

Detection of wind turbines rotary motion by birds: A matter of speed and contrast

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Abstract

To reduce bird collisions on wind turbines, Automatic Detection Systems have been developed to locate approaching birds and trigger turbines to slowdown to 2–3 rotations per minute (rpm). However, it is unknown whether birds can detect this reduced speed and avoid the turbine. We conducted an operant conditioning experiment on domestic doves (*Streptopelia roseogrisea*) and Harris's hawks (*Parabuteo unicinctus*) to assess their ability to discriminate between stationary and rotating miniature wind turbines, depending on the rotation speed and the contrast between the white blades and the background (only for doves for the latter). At high contrast, regardless of the speed tested, hawks were able to differentiate between the rotating and stationary turbines, while doves were not able to discriminate the slow-rotating turbine (3 rpm) from the stationary one. The discrimination threshold increased to 8 rpm for the doves when the contrast was reduced. Our results suggest that the residual wind turbine speed of 2–3 rpm may not be detected by all bird species under all environmental conditions. Increasing the contrast between wind turbines and their environment may improve the detection of low-speed rotation by some birds, otherwise, complete turbine shutdown should be recommended.

KEYWORDS

bird vision, collision, contrast, motion blur, rotary motion, speed detection, wind turbine

1 | INTRODUCTION

The development of renewable energy is crucial for the energetic transition worldwide (IPCC report, 2022). Wind farms have been installed across the globe for three decades, with an increase of 53% in wind power production in 2020 (GWEC, Global wind report 2021). However, this form of energy production may have negative

impacts on biodiversity, particularly on bats and birds (Drewitt & Langston, 2006; Kunz et al., 2007). Although actual avian mortality from collisions with wind turbines is not easily quantifiable, the average number of collisions is estimated to be 8, 7, and 3 birds per wind turbine per year in Canada, France, and Japan respectively (Kitano & Shiraki, 2013; Marx, 2017; Zimmerling et al., 2013). Bird collisions are a concern on all

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continents, but appear to be dependent on the site, type of wind turbine and bird species (Marques et al., 2014; Thaxter et al., 2017).

To reduce these collisions, a number of mitigation strategies are increasingly being implemented. Among mitigation measures, several companies are developing Automatic Detection Systems (ADS thereafter), combining cameras or radars to detect approaching birds, with a computer to analyze bird trajectories and eventually send orders to deter birds and/or “shut-down” the wind turbine (e.g. May et al., 2012; McClure et al., 2021). Yet, in practice when birds are detected, blades are not completely stopped. Wind turbines are generally slowed down by changing blade pitch in opposition to wind direction, aiming to reduce angular speed from a production speed of 15–20 rotations per minute (rpm) to a residual speed of 2–3 rpm (May et al., 2012). Engineers developing ADSs assume that birds (1) are looking at wind turbines, (2) are able to detect them, (3) associate them with potential risk and (4) are able to avoid them when the rotation speed is low. All these points are important and should be addressed to understand why birds collide with wind turbines. We report here a study aiming to give an answer to the second point.

First, the visual system of some birds, such as visual fields, spatial resolution, spectral sensitivity and/or contrast sensitivity may not be adapted to detect wind turbines (Martin, 2017; Martin et al., 2012). For example, to prevent conflicts with the human neighborhood, wind turbines are sometimes painted in a way that they appear inconspicuous in the landscape for human observers, with low contrast between the wind turbine and its background. Birds' contrast sensitivity being, in many species, relatively low compared to humans (Blary et al., unpublished; Ghim & Hodos, 2006; Lind et al., 2012; Potier et al., 2018), this could lower bird abilities to detect wind turbines in the landscape especially in low contrast conditions, such as in fog.

Second, when the contrast is high enough for the birds, they may be able to see stationary wind turbines, but whether this is the case while rotating remains unknown. The visual challenges of seeing a moving object are different from those of a stationary one (Land, 1999). When an object moves with increasing speed, it is perceived as becoming progressively blurrier (Pääkkönen & Morgan, 1994). This phenomenon is called “motion smear” or “motion blur”. Hodos (2002) suggested that motion blur depends on the size and speed of the object, the distance from the viewer as well as the speed at which birds can process time-varying visual stimuli, that is, their temporal resolution. Species with high temporal resolution would perceive wind turbines as more blurred at higher rotating speeds than species

with low temporal resolution. A small and fast-rotating wind turbine at a given distance will also induce more motion blur than a larger and slower one for American Kestrels (*Falco sparverius*) (Hodos, 2002). As a result, a wind turbine of 100 m diameter rotating at 14 rpm would appear blurred at 20 m for this species. However, Hodos (2002) used an electroretinogram experiment to determine this threshold, while a behavioral-based experiment may better reflect the actual perception of birds.

