical cement to attach radio tags to bats, with one researcher comparing the process to an art project (335); and conscript dolphins into experiments testing their ability to detect underwater mines. From this perspective, the book can be read as a compendium of methods used to contain, manipulate, and sometimes kill animals in the name of science, rather than as a survey of the creatural worlds discovered via disinterested inquiry in search of unbiased knowledge.[i]

Here the relevance of issues discussed in Yong's chapter on pain makes itself felt. The chapter begins by introducing a widely used distinction between nociception and pain; according to this distinction, nociception refers to the sensory process by which animals detect damage to their bodies while pain refers to the brain-involving suffering that ensues from that damage (121). Pain, in this account, requires conscious awareness, whereas nociception can occur without it. To flesh out the model, Yong uses the case study of the naked mole-rat, a species of rodent that has evolved to accommodate the high levels of carbon dioxide found in the nesting chambers in which the animals habitually dwell. The nociceptors in these animals that would normally be activated by acids caused by high CO2 levels are instead blocked by them, preventing neurotransmitters from conveying to the brain signals of acidic pain. Yet the grounding distinction between nociception and pain can be accused of anthropocentric bias – of

being 'a relic', as Donald Broom puts it, 'of attempts to emphasize differences between humans and other animals or between "higher" and "lower" animals' (123). Although Yong initially registers support for Broom's position, writing that 'Scientists who study eyes don't get into arguments about whether humans have vision and fish merely have photoreception', he then walks back this statement, referring to research suggesting a contrast between 'spatial vision' and 'simple photoreception' (123). Similarly, the author initially criticises the stance that fish cannot feel pain because they lack a neocortex – given that, as the author puts it, animals often evolve different solutions to the same problems. But he then reverses direction, citing studies suggesting that a particular type of worm, because it has only 10 times as many neurons in total as the number of neurons used by crabs and lobsters just to control their stomachs, cannot 'produce subjective experiences' (126). The author then backtracks yet again, referring to research that raises the possibility of pain in insects. Significantly, this is the only chapter marked by such zigzagging, which can be attributed to the unsettled and unsettling status of questions about animal pain – and to the profound consequences those questions have for human institutions, norms, and practices. As Yong himself puts it, 'When we ask if animals can feel pain, we're asking less about the animals themselves, and more about *what we can do to them*' (133).

The author's response to the far-reaching implications of animal pain is to call for a more granular approach to animal worlds. He suggests that, because even closely related animals perceive the world differently, rather than asking whether cephalods, for example, experience pain, it is more appropriate to ask which ones experience it and how – and to explore the evolutionary advantages that might be associated with having, and in some cases displaying, pain (134). But what is the underlying motivation for this approach? Is it merely to avoid approximative lumping in favour of more precise splitting? Or is the idea that by subdividing Umwelten, one can sequester perceptual worlds in which pain (as humans understand it) features, and then separate those worlds off as special cases – rather than treating all creatures' ways of worldmaking with the respect that Yong elsewhere says is their due? There is also the

issue of how this analytic move squares with what the author describes as the precautionary principle followed by many pain researchers – that is, the principle that it is best to assume that animals can suffer, and to act accordingly (132).

This part of Young's discussion raises another far-reaching question: What is the relationship between animal worlds considered at the species and group levels, on the one hand, and animal worlds considered at the level of individual creatures, on the other? It is one thing to speak in globalising terms about the average or rather species-typical sensory capacities of bats and toothed whales taken as organismic groups. It is quite another to focus on the particularised experiences of an individual bat or dolphin, caught up in animal-specific circumstances and shaped by a unique life history. In stressing the need to divide up classes of creatures vis-à-vis their capacity to sense pain, Yong relies on the three main facets of his strategy for modelling Umwelten: inferring modalities of experience based on observed behaviours; grounding these modes of experience in biomechanical structures, or sensory equipment; and contextualising the resulting behaviour-experience-physiology linkages via possible or probable evolutionary processes. Note, however, that the emphasis on evolution sets a floor for granularity in this connection. It establishes a threshold corresponding not to individual subjective experiences but to the way such experiences may or may not have been adaptive, for the group or species capable of having them, in a given evolutionary context. But how granular should Umwelt exploration be? Why stop at types of cephalods? Why not focus on the experiences of an individual octopus, as in the 2020 documentary *My Octopus Teacher*?

