

be spatially separated, to potentially reduce transcriptional noise (1).

Kim *et al.* have uncovered a new principle of circadian gene repression by Rev-erb $\alpha$  that involves the dynamic reorganization of genome folding at circadian loci. Previously, it was difficult to predict to what extent genome organization undergoes circadian oscillations. Although these experiments suggest that circadian chromatin plasticity is restricted to sub-TADs enriched in circadian genes, it cannot be ruled out that rhythmic changes in chromatin folding do not leave nearby non-circadian genes unaffected. Given the role of transcriptional noise in cell-state transitions and phenotypic heterogeneity driving tumor evolution (7), it will be important to decipher any potential cross-talk between the clockwork and the machinery that regulates stochastic transcriptional fluctuations (1).

The findings of Kim *et al.* also support the emerging theme that metabolic states might directly affect not only chromatin marks (4, 12) but also genome folding via “metabolic sensors” with functions in genome organization. Rev-erb $\alpha$  binds to heme (13), which is synthesized in a circadian- and Rev-erb $\alpha$ -dependent manner (14). Interestingly, heme facilitates Rev-erb $\alpha$  binding to the NCoR complex and its repressor function at metabolic genes (13), suggesting potential cross-talk between circadian genome folding and energy homeostasis. Another example is poly(ADP-ribose) polymerase 1 (PARP1), which senses the amount of oxidized nicotinamide adenine dinucleotide (NAD<sup>+</sup>) (4) and regulates, with CTCF, the rhythmic mobility of circadian genes between transcriptionally permissive and repressive nuclear compartments (15). As E-P contacts and their sub-nuclear localization are dynamic, E-P loop formation and chromatin mobility might be among the first responders to metabolic cues, for example, in response to diet. Further deciphering the cross-talk between metabolic sensors and genome organization will likely shed new light on diseases with deregulated phenotypic plasticity, such as cancer (7). ■

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## ECOLOGY

# A landscape of disgust

Parasite avoidance behavior affects ecology and evolution in ways similar to predator avoidance

By Sara B. Weinstein,<sup>1</sup> Julia C. Buck,<sup>2</sup> Hillary S. Young<sup>2</sup>

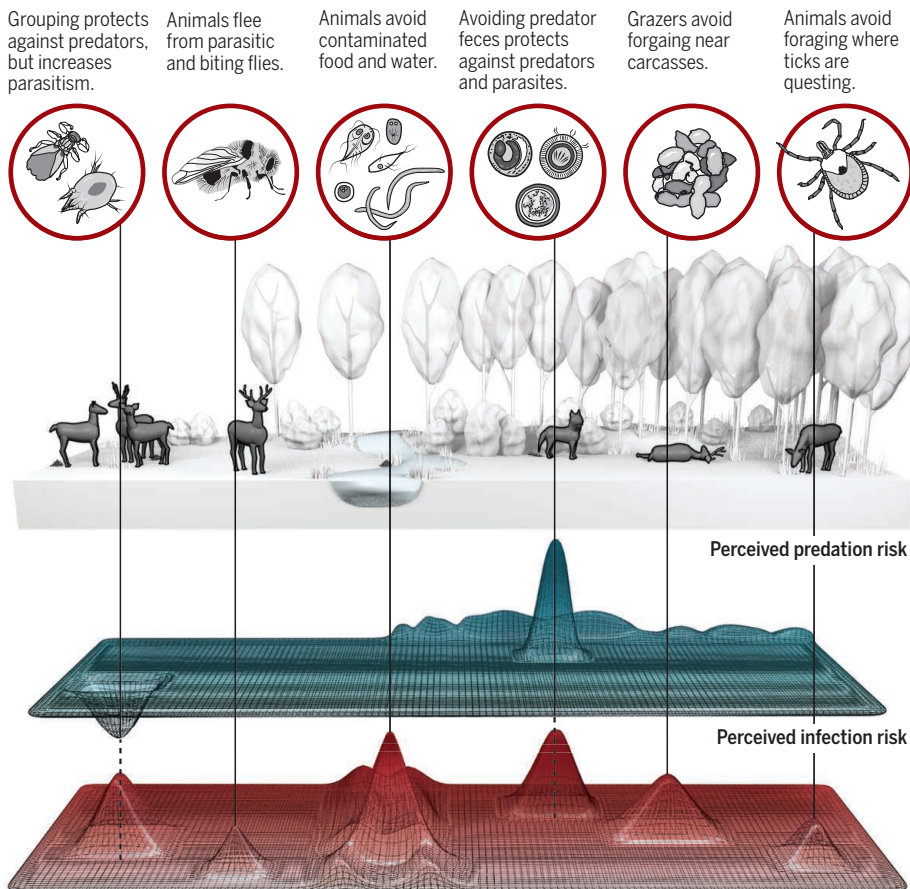
**A**rancid meal, a moist handshake, a pile of feces: These phenomena elicit disgust and avoidance that protect humans from our most pervasive consumer–infectious agents. This avoidance is not specific to humans. Various animals alter their behavior to avoid infection (1). For instance, Poirotte *et al.* recently showed that mandrills avoid parasite-contaminated feces and refrain from grooming infected individuals (2). These primates’ nuanced ability to detect and alter their behavior in response to differential exposure risk

