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Review

Cite this article: Brighton CH, Portugal SJ, Taylor GK. 2026 Bio-informed blade patterns for mitigating bird collisions with wind turbines. *J. R. Soc. Interface* **23**: 20250719.
https://doi.org/10.1098/rsif.2025.0719

Received: 14 July 2025
Accepted: 18 March 2026

Subject Category:
Reviews

Subject Areas:
Environmental science, evolution, ecosystem

Keywords:
flight behaviour, turbine collisions, optic flow, bird vision, blade patterns, sensory ecology

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Electronic supplementary material is available online at https://doi.org/10.6084/m9.figshare.c.8420873.

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Bio-informed blade patterns for mitigating bird collisions with wind turbines

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Although the rapid expansion of wind energy is essential for achieving carbon net zero targets, it may conflict with ecological objectives aimed at conserving and enhancing biodiversity. Birds in general are susceptible to colliding with wind turbines, and the impact of these structures may be especially significant for certain species. By examining how birds acquire, process and respond to environmental information, we propose a new collision mitigation approach that integrates sensory ecology with gaze strategy, flight behaviour and natural avoidance mechanisms. To enhance collision avoidance, we propose investigating blade patterns that alter the optic flow perceived by birds—the dynamic visual contrast resulting from their movement through the environment. Empirical behavioural research is now needed to assess the effectiveness of these designs. Given the diversity of affected species and environments, there may be no universal solution, and mitigations must also take account of the practical implications for developers and manufacturers. Our aim is to inspire and guide new research towards bio-informed solutions that protect wildlife without inhibiting clean energy generation.

1. Introduction

Humans have drastically altered the aerial environment of birds by building structures that reach into their lower airspace. These obstructions pose novel sensory and perceptual challenges that birds are not naturally adapted to deal with, while also offering attractive new opportunities for perching, nesting, foraging and soaring. Consequently, and despite their ability to negotiate obstacles in cluttered habitats like forests, birds often collide with artificial structures including power lines, communication masts, buildings, fences, windows and lights [1]. Dynamic structures such as wind turbines seem to be especially hard to avoid [1–3], and although wind farms are responsible for only a fraction of all collision mortality, they pose a growing hazard owing to the rapid expansion of wind energy that is needed to reach net zero [4]. Estimating the scale of global collision mortality is challenging (see below), but with the total installed capacity of wind energy generation projected to double [5] from 1 to 2 TW between 2024 and 2029, continuing attention to this issue is essential.

Birds see the world differently from humans, so to gain a full understanding of why birds collide with wind turbines—and hence to determine what may be done to mitigate this—it is necessary to take account of the sensory, perceptual and cognitive drivers of their flight behaviours. Yet, only a few studies to date have addressed the problem from the perspective of sensory ecology and flight behaviour, using scientific knowledge of avian vision and flight to inform the design of visual mitigations [6–8]. Recorded collision rates are often several times higher for bats than birds—perhaps because of

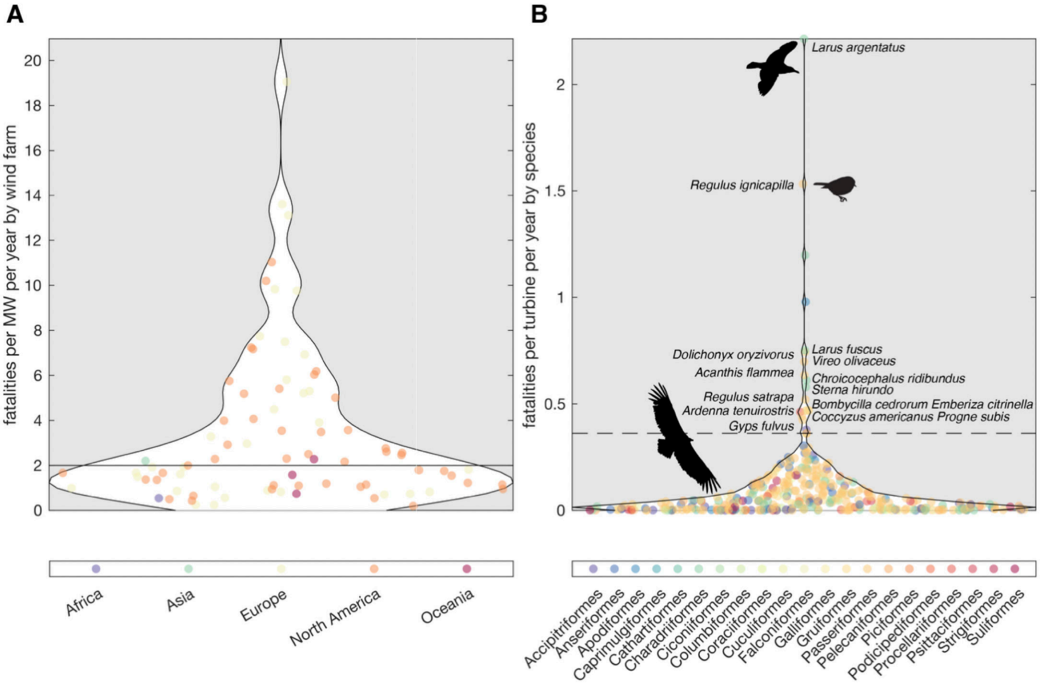

Figure 1. Annualized bird mortality rates from collisions with onshore wind turbines. Violin plots show mortality estimates from carcass count data across 124 studies in the Thaxter *et al*. [15] dataset. Data points (jittered for visibility) represent annualized mortality for a wind farm or species, based on studies reporting collisions. Corrections for search efficiency and scavenger removal are applied if reported; otherwise, raw counts are used. Annualizing seasonal data may overestimate true mortality, as monitoring often targets peak periods. (A) Mean collision mortality by wind farm ($n = 83$), weighted by study duration; solid black line shows the median. (B) Mean species-specific mortality ($n = 385$), also weighted by study duration; only studies with non-zero collisions included, making this an upper bound. Dashed line shows the 95th percentile. Species names are shown for the top 5%, excluding single-carcass records from low-effort studies, which can inflate rates by chance.

their reliance on echolocation and their tendency to forage on insects that may be attracted to turbines [9]—but as bats face a different set of sensory challenges, we focus exclusively on the visually guided flight behaviours of birds. We begin by reassessing the empirical evidence on collision mortality and collision avoidance in birds, before analysing the visual systems of birds in conjunction with the flight behaviours they guide. We then draw these strands together to analyse why birds collide with wind turbines, before using these insights to suggest improved visual mitigations [10,11] and to identify key priorities for future research. The scope of this review is limited to frontal bird approaches to wind turbines; rear-approach scenarios fall outside its remit.

2. Collision mortality across wind farms

Estimating global collision mortality is difficult because avian collision rates are inconsistently recorded, estimated and reported [12], and are known to vary strongly with site, season, species, turbine and environmental conditions [13–15]. Onshore collision rates can be estimated indirectly from carcass counts, but these must be adjusted to correct for search efficiency and scavenger removal, requiring considerable search effort and careful calibration. As carcass searches are impossible at sea, there are currently no reliable estimates of offshore collision rates. Remote-sensing techniques have recently been introduced that would allow collisions to be monitored directly, but these have yet to yield meaningful data on offshore collision rates owing to the infrequency [16] of collision events.

The most extensive meta-analysis of avian collision rates to date was undertaken by Thaxter *et al*. [15], who related collision rates recorded for 363 species to species-level characters and turbine characteristics, treating co-occurring species without recorded collisions as pseudo-absences with an assumed collision rate of zero. Their model was fitted mainly to data from Europe and North America, but when boldly extrapolated to nearly 10 000 species of birds occurring worldwide, yielded a median predicted collision mortality rate by species of 0.021 fatalities per turbine per year (1st, 3rd quartiles: 0.015, 0.031). Recompiling their dataset to include unidentified carcasses and correct errors in data entry, we find a median collision mortality by wind farm (figure 1A) of 2.0 fatalities per MW per year (1st, 3rd quartiles: 1.08, 4.75) for all birds. This figure is likely to be representative, although recorded collision rates can be an order of magnitude higher in some locations, including at the well-known hotspot of Altamont Pass, California. Unfortunately, these statistics take no account of collision rates in China, which accounted for 40% of global installed onshore wind capacity in 2023 compared with 46% in Europe and North America [5]. Studies of wind turbine collisions in China are scarce, but a recent study in the coastal area of Yancheng, Jiangsu Province, found an uncorrected mortality rate of 0.33 bird collisions per MW per year [17] which is within the range recorded elsewhere (figure 1A). Hence, at a total installed capacity of 10^6 MW in 2024, of which greater than 90% is onshore [5], total global collision mortality from wind turbines is likely to be of the order of 10^6 birds per year currently.