If blurring at high speed seems obvious, low rotation speed may also be problematic. For instance, in humans, an object moving at low speeds is evaluated as being much slower than its actual speed. Under a speed threshold, this may create a stationarity illusion (Cavanagh et al., 1984). This threshold is negatively correlated to the contrast between the object and the background (Campbell & Maffei, 1981). As both humans and birds have a conceptually similar camera-type eye (Land & Nilsson, 2012), it may be possible that birds detect a wind turbine rotating at low speed, or with low contrast with its background, as stationary.

If slow-speed rotating wind turbines are assessed as stationary by birds, the wind turbines' “shut-down” triggered by ADS may be counterproductive as it may indeed increase the likelihood for birds to take the decision to cross the rotor. Understanding how birds see the rotation of wind turbines is necessary to improve the efficiency of mitigation measures. We performed a set of operant conditioning experiments on two species with different ecologies: domestic dove (*Streptopelia roseogrisea risoria*) and Harris's hawk (*Parabuteo unicinctus*). Both species belong to avian phylogenetical orders (respectively Columbigiformes and Accipitriformes) well known to be impacted by collision with wind turbines (Thaxter et al., 2017) and their visual systems have been well studied (Martin, 2017; Potier, Mitkus, et al., 2020). We aimed to identify (1) if these birds are able to distinguish high turbine rotation speeds, likely blurred, from stationary turbines; (2) if the residual rotation induced by ADSs (2–3 rpm) can be differentiated from a stationary turbine and (3) if the contrast between the turbine and the background impacts the detection of the blades' speed by birds.

2 | MATERIALS AND METHODS

2.1 | Experimental subjects

Experiments were carried out in two different bird housing sites in France. The experimental subjects were five healthy adult domestic doves (hereafter doves) housed at the Centre for Functional and Evolutionary Ecology

(CEFE) and five healthy adult Harris's hawks (hereafter hawks) housed at the falconry park Les Ailes de l'Urga (Table S1). Birds were kept in outdoor aviaries, subjected to natural lighting and photoperiod. When experiments were planned during the day, birds were fed only during the experiment. On non-experimental days, they were fed in the morning. Doves were fed 10 g per day of a seed mixture specially designed for doves (Prestige Doves, Versele Laga), which corresponds to the quantity of food ingested per day ad libitum. Hawks were fed with chicken meat and maintained at above 90% of their full weight. For both species, water was ad libitum. Training and experimentation took place 3–7 days per week.

2.2 | Ethics statement

Experiments were carried out in accordance with the European Union directive on the protection of animals used for scientific purposes (2010/63/EU) and the French legislation. The protocol and species studied were approved by a local French ethics committee in animal experimentation and authorized by the French general direction of research and innovation (APAFIS# 31775-2021041311196892 v5). In agreement with French law, hawks were handled by their usual trainers under the permit of the park Les Ailes de l'Urga (national certificate to maintain birds no. DDPP-19-108 and for public presentation no. 27-10-2006 and no. DDPP-18-283).

2.3 | Experimental set-up

Two miniature wind turbines (hereafter “turbines”) were designed for the experiment (Figures 1 and S1a). Blades were made of white PVC 10 mm thick (expanded PVC Celuka, Prolians). Their design and proportion correspond to a turbine diameter of 160 cm, a blade width varying between 7 cm at the base and 2 cm at the tip, and a hub diameter of 7 cm. Blades and the hub were attached to a horizontal rod connected to an electric motor (SD1-4.2A-21, IMO Precision Controls) that allowed the turbines to rotate clockwise, or counterclockwise from 3 to 286 rpm. The rotation speed of these turbines was measured using a 3-axial accelerometer (Axytrek, Technosmart) placed at the center of the hub, pointing downward. The frequency of oscillations on the X-axis of the accelerometer were then used to obtain the number of rotations per minute (Figure S2).