suggests close parallels to the “landscape of fear” elicited by predators (see the figure), with perceived peaks and valleys driven by parasite abundance and exposure risk.

Owing to the high cumulative fitness costs of parasitism over an individual’s lifetime, there will be strong selection for parasite avoidance. Yet, because most parasites are difficult to detect, avoidance often relies on indirect cues that are driven by long-term associations. Many species avoid feces and carcasses, regardless of infection status (1). Infection can also alter the chemical composition of sweat, breath, and feces, allowing more targeted avoidance of infected individuals (3). For instance, mandrills identify

## Overlapping landscapes of fear and disgust

Animals detect predation threats, creating a three-dimensional fear landscape with mountains of risk and valleys of safety. Animals can also detect infection threats, which form a landscape of disgust. The resulting overlapping landscapes have far-reaching ecological and evolutionary consequences.



Grouping protects against predators, but increases parasitism.

Animals flee from parasitic and biting flies.

Animals avoid contaminated food and water.

Avoiding predator feces protects against predators and parasites.

Grazers avoid foraging near carcasses.

Animals avoid foraging where ticks are questing.

and avoid infected conspecifics on the basis of olfactory cues associated with the altered chemical composition of infected feces (2). Thus, whereas prey “fear” predators, parasite avoidance is more akin to disgust—an innate aversion to cues associated with parasites (1). As with predator avoidance, parasite avoidance incurs costs such as altered social interactions, reduced reproductive opportunities, diminished foraging, and increased energy expenditure (4). To predict when parasite avoidance is most likely to occur and understand its consequences, it must be integrated into the same trade-off framework that is widely applied to predator avoidance.

Beyond its direct effects on hosts, parasite avoidance has cascading effects at a range of scales and in various systems (5). Ants and their parasitoids provide a useful model system for studying the cascading effects of parasite avoidance on herbivory. Azteca ants experimentally exposed to parasitoid flies dramatically reduce their activity levels to avoid infection. This reduces the ants’ ability to attack their herbivorous prey, the coffee berry borer, and allows the latter to consume more coffee berries (6). Such ecological impacts of parasite avoidance are not limited to top-down effects on vegetation; they also alter mutualism, competition, and predation.