Table 1. Wind turbine collision risk by species. Top 20 species ranked by collision risk, assessed as the number of fatalities per million birds of that species per MW per year. This metric is calculated by normalizing the mean recorded collision mortality rate for each species at locations with collisions recorded by the median of its estimated global population size. Note that 14 of this top 20 are soaring birds, and that the remaining 6 are all nocturnal migrants or foragers. For robustness, this ranking excludes 10 datapoints corresponding to singleton carcass finds and another 9 datapoints corresponding to multiple carcass finds at single sites. Since 8 of these 19 exclusions are soaring birds and another 7 are nocturnal migrants, this decision does not impact our overall conclusions; of the remaining 4 exclusions, 3 are species endemic to New Zealand or Australia that are associated with a small global population size.

rank	common name	species name	order	collision risk	risk factor
1	European herring gull	*Larus argentatus*	Charadriiformes	3.0	soaring
2	swamp harrier	*Circus approximans*	Accipitriformes	1.9	soaring
3	white-tailed sea-eagle	*Haliaeetus albicilla*	Accipitriformes	1.4	soaring
4	wedge-tailed eagle	*Aquila audax*	Accipitriformes	0.9	soaring
5	griffon vulture	*Gyps fulvus*	Accipitriformes	0.7	soaring
6	golden eagle	*Aquila chrysaetos*	Accipitriformes	0.6	soaring
7	short-toed snake-eagle	*Circaetus gallicus*	Accipitriformes	0.4	soaring
8	Eurasian eagle-owl	*Bubo bubo*	Strigiformes	0.3	nocturnal foraging
9	western grebe	*Aechmophorus occidentalis*	Podicipediformes	0.2	nocturnal migration
10	sharp-shinned hawk	*Accipiter striatus*	Accipitriformes	0.2	soaring
11	lesser kestrel	*Falco naumanni*	Falconiformes	0.1	soaring
12	black-billed cuckoo	*Coccyzus erythropthalmus*	Cuculiformes	0.1	nocturnal migration
13	red-tailed hawk	*Buteo jamaicensis*	Accipitriformes	0.1	soaring
14	ferruginous hawk	*Buteo regalis*	Accipitriformes	0.1	soaring
15	prairie falcon	*Falco mexicanus*	Falconiformes	0.1	soaring
16	yellow-legged gull	*Larus michahellis*	Charadriiformes	0.1	soaring
17	Wilson's snipe	*Gallinago delicata*	Charadriiformes	0.1	nocturnal migration
18	common firecrest	*Regulus ignicapilla*	Passeriformes	0.1	nocturnal migration
19	upland sandpiper	*Bartramia longicauda*	Charadriiformes	0.1	nocturnal migration
20	black-headed gull	*Chroicocephalus ridibundus*	Charadriiformes	0.1	soaring

3. Collision risk across species

Comparing the same data across species shows that the hazard of a spinning turbine blade is indiscriminate with respect to body size. Indeed, the top 5% of species with the highest mean recorded collision rates per turbine include some of the world's smallest and largest birds, spanning three orders of magnitude in body mass from small common firecrests (*Regulus ignicapilla*) to large griffon vultures (*Gyps fulvus*) (figure 1B). Normalizing the mean recorded collision mortality rate for each species by its global population size allows us to assess its collision risk as the number of fatalities per million birds of that species per MW per year (table 1). Insofar as global population size can serve as a proxy for local abundance [15], this metric relates both to the individual probability of collision and to the demographic impact of such collisions when they occur. Of the 20 top-ranked species on this metric (table 1), 14 are soaring birds that exploit the same wind resource as wind turbines, while the other 6 are nocturnal migrants or foragers that face the sensory challenge of seeing unlit structures in darkness and may also be attracted to artificial light at night [18]. A formal comparative analysis is needed to test these associations, but flight ecology clearly places some species at higher risk of collision than others, and visual mitigations ought to be designed accordingly.

Large soaring birds may be especially vulnerable to collisions because of their flight morphology and flight behaviour [19,20]. Other things being equal, a larger wingspan increases the probability of colliding with a turbine blade when flying through the rotor-swept zone. Larger birds are less well able to fly slowly because of the adverse scaling of aerodynamic power requirements with body mass [21,22]. Hence, when visual information is limited by poor visibility, large soaring birds may be unable to respond to the increased perceptual challenge by slowing down. However, perhaps the greatest risk factor of all is the fact that soaring birds use the same wind energy resource as turbines. Onshore wind turbines are often located at the top of steep slopes, where the wind is deflected upward, forming an orographic updraft [23]. Land-soaring birds such as condors [24], vultures [25], hawks and eagles [26,27] rely on such updrafts to sustain their flight [28,29] and are, therefore, indirectly attracted into rotor-swept zones [25], producing an increased collision risk through association. It is even possible that some soaring birds may be directly attracted to the wake behind a wind turbine as a source of energy for gust soaring [23]. Against this backdrop, it is not surprising that the majority of species with the highest collision risk are large soaring birds (table 1).

4. Turbine avoidance behaviours

Although the demographic impact could be high for some species—particularly for large soaring raptors and seabirds with low reproductive rates—collisions with wind turbines are rare events even for the worst affected species. This already suggests that individual birds must avoid wind turbines successfully most of the time, and hence that collisions may be most likely to occur under adverse conditions. This conclusion is further borne out by collision risk modelling, which models the rate at which collisions are expected to occur given the observed height, speed and density of flight tracks through a wind farm. Typically, the collision rate predicted by the standard Band collision risk model [30] must be multiplied by a correction factor of approximately 0.01 to align predicted to observed collision rates [31]. This suggests that most birds modify their flight tracks in response to wind turbines at least 99% of the time, with somewhat lower avoidance rates of 95% reported in some vulnerable species such as white-tailed sea-eagles (*Haliaeetus albicilla*) [32]. It is an open question why birds fail to avoid turbines on the rare occasions that they do, but at least some mass collision events seem to have been associated with adverse atmospheric conditions such as fog [33]. However, the magnitude of the correction factors needed to model avoidance is encouraging for collision risk mitigation (if not for the utility of the underlying collision risk model), because it suggests that birds see, recognize and respond to the threat of a wind turbine most of the time, and hence that visual mitigations might yet be effective in re-enabling avoidance behaviours under adverse conditions.

Studies of avoidance responses typically distinguish behaviours occurring on three distinct spatio-temporal scales: macro-avoidance, where the bird avoids the footprint of a wind farm altogether; meso-avoidance, where the bird avoids the rotor-swept zone specifically; and micro-avoidance, where the bird avoids the moving turbine blade itself. Different flight behaviours are engaged when birds adjust their flight path at a distance rather than through close-range evasion [34]. Most studies focus on spatial scales large enough to be monitored using radar monitoring, aerial surveying or biologging. These larger-scale avoidance behaviours are of particular interest from an ecological perspective, because the displacement effects that result from macro-avoidance cause an effective loss of habitat, and the barrier effects resulting from meso-avoidance cause an effective loss of airspace [35–39]. Radar-based systems may not be able to operate effectively in the vicinity of a turbine, but camera-based systems designed to enable the curtailment of turbine operation in response to approaching birds [40–42] have recently allowed micro-avoidance [16] behaviours to be recorded in the vicinity of a turbine blade [43]. These recordings have shown that birds adopt a variety of flight behaviours in the vicinity of turbine blades, sometimes even flying along the edge of a turning blade. Evidently, the sensory challenges that are associated with these different flight behaviours will vary with the range at which avoidance occurs.

For instance, the phenomenon of motion smear that we may experience when watching a ceiling fan has dominated thinking on visual mitigations to date, but only becomes an issue for larger turbines when viewed at close range [44]. Motion smear occurs when image contrast moving across the retina outpaces the speed at which the visual system can respond to changes in luminance. This has been found to happen as the image speed of the blade tip reaches approximately $2\pi/3$ rad s^{-1} in American kestrels (*Falco sparverius*) [44]. The image speed of the blade tip is equal to the rotor speed divided by the ratio of the viewing distance to the rotor radius, so as large-scale wind turbines typically have rotor speeds up to 20 r.p.m., or $2\pi/3$ rad s^{-1}, it follows that motion smear is only expected to occur when the bird is within one blade length of the blade tip. For the very largest offshore wind turbines such as the GE Haliade-X (rated rotor speed: 7.81 r.p.m.), the range at which motion smear first occurs will be less than half a blade length. Motion smear will, therefore, be most problematic during micro-avoidance, yet blade patterns designed to counteract motion smear [45] typically aim to make the entire rotor-swept area visible for meso-avoidance. For example, the visual mitigation of painting a single blade black has been trialled with the goal of creating an ON-OFF signal [45] that would make the rotor appear as a dark spinning wedge rather than as a semi-opaque disc under motion smear. However, if motion smear only becomes an issue when the bird is much less than one blade length from the blade tip, then this mitigation should only be expected to affect the visibility of one of the three blades, rather than the visibility of the entire rotor. Straightforward contrast enhancement, therefore, seems to be a more likely explanation of why painting a single blade black has been found to reduce collisions of at least one species at Smøla Wind Farm, Norway [45].