For doves, the experiment took place in an outdoor aviary built as a Y-maze set-up (see Figure 1a,b for aviary dimensions), with one starting arm where the bird was released, and two peripheric arms where the bird had to

make a choice (Figures 1a,b and S1b). Windbreakers were placed all around the aviary to limit visual external stimuli, and a tarpaulin was placed on the ground to prevent birds from accessing possible food on the soil.

One turbine was placed at the end of each peripheric arm, with the hub at 1 m high. A plexiglass panel of 200 × 200 cm and 3 mm thick was placed 10 cm in front of each turbine to prevent the bird from coming into contact with the turbine and to prevent the airflow generated by the rotating turbine from entering the aviary (Figure 1a,b). A remotely triggered food dispenser was installed 45 cm from each turbine, 65 cm high, (Figure 1a,b). A wooden perch was attached to the dispenser for the birds to land on when making a choice.

A black-painted wooden panel (Black, mat, Dulux valentine) was placed 10 cm behind each turbine (Figure 1a,b). This panel could be covered by a dark gray fabric (ref: 223969, Mondial Tissus, <https://www.mondialtissus.fr/>) or a light gray fabric (ref: 231272, Mondial Tissus) in order to decrease the contrast between the white turbines and the background. The Michelson contrast between the turbine and the background, measured every experimental day with a luxmeter (Hagner Screen-Master, B. Hagner, Sweden) because of outdoor conditions, was 0.88 ± 0.002 (mean \pm SE) for the black background, 0.56 ± 0.004 (mean \pm SE) with the dark gray fabric and 0.25 ± 0.003 (mean \pm SE) with the light gray fabric. Since the experimental aviary was outdoors, the illuminance and the contrast between the turbines and the background were measured at the beginning of each session.

A box (28.5 × 25.5 × 25.5 cm) made of five wooden panels and a 3 mm thick plexiglass transparent door was used as a starting point for each trial, allowing the birds to see the turbines. The illuminance at the wooden box was $43,776 \pm 1,691$ lx (TES 1339 Light Meter Pro., TES Electrical Electronic Corp.). This box was placed 110 cm from the ground, at the entrance of the starting arm, and 300 cm apart from each turbine (Figure 1a). Given the proportions of the turbine (width/length), this situation was equivalent to a bird looking at a 100 m diameter real wind turbine from a distance of 187.5 m.

As birds were placed at 3 m from the blades when they made the choice, the corresponding spatial frequency was $1.32 \text{ cyc deg}^{-1}$. This ensures that turbines were visible to the birds, as the maximum Rock doves' (*Columba livia*) visual acuity is 18 cyc deg^{-1} (Hodos et al., 1976) and the lowest Michelson contrast detected for a spatial frequency of $1.32 \text{ cyc deg}^{-1}$ is 0.08 (Hodos et al., 2002).

For the hawks, the experiment took place in a windowless room, lit by a ceiling lamp (Trådfri LED 1000 lm, IKEA) and a light diffuser ((LEE filters 452, Andover,