Like the predator-induced landscape of fear, a parasite-induced landscape of disgust (see the figure) has far-reaching consequences for population dynamics, species interactions, and ecosystem structure. However, whereas direct effects of predators are naturally restricted to prey species (7), a parasite-induced landscape of disgust extends to all animals, including very large species and top predators that are typically immune to predation (8). For example, a recent synthesis by Moleón *et al.* showed that carnivores avoid foraging on other carnivore carcasses and rarely engage in cannibalism (9). Feeding on conspecifics increases disease transmission, and forgoing this food resource reduces exposure to shared parasites (10). At a landscape level, this avoidance behavior dramatically alters the amount of carcass material that is available in an ecosystem, with important downstream effects. For instance, carcasses not consumed by mammalian scavengers may support more diverse and abundant arthropod communities (9). Furthermore, when carcasses decompose, their nutrient inputs increase plant growth (11). Like the ecosystem-level impacts of predator avoidance, the ecosystem-level impacts of parasite avoidance are likely to be substantial.

Parasite and predator avoidance can exert opposing pressures on host and prey species. For example, tadpoles increase their activity levels to protect themselves from trematode infection, but this increases their susceptibility to visual predators (12). The tadpoles fear and avoid both predators and parasites, but do not perceive these threats as equal. When experimentally forced to choose between predation and parasitism risk, tadpoles opt for infection (13). This makes sense because predation has a larger short-term fitness effect than does parasitism, and the optimal behavior avoids the greatest immediate threat.

However, parasite and predator avoidance are not always mutually exclusive. For instance, avoiding predator feces protects prey against both predators and their parasites (14), and, when animals group together, they dilute their risk of attack by both predators and some parasites (for example, ticks, botflies) (15). Although predator avoidance has received more attention, parasite avoidance also has strong effects on foraging, movement, and social interactions (1).

Parasite avoidance is likely to have important consequences. For example, grazing animals such as cows, sheep, and horses avoid fecal contaminated forage (4), and changing livestock practices to recognize the needs and capabilities of animals to avoid parasites will reduce the cost associated with avoidable livestock diseases. Furthermore, conservation planning and projections may benefit from knowledge of how shrinking and fragmented habitat limits the ability of animals to avoid risky sites and conspecifics. As populations of large predators continue to decline, parasite avoidance may become a relatively stronger driver of ecological processes. Integrating parasites into the ecology of fear is thus crucial to understanding the general ecological and evolutionary effects of parasites on ecosystems and predicting how ecosystems are likely to respond to the rapidly changing environments of the Anthropocene. ■

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#### PSYCHOLOGY

## Logic in babies

### 12-month-olds spontaneously reason using process of elimination

By Justin Halberda

**T**he success of science rests on our human ability to reason logically. But where does this ability come from? Is it an inherent attribute of mind that even a young child might possess, or is it a hard-won accomplishment mastered later in life? On page 1263 of this issue, Cesana-Arlotti *et al.* (1) reveal that one essential form of logical inference, process of elimination, is within the toolkit of 12-month-old infants. This reveals the earliest known foundations of our human ability to reason logically. The race to document the range of early logical abilities shared by infants, adults, and nonhuman animals, and to determine how these foundational abilities empower our broader capacities to reason, has begun.

Every scientific method requires a supporting logic. For Francis Bacon (2), this was unfettered empirical observation followed by induction (reasoning from many cases to form a general principle). Karl Popper (3) stressed the importance of hypothesis testing and the ability to refute hypotheses found to be false (science as an extended instance of process of elimination). And Thomas Kuhn (4) highlighted the dramatic changes that occur during scientific revolutions, in which wholly new models of phenomena are created through model building and abduction (sometimes called “inference to the best explanation”). Examples of such revolutions are the Copernican Revolution (5) producing the heliocentric model of the solar system, and the Einsteinian Revolution of special relativity in which space and time become one (6). In each of these cases (induction, hypothesis testing, abduction), the work of science is supported by an underlying logic. No logic, no science.

Where does our human faculty to reason logically come from? At the end of the previous century, Susan Carey suggested that such logic might be deep in our developmental roots: A young child might reason using intuitive theories, models, and abduc-

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# Science

## A landscape of disgust

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