Studies assessing the effectiveness of turbine curtailment confirm that rotating blades pose a greater hazard than static blades [46], but the mechanisms underlying this increased risk remain unclear; whether due to motion smear, difficulty of recognizing rotary motion as a threat, or the limited time available for birds to respond. Experimental work with homing pigeons (*Columba livia*) shows that reducing blade rotation speed alone does not reliably prevent collisions [46], indicating that perceptual and behavioural constraints, rather than reaction time, may be key determinants of risk, and that curtailment-based mitigation may only be effective when turbines are fully stopped [47]. Complementary modelling work estimating the distances at which birds can detect turbines further underscores the role of visual detection thresholds in shaping collision outcomes [48]. Together, these findings indicate that mitigation strategies informed by avian sensory and perceptual ecology—such as bio-inspired blade patterns designed to enhance detection and recognition—may offer a more effective and economical alternative to operational curtailment. In summary, although turbine appearance can influence collision risk, current visual designs are unlikely to be optimal; developing bio-informed blade patterns grounded in bird visual physiology, movement ecology and flight behaviour represents a promising pathway for reducing avian mortality around wind energy infrastructure.

5. Seeing the world through a bird's eyes

To understand why birds sometimes collide with human-made structures, it is essential to consider not just their eye anatomy, but how their visual system processes motion and interprets the dynamic environment around them.

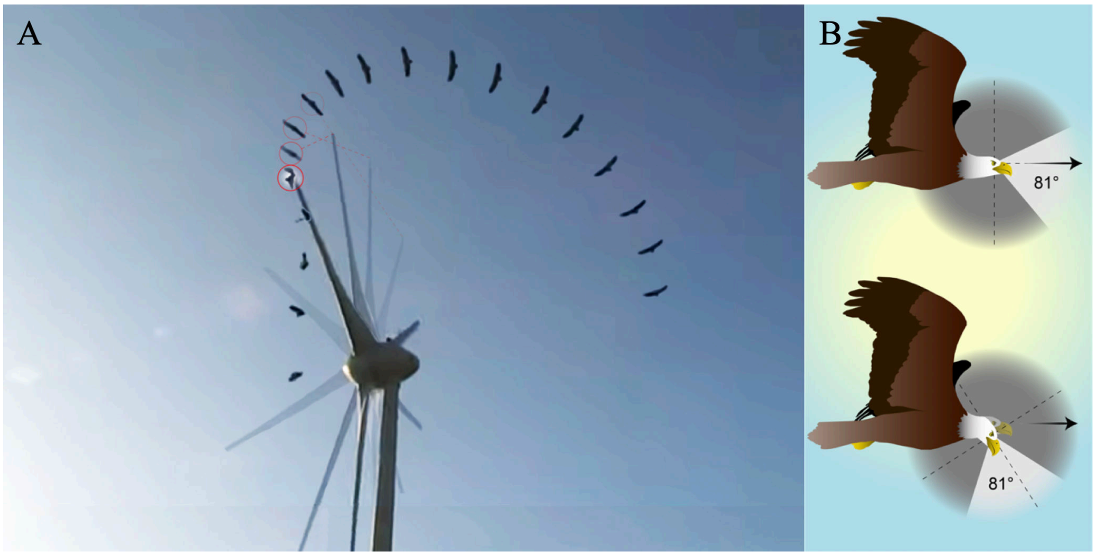

Figure 2. Raptor vulnerability around turbines. (A) Sequence of still images sampled at regular intervals from a video of a griffon vulture (*Gyps fulvus*) colliding with a wind turbine in Lendas, Crete. Note the apparent lack of any avoidance response. The red circles highlight the bird's position and corresponding blade positions as it approaches the moment of collision. Source: https://www.youtube.com/watch?v=1RcTjdY1aN4. (B) How a bird may fail to see the way ahead. Depiction of the vertical extent of the frontal visual field of an eagle (light grey) [52], showing how the blind area (dark grey) points in the direction of travel when looking downwards in flight. The dashed lines represent the median sagittal plane of the bird's head; the field of view is binocular everywhere in this plane.

The visual systems of birds differ from our own at every level from their optical arrangement through to their retinal composition and neural processing [49–51]. In conjunction with the bird's head direction, the arrangement of the visual field determines which parts of the environment are visible to the bird (figure 2) and can closely influence its behaviour at any given moment [52–54]. For example, many raptors have large blind areas that project above and below the binocular field in the forward-facing hemisphere [55,56]. They also look downwards when scanning the ground during flight, which makes obstacles ahead more likely to go unnoticed [54–56] and may explain their tendency to collide with aerial structures [55,56].

Most birds are tetrachromatic, with four types of single-cone photoreceptors whose spectral response is sharpened by pigmented oil droplets [50]. In addition to these chromatic cones, birds also have a double cone that is thought to mediate luminance- and motion-related visual tasks [57]. This visual system—often extending into the ultraviolet—should in principle aid object detection relative to human trichromatic vision, although effective UV sensitivity in larger species can be reduced by selective absorption in the ocular media, particularly the lens and cornea, in addition to optical scaling effects related to eye size [58–60]. This may explain why UV-reflective paint on wind turbines does not reliably reduce collisions [61].

A bird's ability to resolve fine detail depends on visual acuity, which is influenced not only by optical quality but also by the density and arrangement of photoreceptors across the retina. Diurnal birds tend to have high acuity compared with other vertebrates of similar eye size, prioritizing resolution over sensitivity [62,63]. Among diurnal raptors, acuity declines sharply under low light in some species (e.g. wedge-tailed eagles, *Aquila audax*) but remains relatively stable in others (e.g. brown falcons, *Falco berigora*) [64,65]. Many birds, particularly raptors, are bifoveate: each retina has two regions of high photoreceptor density, called foveae [66,67]. The deep fovea, aligned laterally, maximizes optical performance in peripheral vision, while the shallow fovea lies within the frontal binocular overlap and supports close-range frontal vision, albeit at lower resolution [67,68]. This contrasts with humans, whose single fovea provides high-acuity vision straight ahead [69]. Foveae are not present in all birds but are common in species that rely on precise visual discrimination for survival.

While acuity is important for resolving detail, object detection depends on contrast sensitivity—the ability to distinguish objects from their background. Birds generally have lower contrast sensitivity than mammals [70], but crepuscular species that do not maximize acuity may better detect obstacle edges under dim light [71]. Reduced acuity or contrast sensitivity may also amplify any potential effects of motion smear as a bird approaches a fast-spinning turbine [44].

Birds' brains are specialized for motion detection. Some neurons respond to increases in light (ON cells), others to decreases (OFF cells). This separation allows detection of both bright and dark edges, which is crucial for identifying obstacles. Birds also track changes over time, focusing on moving objects while filtering out stationary backgrounds. ON–OFF mechanisms are well documented in invertebrates [72] and incorporated into bioinspired models [73], providing a conceptual framework for understanding motion detection in birds [74,75]. These mechanisms give birds a reliable way to perceive motion and provide a biologically plausible explanation for how they detect obstacles—such as turbines—during flight.

Bird's motion perception also depends on spatial resolution, frontal binocularity and optic flow sensitivity. While high-acuity regions are oriented laterally or frontally, motion detection across the visual field is often coarser, enabling birds to detect large moving objects even if fine detail is unresolved [76]. Frontal binocular overlap enhances depth perception and motion detection directly ahead, which is critical for avoiding collisions. Birds also rely on optic flow—the overall pattern of motion across the retina—as a continuous cue for speed and distance [77]. Together, these features allow birds to navigate complex environments and are essential considerations for designing collision-mitigation strategies.

Even with these neural mechanisms, a bird's perception of a moving object such as a turbine blade may differ markedly from humans. For example, pigeons presented with drifting gratings—diagonal black bars moving horizontally against a white