Arguably, there are multiple strategies for moving below Yong's evolutionary threshold to reach the level of the life histories – and the particularised experiential worlds – of individual animals. One strategy entails documenting the lives of individual creatures, as in *My Octopus Teacher*, by striving to meet them where they are. The goal of this strategy is to gain greater insight into particular animals' circumstances, habitual behaviours, and possible perceptions, motivations, and emotions, the forms that their gradations of enjoyment and suffering may take, by writing biographies that extend beyond the human (see Krebber and Roscher). Another strategy involves imagining other-than-human Umwelten through the resources afforded by fiction (including the as-if domain of thought experiments) and by other kinds of artistic

expression. Yong himself makes occasional use of this second strategy, relying on the alien's heat-detecting vision in the movie *Predator* to imagine how rattlesnakes see, suggesting that readers press their hands against the wall to imagine how star-nosed moles navigate their environments, and for that matter using a phrase from a William Blake poem in his book's title. He also concludes the Introduction with this quotation from Proust: 'The only true voyage … would be not to visit strange lands but to possess other eyes … to see the hundred universes that each of them sees' (16). But a telling passage toward the end of the chapter on uniting the senses reveals the author's distrust of fictional or mythic discourse as a means for acquiring the 'other eyes' needed to explore animal worlds:

> Our experiences of the world feel disconnected from the very sense organs that produce them, which makes it easy to believe that they are purely mental constructs divorced from physical reality. That's why our stories and myths are so full of characters who can transfer their consciousness into the bodies of animals … Such feats, in which humans literally step into the sensory worlds of other animals, feel like the ultimate form of Umwelt-appreciation. But they also fundamentally misunderstand the concept. An animal's sensory world is the result of solid tissues that detect real stimuli and produce cascades of electric signals. It is not separate from the body, but of it. You can't simply imagine how a human mind would work in a bat's body or an octopus's, because it wouldn't work. (333)

In this passage, Yong engages in the same lumping tendencies that he criticised in research on animals' capacity to experience pain. There is, in fact, a vast ecosystem of imaginary Umwelten, with the variety of ways of conjuring animal worlds in literary, visual, performance-based, and other art mirroring the variety of species whose different sensorimotor capacities the author aims to emphasise. The tradition of animal autobiography, for example, encompasses a whole array of world-building strategies, from the relatively anthropocentric orientation of Aesop's fables, which use animals largely as vehicles for human concerns, to works whose creators do seek to imagine their way into other-than-human bodies, lifeways, and experiences. Relevant here are the tales by Kafka featuring humanimal narrators, or the perceptual worlds evoked by Ceridwen Dovey's retelling of animals' life stories in *Only the Animals*. Likewise, visual art by the German-Iraqi artist Lin May Saeed, who portrays animals suffering under but

also subverting anthropocentric regimes, figures forth entirely different worlds than those imagined, or not imagined, by landscape paintings in which horses or livestock function as so many props for human-centered environments and purposes.[ii] Or consider the performance art of Evan Silver, whose *Cryptochrome* (2023) uses the resources of the stage – costumes, music and song, lighting, choreography – to enact what it might be like to have the magnetoreceptive capabilities so brilliantly described, in another register of discourse, by Yong.[iii] In short, just as animals themselves have evolved different solutions to the same problems, humans have developed different analytic-expressive frameworks for exploring, understanding, and engaging with animal worlds. In this era of ecological and biological devastation, when *Homo sapiens* is eliminating the very possibility of other-than-human worlds and ways of worldmaking, all of these frameworks are critically important. It will take their combined force to counter the anthropocentrism against which Yong's book constitutes, in the main, such an eloquent argument.

Notes

[i] See Shah for a discussion of how breeding mice for – and using them in – laboratory research harms not only the mice but also the research itself.

[ii] On Kafka's humanimals, see Dekoven. On the spectrum of formal possibilities in animal autobiography and other narrational modes, see Herman. On Saeed's work, see Wiesenberger.

[iii] To quote the description of the performance included on Silver's website: '*Cryptochrome* is a ritual meditation and song cycle that invites audiences on a kaleidoscopic journey across the animal kingdom to reflect on how and why we voyage. Named after a protein believed to be responsible for the ability to navigate using the Earth's magnetic field, the work explores forms of perception and intuition beyond the limited scope of the visible.' See https://evansilver.net/Prophecies as well as the review of Silver's performance by Shaw, who refers to it as a form of 'eco-cabaret'.

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