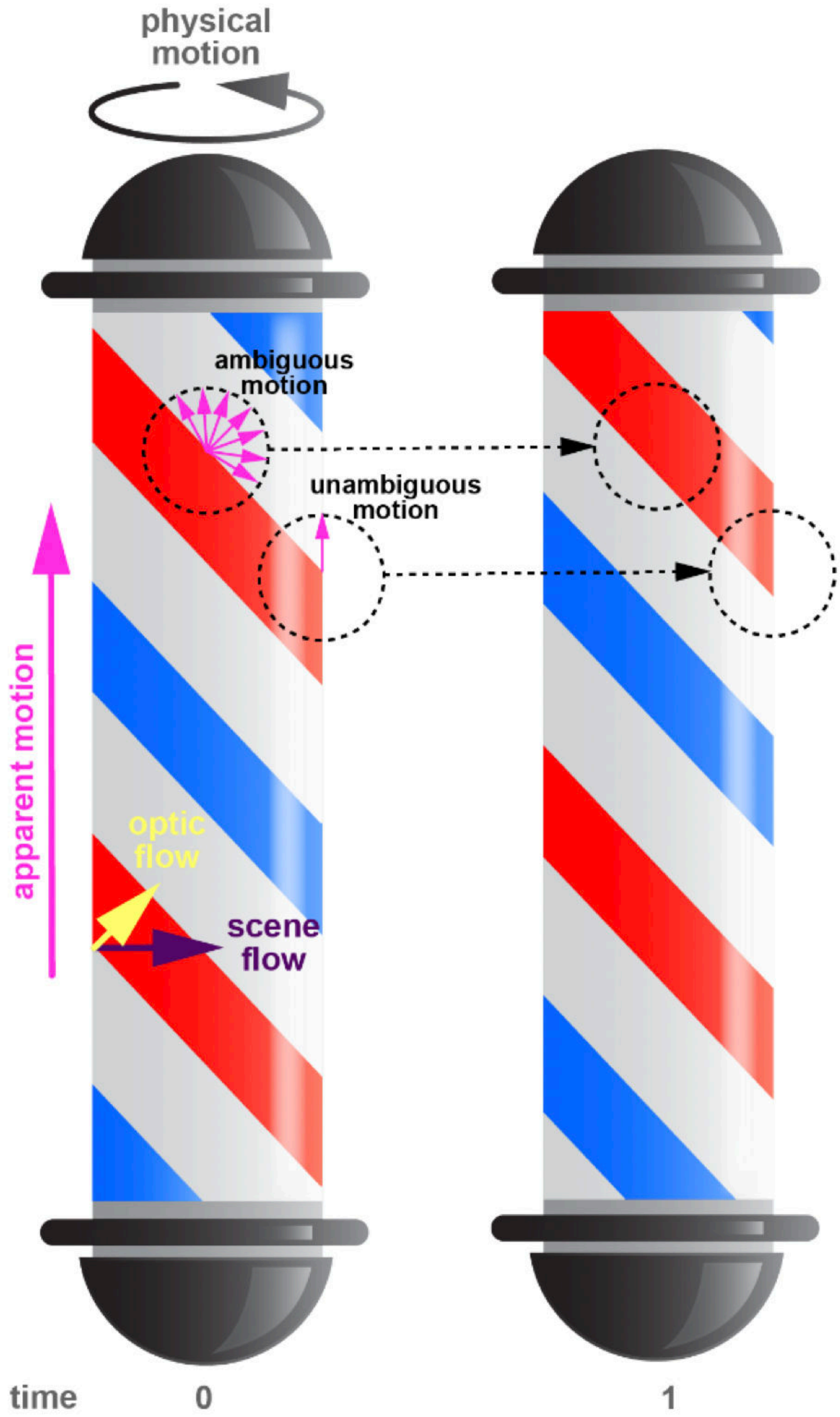

Figure 3. Illustration of the barber-pole illusion seen by humans, highlighting the biases implicit in our visual processing. When a diagonally striped pole rotates about its vertical axis, a human perceives the stripes as moving vertically (magenta arrow), despite the local optical flow (yellow arrow) being perpendicular to the stripes and despite the local scene flow (purple arrow) being horizontal. The apparent direction of motion is partly determined by whether the ends of the stripes are visible. If the edge of the pattern is visible, then the motion of a stripe can be inferred from the movement of its end (small magenta arrow), giving the appearance of vertical motion; if the edge of the pattern is not visible, then the direction of the stripes is ambiguous (small magenta arrows) and cannot be determined. This ambiguity is known as the aperture problem.

background—respond only to local optical flow perpendicular to the edge [78]. In contrast, humans perceive global motion patterns, where the diagonal stripes appear to move parallel to the shapes' axis (e.g. vertically, in the barber-pole illusion; figure 3). This indicates that pigeons do not experience the illusion as humans do, thus it remains unclear whether birds perceive a rotating turbine blade as a coherent spinning object or focus solely on local motion cues. If the latter, they may receive insufficient warning of an impending collision, emphasizing the need to consider not just visibility but also motion perception when designing turbine patterns.

6. Close-range guidance behaviours of birds

Birds' eyes are located close together, which limits the range over which stereoscopic depth estimation could possibly be effective, and there is evidence against the use of stereopsis for depth sensing by birds except owls [53,79,80]. Birds instead estimate the distance to foreground objects from their apparent motion [81,82], although there are several different ways in which this could be done. Because the retinal motion of an image feature depends on the ratio of its speed and distance relative to the observer, the optical flow produced by the observer's forward motion is slow for objects at a distance, but faster for objects at closer range [83]. For an observer moving at a known speed, the absolute distance to a foreground object can therefore be estimated from the optical flow it produces. However, since the absolute speed of a turbine blade is faster at the tip than at the base, this may affect distance judgement. Distance can also be estimated in a relative sense using the principle of motion parallax, wherein a change in position produces greater apparent motion of near than far objects [84]. Depth sensing via motion parallax therefore requires a background against which to measure the motion of a foreground object [85], but in an open wind farm setting, the background will often be a featureless sea or sky, so the availability of motion parallax cues may be limited to the turbine array itself.

Little is known of how birds avoid obstacles in open environments. However, in common with many insects [86], budgerigars (*Melopsittacus undulatus*) flying down narrow passages have been found to balance the speed of optic flow between their eyes, leading naturally to a centring response [77]. If birds moving through wind farms were to balance the optical flow of adjacent turbine towers in the same way, then this should likewise cause them to fly through the centre of the gap they create. On the other hand, Anna's hummingbirds (*Calypte anna*) have been found to attend to the vertical extent of features in their lateral visual field, moving away from taller visual features [87]. This kind of response could, in principle, produce avoidance of vertical turbine towers, but as these studies have involved slow straight flight in enclosed environments, using simple high-contrast grating patterns designed to induce strong optic flow, it is unclear whether their results can be extrapolated to open wind farm environments. Avian gap-aiming behaviours have also been studied in slow manoeuvring flight through cluttered indoor environments [88–91], but it is again an open question how these clutter negotiation behaviours will relate to flight behaviour in open wind farm environments.

Optic flow expansion cues can signal time to collision without requiring any explicit representation of either absolute or relative distance [92–94]. This has been best studied in relation to the use of such cues to control perching [92–94], but Anna's hummingbirds hovering at a feeder have also been found to exhibit flight responses consistent with the avoidance of visual looming stimuli signalling an impending collision [95]. However, a key difficulty with using looming stimuli for collision avoidance is that they only become effective at close range, which makes them more suitable for eliciting a last-ditch evasion response than a pre-emptive avoidance response. Moreover, because looming stimuli are associated with radial expansion of an object's image, the radial edges of a wind turbine have limited potential for generating looming optical flow, and this will be even harder to detect if the turbine blades are simultaneously turning (figure 4) and may vary according to which part of the blade (centre, mid, tip) a bird encounters. As a bird approaches a turbine, the nacelle and inner regions of the blades probably generate a prominent expanding optic flow field. This expansion can provide valuable information about the direction of travel and time to contact, allowing birds to estimate approach speed and collision risk through looming cues.

In principle, optical flow can be generated by pattern contrast on the surface of an object, or edge contrast with respect to the background. However, since a white or grey wind turbine displays little pattern contrast on its surface, edge contrast will be the dominant source of optical flow (figure 4). This will vary greatly with lighting conditions, viewing direction and cloud cover: for example, depending on the ambient conditions and visible background, the passage of a turbine blade could produce a brightness increment followed by a brightness decrement, or the reverse. In vertebrate visual systems, brightness increments and decrements are processed by separate ON and OFF channels [96], so the approach of the blade's leading edge will be sensed by the ON channel in the first case and by the OFF channel in the second. Brightness may be important to birds in other ways too. For example, flying insects have been found to target gaps in clutter using brightness cues [97], and birds may behave similarly [98]. This being so, the brightness of a turbine tower could serve as an attractor if it is perceived as a gap by a bird—particularly when viewed against a darker background—thus changes in weather will affect the contrast gradient between the turbine and more variable background (sky, land or sea). In addition, a turbine might act as a wind break, which could explain the tendency of ptarmigans, *Lagopus* spp., to collide with the bases of turbine towers in moorland environments [99]. Understanding how a wind turbine will appear to a bird under different ambient conditions therefore requires optical analysis of the light falling on the retina under a range of atmospheric conditions and from a range of viewing positions, coupled with physiological understanding of the response of the bird's visual system to this incoming light.

7. Why do birds collide with conspicuous objects?

Birds are highly accomplished at negotiating obstacles in their natural environment, so it is not immediately obvious why they should be prone to colliding with built structures such as wind turbines. In very general terms, there may be three possible categories of explanation: (i) they fail to see a wind turbine at all; (ii) they see a wind turbine but fail to perceive it as a hazard; and (iii) they perceive a wind turbine as a hazard but fail to take effective action. We have already given examples of the first of these in relation to visual fields (i.e. some species may not see ahead when the head is looking down), motion smear (i.e. a turbine blade may become invisible at very high speed) and visual contrast (i.e. a turbine blade may be difficult to detect under some lighting conditions). In addition, birds may be distracted by other birds (e.g. when involved in territorial, predatory or defensive behaviours).

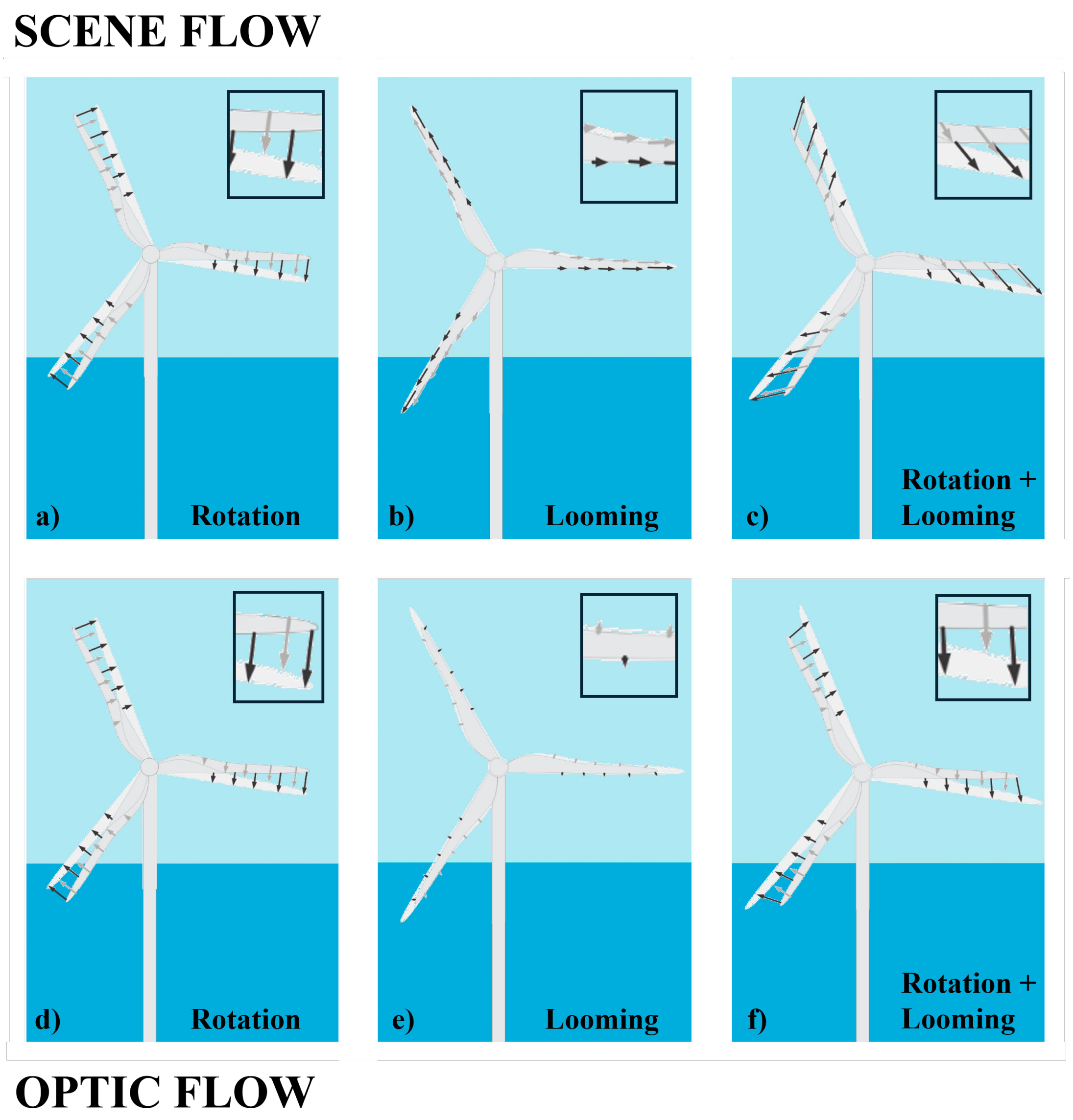

Figure 4. The motion flows experienced by an observer when viewing a wind turbine. Visual representations of the displacement fields (arrows) experienced by an observer as it moves directly towards the rotor hub of a wind turbine, representing the scene flow (i.e. the physical motion of the points being imaged; top row) and the optical flow (i.e. the local motion of the image contrast; bottom row). Left column: stationary observer viewing a rotating turbine (a and d); middle column: observer moving towards a stationary turbine (b and e); note that the looming cues present in the scene flow are barely discernible in the optical flow, which is because the edges of the blades are radial (see text for discussion); right column: observer moving towards a rotating turbine (c and f). Here, optic flow is considered to be generated by edge contrast and is, therefore, perpendicular to the blade's leading edge. The black arrows indicate the leading edge of the blade, while the grey arrows indicate the trailing edge.

Concerning the second category of explanation, we have described how the radial edges of wind turbines limit their potential for generating looming optical flow at a distance (figure 4), particularly when the blades are rotating and exacerbated by the variation in absolute speed along their length. The rotational motion of a wind turbine may therefore make it harder for a bird to perceive it as a collision hazard. Likewise, a bird's own rotational motion could also make it harder for it to detect an impending collision when turning. This is because rotational self-motion produces the same angular velocity of image motion at any viewing distance (cf. translational self-motion, which produces image motion in proportion to the ratio of velocity to distance). It follows that the rotational component of an optical flow field may overwhelm any translational component when turning unless the head is stabilized rotationally, which will limit a bird's ability to extract structure from motion.

Comparatively little is known about the gaze strategies of birds in flight, but zebra finches (*Taeniopygia guttata*) flying around obstacles [100] use a saccade-and-hold strategy [86], in which their head direction is shifted quickly in a saccadic motion, and then held stable with respect to the visual environment. Likewise, a recent study on Harris's hawks (*Parabuteo unicinctus*) used computer vision tools to synthesize the visual cues available to birds during obstacle avoidance and found that they fixated their gaze on the edge of the obstacle [101]. This gaze stabilization strategy relies on the bird being able to discern the obstacle's edge clearly. This is relatively easy against stationary obstacles but becomes risky when faced with moving objects such as a fast-rotating turbine blade, since edge-aiming only partially compensates for its motion—i.e. a bird flying over an upward-moving obstacle will have reduced clearance. Hence, whether birds perceive a wind turbine blade as a collision hazard may depend on the effectiveness of their gaze stabilization strategy in relation to moving obstacles.

Indeed, work on Harris's hawks has found they may not attend to vertical motion of a horizontal bar when deciding whether to fly above or below it [102]. Although surprising at first sight, this finding makes sense mechanistically if, in stabilizing its gaze with respect to the obstacle's edge, the bird loses the range information that would otherwise be provided by translational optical flow. It also makes evolutionary sense, because the visual systems of birds have evolved naive to human artefacts. Structures in the natural environment tend to move much slower than a bird flies, so it is a reasonable prior expectation that the apparent motion of an obstacle's edge will be due to the observer's own self-motion. Likewise, natural structures that do move, such as branches, tend to swing rather than to spin, so a lack of any innate understanding of rotary motion, coupled with a lack of any safe way to learn the risks this poses, may explain why birds do not necessarily perceive a rotating turbine blade as a hazard.

Although it is reasonably straightforward to see why birds may not have evolved to deal with fast-moving structures, it seems surprising that they should collide with static structures such as turbine towers [99]. We have already noted that bright structures could serve as attractors if perceived as a visual gap against a dark background, and while it is hard for us to imagine seeing a turbine tower in this way, the primary function of the frontal visual field of a bird appears to be for seizing food at close range, with the lateral parts of the visual field specialized for acute vision over longer distances [53,76]. More generally, birds flying in open airspace may not expect the environment ahead of them to be cluttered [6] and may therefore fail to display any kind of avoidance response to wind turbines at all [103]. Indeed, a prior expectation that open airspace will be free of obstacles is in effect built into the visual fields of soaring species that are unable to see what is ahead when looking down [54–56].

Few studies have considered the interaction of avian vision and flight behaviour when assessing why birds collide with conspicuous objects. To our knowledge, there has been no empirical work investigating the fine-scale steering strategies of wild birds negotiating obstacles in natural or built environments, let alone in the specific context of a wind farm. An important next step is therefore to ascertain exactly how collisions with wind turbines occur. Doing so requires a comparative approach because different species may exhibit different responses. For example, species that typically perform low-level flight, such as grouse or dynamic soaring seabirds, may not encounter the rotor-swept area at all, such that it is the turbine tower that poses the collision risk [99]. Such species will, therefore, require different mitigations to species that typically fly higher, such as raptors, that often enter the rotor-swept area [103]. Yet in ptarmigans, only 24% of carcasses were found within 10 m of the turbine base (and 0% for eagles), suggesting collision with the blades is the more frequent source of mortality overall [99]. New work is needed to assess the gaze of birds in the vicinity of wind turbines and to infer the behavioural processes which lead to a collision.

8. Wind turbine mitigation from a bird's perspective

Given the conclusions of the preceding section, a promising approach to mitigating bird collisions may be to modify the appearance of wind turbines to make them: (i) easier to see in the first place; (ii) easier to perceive as a hazard; and (iii) easier to respond to effectively. The focus of studies to date, as outlined below, has been on (i)—approaches to make the turbines more visible—and the resulting mitigations have not differentiated between (i), (ii) and (iii). One laboratory study tested how visual acuity influences pattern detectability in American kestrels (*Falco sparverius*) and red-tailed hawks (*Buteo jamaicensis*) [104], and found that a pattern of two broad black bands running across the width of a white mock turbine blade provided the highest detectability among the patterns tested, with narrower stripes providing lower detectability (figure 5). The same study also showed how certain environmental conditions such as dim illumination (e.g. dawn, dusk) or low contrast (e.g. haze, fog) can reduce a raptor's ability to resolve the image of a rotating blade [104]. This highlights the need to consider the spatial contrast sensitivity of birds in low-light conditions when designing stripe patterns or colours to improve blade visibility.

A second retinal electrophysiological study using American kestrels and computer-generated representations of rotating blades [44] aimed to develop blade patterns that would allow the photoreceptors to 'rest' for longer between successive visual stimulations, thereby reducing the effects of motion smear (figure 5). The best visibility was achieved by using a staggered thin-stripe pattern on all three simulated blades, or by combining a single black blade with two white blades [44]. Visibility depended on the distance between the eye and the blade image, the size of the blades and their rotation speed. Specifically, despite the higher angular frequency of a smaller diameter turbine, pattern visibility was maintained to closer distances with smaller turbines but was lost further away for larger turbines [44,105]. Background colour contrast was also found to be important, but above a critical retinal-image velocity, even the most effective pattern-background combinations lost their advantage and became blurred. The approach angle of the bird was also found to be important in designing effective blade-pattern deterrents. For example, a bird approaching the blade from the side sees only a small projected area, for which a suggested solution was to attach a black rectangle to the tip of one of the three blades, perpendicular to its long axis [44].

The main limitation of these laboratory studies is that they only evaluated the visibility of different blade patterns and did not investigate how successful they were at mitigating collisions. To date, there have only been two complete field studies testing the effectiveness of modifying the appearance of a turbine blade as a mitigation against bird collisions [45,99], and one preliminary study using UV paint [104]. These completed studies were conducted at the Smøla wind farm in Norway, using a Before–After–Control–Impact approach with fatality searches, spanning a total of 11 years pre- and post-treatment. The first study tested the efficacy of painting one of the three rotor blades black to improve detectability [45], which reduced the annual fatality rate across all bird species by over 70%, relative to neighbouring unpainted control turbines. The reduction in collision risk was most pronounced for raptors, perhaps owing to their higher visual acuity; however, the results of this study were based on only four painted turbines in the array and hence only very small sample sizes. The second field study at Smøla concerned the risk to low-flying ptarmigans from static turbine towers [99], painting the lower 10 m of the tower black. Overall, there was a 48% reduction in the number of recorded carcasses per search at the painted towers relative to neighbouring unpainted towers, which is consistent with the suggestion that some birds might perceive the brightness of an unpainted turbine tower as a visual

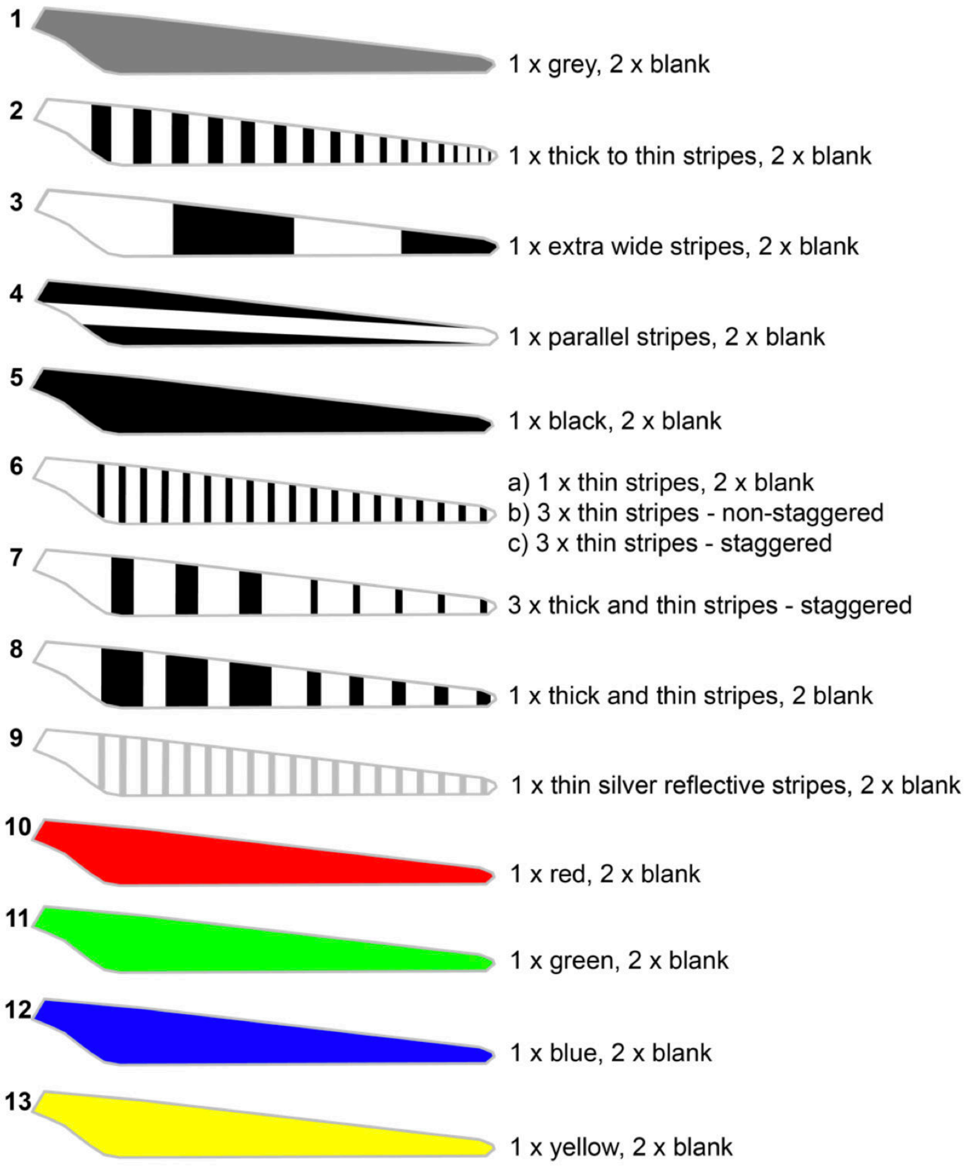

Figure 5. Summary of all the blade designs that have been tested experimentally (in electrophysiological studies and field trials) to date. Patterns 1–4 from McIsaac [104]: two wide black stripes (3) provided the highest conspicuity of the patterns tested under laboratory conditions. Patterns 5–13 from Hodos [44]: the highest visibility under laboratory conditions was achieved from a staggered thin-stripe pattern on all three blades (6c and 7; 'staggered' refers to the relative positioning of the stripes between the three blades), and from a single black blade combined with two white blades (5). All the blade colours tested by Hodos (10–13) were significantly more visible than a blank blade, with no significant differences between them, while the black blade tested by McIsaac (5) provided visibility most consistently across different backgrounds. To date, only the single black blade design (5) has been tested in the field [45].

gap. However, this effect was partly due to a large increase in fatalities per search at the control turbines, with no increase or decrease at painted towers. In summary, the results of these laboratory studies [44,104] and field trials [45,99] are promising, but for reasons we now explain, it is unlikely that the modifications they tested were optimal.

9. Refining blade patterns for improved collision mitigation

The visual appearance of a wind turbine, especially when coupled with rotation of its blades (figure 4), presents an unnatural stimulus to which birds are not well adapted to respond. Recalling categories (ii) and (iii) above, are there other modifications, even better than the basic mitigation of painting a turbine blade or tower black, that could help activate the natural collision avoidance responses of birds? In particular, are there other blade patterns that would make them easier to perceive as a hazard and easier to respond to effectively? Since answering this question fully requires new optimization experiments in the laboratory and field, we focus here upon identifying future study directions which might prove fruitful.

The finding that painting a wind turbine blade black is successful in reducing collisions of diurnal birds [45,99] makes sense given the limited contrast sensitivity of most birds [70]. Painting the blade black maximizes its achromatic edge contrast against a bright daytime sky, and thereby maximizes the optical flow stimulus associated with the blade's rotation. Unfortunately, painting a single black blade does not resolve the difficulty of detecting optical flow expansion cues at a distance, because it does not alter the fact that the blade's long edges are radial and therefore produce little looming optic flow as a bird approaches the rotor-swept area (figure 4). Furthermore, the notion that painting a blade black increases contrast does not take account of the changing light levels through the day and is likely to be counter-effective against a dark night-time sky. Indeed, it would not be surprising to find that painting a blade black increased collision risk at night or against dark backgrounds. Finally, painting a blade a uniform colour may not assist a bird in detecting a collision until the last moment, because the optical flow field that results from the blade's rotation will still be tangent to its circular path (figure 4), and evidence from tests of the barber-pole illusion (figure 3) suggests that birds attend only to the local optical flow [78].

While the original motivation for painting one blade black was to reduce motion smear by providing an alternating pattern of light and dark blur, it seems unlikely that the motion of a large turbine blade will generate motion smear except at very close range. The motion smear theory can, in principle, be tested by using detailed trajectory tracking to assess the collision rates across the painted and unpainted blades. If motion smear is causing birds to collide with the blades, then we would expect the collision rate to be equal across all blades (white or black), whereas if the problem is associated with contrast, then we would expect a reduction in collisions against the black blade compared with the white blades. If motion smear is not the problem, it is probably down to the visual contrast of the blades against the background.

Foreground–background contrast is known to be important in how birds perceive moving objects including turbines [106], but turbine placement is not usually considered in the context of the visual background against which an approaching bird will view the turbines. Flight height—and consequently horizon position—is likely to influence visual contrast since it will determine whether a turbine is seen against the sky, against terrestrial features or over water. For example, a high flight path in bright conditions may lead to reduced contrast or visual confusion when a turbine is viewed against a rippling and glinting sea surface, whereas in terrestrial settings, it may lead to increased contrast if the turbine stands out against a more uniform background, such as fields. Thus, flight height is not only important for determining whether a bird encounters the rotor-swept area in the first place, but also for determining how the rotor is perceived. This is an obvious reason why having a stripe pattern rather than a solid black blade may be beneficial, because it increases the internal contrast of the blade and can compensate for different visual backgrounds [7]. The importance of high-contrast patterns in birds has been shown by a study which linked the contrast colouring of the ventral wings of many species to a visual collision-avoidance mechanism [107]. Larger species, which are less manoeuvrable, and colonial species, which are subject to frequent encounters with conspecifics, were found to have more conspicuously contrasting ventral wings than smaller or non-colonial species, as they have a greater risk of in-flight collisions.

In the context of wind turbines, the only contrast patterns that have been tested in laboratory studies to date [44,104] have involved stripes running across the blade (figure 5). A recent review paper which considered vision-based mitigations in light of perceptual and behavioural aspects of seabirds has also suggested that improved visual contrast of turbines is best achieved by using achromatic patterns [7]. Martin & Banks [7] proposed that a pattern which increases the internal contrast of the turbine is superior to enhancing its contrast against the background [7]. They recommended dividing the blade into thirds along its length and having alternating blocks of black and white to create a flickering contrast pattern as the blades rotate. For the reasons already stated, this is likely to be a better method for improving the detectability of offshore turbines, for a range of diurnal bird species, than a single black blade. They also suggested applying a similar high-contrast pattern to the turbine tower, so that as each blade sweeps past it, additional flicker cues could enhance optical flow and improve detectability. However, while these transverse stripes on the blades should enhance optical flow expansion cues at a distance by introducing circumferential edges, they will produce minimal optical flow tangent to the blade's circular motion because of the radial direction of their associated contrast gradient. The contribution of pylon patterning to overall optical flow remains uncertain, but it may provide a complementary cue, particularly in situations where the blades themselves are less detectable against complex backgrounds.

The solution that we propose is therefore to orient the stripes diagonally across the blade, to promote both expansion and rotation cues (figure 6A), where variation in the orientation of the stripes along the blade's length may be designed to create specific patterns of optical flow as a bird approaches. Notably, patterns specifically designed to generate targeted optical flow—guided by the collision-avoidance responses observed in birds; which distinguishes our approach—do not appear to have been tested to date (figure 6). In addition, patterns should enhance the leading or trailing edges (figure 6B), making use of the finding that birds fixate their gaze on the edges of obstacles [101], although in this case the preferred location for a painted stripe will depend on the details of the bird's gaze strategy. Less structured or more random patterns may better reflect the kinds of visual textures encountered in nature and help birds recognize turbine blades as potential hazards. Collisions with small moving objects can also be avoided when the target remains on a constant bearing as its range decreases—a strategy raptors use when hunting in swarms [108]—and blade patterns could be designed to exploit this principle (figure 6C).

Motion vision in birds operates as a low-pass temporal filter, making birds more sensitive to slower motion while reducing detection of very fast-moving objects, such as turbine blade tips. Because the temporal frequency of the visual signal depends on both the blade's rotation speed and its spatial pattern through optic flow, different parts of a blade are detected with varying efficiency, with contrast near the tip perceived at higher temporal frequencies than near the hub, limiting detectability. To address this, turbine blades could feature spatially varying or non-uniform patterns, including radial (looming) or fractal designs with repeating visual motifs at different scales, to enhance rotational motion detection across multiple distances and scales, and potentially improve early recognition of the blades.

Any solution must take account of the practical implications for developers, and the risks associated with painting turbine blades black have yet to be fully quantified. Insurers are naturally risk averse, and possible overheating of a black-painted blade is a concern. On the other hand, it is also possible that there might be an aerodynamic benefit from painting only one side black. Studies in seabirds with black and white contrast plumage showed they may experience a 20% improvement in efficiency through enhancement of their lift-to-drag ratio caused by the differential heating of the boundary layer on the upper surface

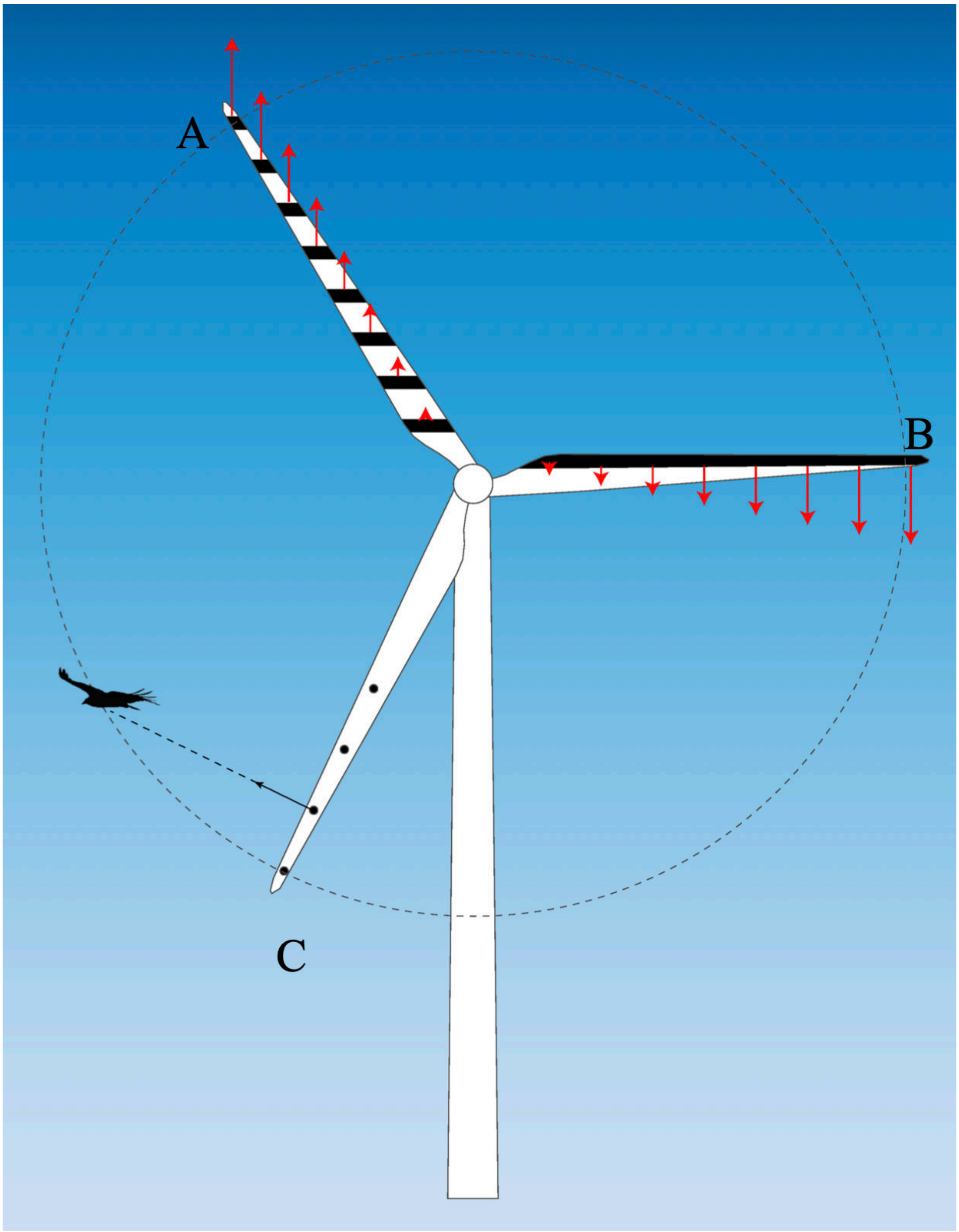

Figure 6. Bio-informed blade patterns which exploit the principles of bird vision. (A) Oblique stripes, designed to cause the blade's rotation to generate a combined looming and rotational stimulus (red arrows). (B) Trailing-edge stripe, designed to direct edge-targeting behaviour away from the leading edge and to maximize rotational optic flow (red arrows). (C) Object markers, designed to promote collision avoidance: at the instant shown, there is no motion cue directly indicating the bird's risk of being struck by the blade tip, whereas the second marker will be perceived as a collision hazard promoting evasive action (black arrow).

of a black wing [109]. Trials involving different coloured paints might also be warranted, given that in laboratory tests using a single coloured or black blade (figure 5) against naturalistic backgrounds, no significant differences in blade visibility for the birds were found [44]. Many European countries are already required to have red stripes painted at the tips of turbine blades for aviation purposes (to signify the proximity to an airstrip). Since red paint is authorized for use on turbines and is unlikely to cause overheating, it could be a practical alternative to black paint for insurance purposes. While any paint will absorb some solar radiation and cause minor heating, red reflects more light than black and is not expected to produce such harmful thermal effects, though its efficacy in reducing collision risk still requires empirical testing.

10. Summary and future work

A bird flying through its environment experiences a very different sensory landscape to a human moving through the same environment, so extrapolating entirely from human perception is not a reliable approach to assessing the collision susceptibility of birds [6]. Unfortunately, there has been comparatively little work leveraging what we already know of the visual systems and guidance behaviours of birds. Painting turbine towers and blades black (with reference to a bird's visual perception) has been shown to be effective at reducing collisions for some species, but we propose that stripe patterns will be more effective as they enable birds to better estimate the optic flow as they approach a turbine over a wider range of background types and light levels, by improving the internal contrast of the blades. Since red paint avoids many of the potential issues for developers, future work is needed to test whether red stripes are as effective as black in enhancing turbine detectability.

We therefore recommend testing these novel blade patterns—including both diagonal and horizontal stripes, which are not currently deployed—across a range of colours, starting with laboratory experiments and followed by field trials of the most promising designs. Laboratory testing could involve presenting patterned blades or simulated blade elements under controlled conditions (e.g. in aviaries or flight arenas) to assess their detectability and the elicitation of avoidance responses. A pattern would be considered successful if it measurably enhances visual salience or triggers behavioural responses indicative of collision avoidance, such as changes in approach distance, reaction time or steering behaviour. These experiments require an understanding of both the underlying visual physiology and the close-range guidance behaviours birds use to avoid obstacles.

One approach to evaluating pattern effectiveness is to measure the centring response; the tendency of a bird to position itself equidistant between visual boundaries while flying through a narrow passage, such as a tunnel or corridor. This response can reveal how different blade patterns—diagonal, horizontal or absent—affect a bird's perception of a safe flight path. Patterns that are more visually salient may elicit stronger or earlier centring behaviours, providing an indicator of enhanced collision avoidance [77].

More broadly, studies should consider the bird's flight trajectory relative to the turbine, since the retinal image velocity of the blades depends on both their distance from the bird and their rotational speed. Simply knowing the rotation speed of the blades is insufficient to predict visibility or detectability without accounting for these spatial and behaviour factors. These elements can be explored using controlled flight tunnels, virtual reality simulations or motion-capture tracking of free-flying birds in semi-natural conditions. Modelling the behavioural algorithms birds use to navigate three-dimensional flight paths through wind farms can further inform blade design, drawing on simulation approaches previously applied to gap-oriented steering [88,89] and target-oriented pursuit behaviours [110,111].

Taken together, these approaches allow researchers to quantify how different blade patterns influence approach angles, steering responses and avoidance behaviour. The ultimate goal is to enhance the overall conspicuity of turbines under a range of natural conditions, ensuring that birds detect the structure in time to avoid collisions.

Research into the interaction between bird flight and vision has confirmed that optical flow cues induced by self-motion are important for estimating the direction of travel and time-to-contact with objects when navigating through artificial environments [77,100] and performing perching manoeuvres [92,94]. However, species with different visual characteristics and flight behaviour will differ in their reliance on different kinds of visual cue. Translational optic flow cues are limited during cruising flight at altitude, so motion parallax with respect to background features may be crucial to a bird's ability to detect sparse foreground objects. Such information may be lacking when turbines are viewed against the backdrop of an open skyscape or seascape. Likewise, an animal also needs body-scaled information about its environment, so a lack of reference features in the proximity of an offshore wind farm may cause birds to misjudge the size of turbines and hence where is safe to fly.

Given the rate at which new wind turbine installations are being planned and built, research is urgently needed to develop and test blade patterns that enhance visibility and reduce bird collisions. Future work should therefore focus on the efficacy of bio-informed blade patterns and colours under different environmental and lighting conditions. This can be assessed through a combination of laboratory experiments, field studies and long-term monitoring, providing direct evidence of which visual modifications are most effective at enhancing conspicuity and eliciting timely avoidance responses. In addition, several complementary areas of research can help inform the design of these blade patterns and provide mechanistic insight into bird–turbine interactions:

- Visual guidance strategies of birds in flight. Using photogrammetry to record head movements, behavioural algorithms to model collision avoidance [89], or reconstructing the optic flow cues [101] to identify how birds perceive turbines and where they fail to detect the path ahead, thereby revealing which blade pattern features (e.g. orientation, contrast, spatial scale) are most likely to enhance early detection.
- Focus of attention in collision-prone species. Recording the frequency and amplitude of head movements during flight towards large stationary structures may reveal which part of the turbine—blades or tower—are most salient.

Importantly, all 'real-world' trials need to consider the statistical power and feasibility of collecting sufficient data across different conditions—long-term studies on a few turbines may fail to capture small but meaningful improvements in collision rates, but larger sample sizes are resource-intensive, so a balance is required.

A great diversity of bird species is affected by collisions with wind turbines, each with their own specific as well as general perceptual challenges. It is therefore likely that no universal solution exists for minimizing bird collisions. The development of more effective mitigation schemes could speed up consent processes and reduce reliance on blunter measures (i.e. those that do not address the root cause of collisions) and costlier approaches (e.g. shutdown-on-demand), providing a commercial incentive for energy companies to help conserve and promote biodiversity. The simplest mitigation of painting turbines black has been shown to significantly decrease bird collisions, albeit across a very small number of species and turbines, and thus may not be the 'silver bullet'. Energy companies will be required to consider issues relating to the visual effects on humans [112], aviation regulations, the mechanical effects on the blades (e.g. the effect of temperature on their durability), and the lead-in times for permissions, preparations, application and curing of paint (a much larger consideration within operational wind farms). Unlike the findings from Smøla [45], a recent study in The Netherlands that tested a single black blade on seven turbines found no significant reduction in gull collision rates [113]. This result suggests that the effectiveness of a single black blade may be species-specific or context-dependent, highlighting the need for further work to understand which conditions, and for which species, blade patterning is likely to be effective.

Collision-reducing solutions require a transdisciplinary approach to simultaneously resolve the remaining challenges, involving action from manufacturers, developers and operators, as well as consenting agencies and non-governmental organizations (NGOs) [114]. We conclude that the appearance of wind turbine blades matters, as it directly impacts how birds interact with them. The collision problem is therefore more complex than a bird simply not looking ahead or not having the turbine blade in its visual field, because there is already evidence that painting blades or turbines affects collision risk in some species. But without behavioural studies of how different species respond to different patterns, whether in simulation, in the laboratory or in the field—we cannot yet say how successful blade painting may be. With 14% of birds now threatened with extinction globally [115], it has never been more critical to identify solutions that avoid creating sensory traps around wind farms. This conflict between environmental goals—expanding renewable energy while protecting wildlife—can only be resolved through collaboration between wind turbine manufacturers, wind farm developers, government, academia, environmental consultancies and NGOs. Such collaboration is essential to developing new technologies and policies that mitigate bird collisions without significantly limiting clean electricity generation [116], thereby enabling us to tackle the coupled climate and nature emergencies together.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. Data extracted from the literature are provided as supplementary information.

Supplementary material is available online [117].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. C.H.B.: conceptualization, investigation, writing—original draft, writing—review and editing; G.K.T.: conceptualization, investigation, resources, writing—review and editing; S.J.P.: writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

Funding. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 682501). This paper was also supported by funding from gifts in wills to the British Trust for Ornithology (BTO) for which we are extremely grateful. Additional funding was provided by the Biotechnology and Biological Research Council (BBSRC) grant to S.J.P. and G.K.T. (grant no. CBR01610).

Acknowledgements. We thank Marco Klein Heerenbrink, Aonghais Cook and Philipp Boersch-Supan for helpful discussions, and Marco for assistance with visualizations. We also thank Niall Burton for reviewing and providing comments on an earlier draft of the manuscript. We are grateful to the anonymous reviewers who improved our manuscript.

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