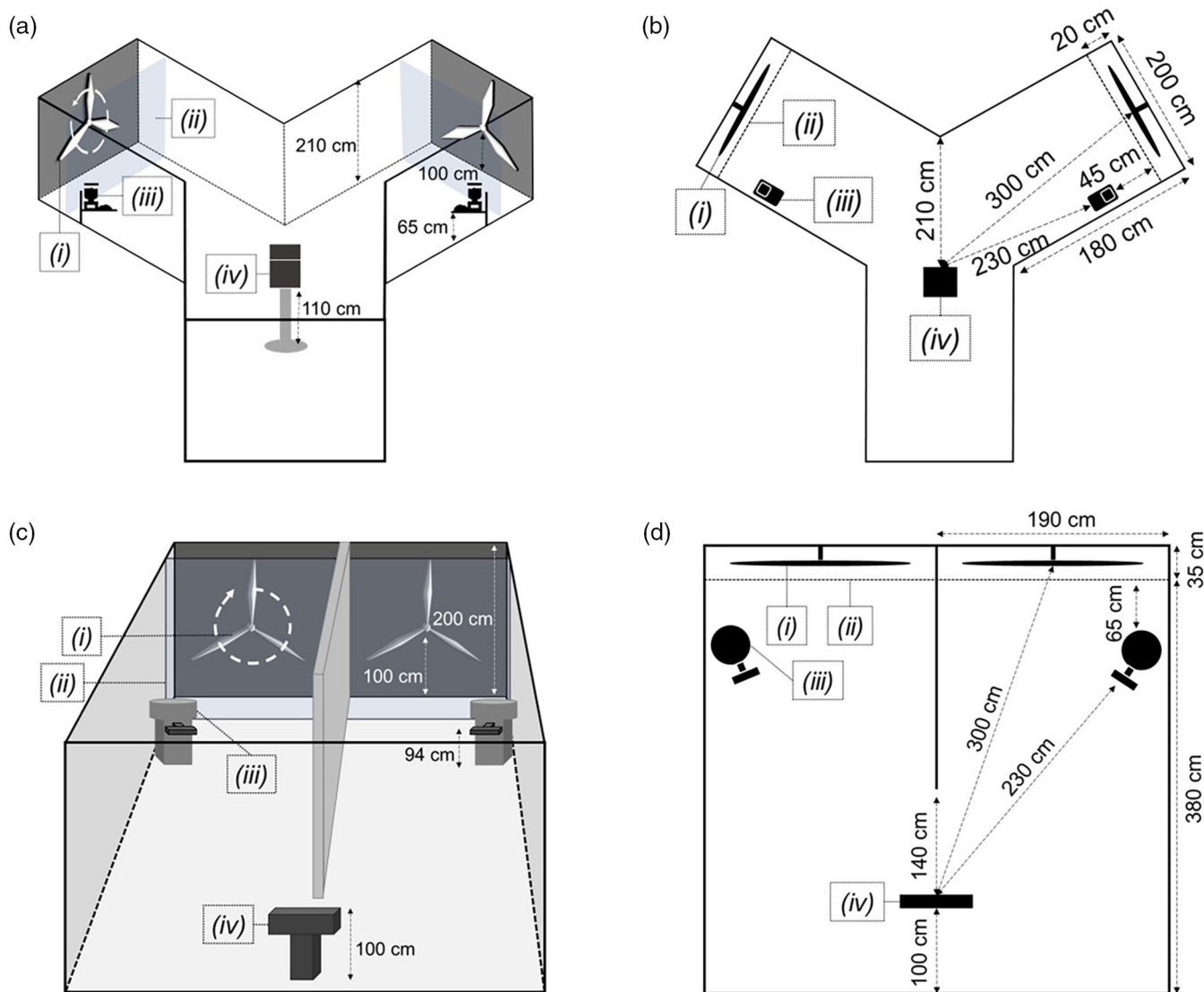


FIGURE 1 Experimental set-up in 3D for doves (a) and Harris's hawks (c) and 2D for doves (b) and Harris's hawks (d), with (i) wind turbines, (ii) plexiglass panels, (iii) feeders, and (iv) the bird starting point.

UK) (Figures 1c,d and S1c). The same miniature wind turbines used for doves were placed side by side at 1 m high facing the bird, separated by a 175 cm long, two meters high, wooden panel (Figure 1c,d). As for the doves, a plexiglass panel of 190×200 cm and 3 mm thick was placed 30 cm distant from the turbines and a black-painted wooden panel of the same size was placed behind it (Figure 1c,d) (Black, mat, Dulux valentine). The Michelson contrast (value of 1) between the white turbines and the black background was measured once (Hagner ScreenMaster, B. Hagner, Sweden) because of constant indoor conditions. Hawks were placed on a perch in a wooden box of $120 \times 100 \times 60$ cm at 1 m height, in the middle of the room, placed 3 m from each turbine (Figure 1c,d). The illuminance at the wooden box was 19.67 lx (TES 1339 Light Meter Pro., TES Electrical

Electronic Corp.). A remotely triggered food dispenser was installed 65 cm from each turbine, 94 cm high, symmetrically on each side of the room (Figure 1c,d). A wooden perch was attached to the dispenser. Every wall of the room, except behind turbines, was covered with a gray fabric (ref: 223969, Mondial Tissus).

2.4 | Behavioral experiment

Experiments took place from April to June 2022 for doves and from May to July 2022 for hawks. We used an operant conditioning technique, involving conditioning and testing phases. The conditioning phase was performed with the highest contrast, that is, black background. For doves, the testing phase was first performed with the

maximum contrast, then with the intermediate contrast and finally with the lowest contrast. Due to the limited time available for experiments with hawks (5 weeks), hawks were tested only with the highest contrast, that is, black background.

2.4.1 | Conditioning phase

Birds were required to choose between two stimuli. The positive stimulus, rewarded, was a stationary turbine. The negative stimulus, unrewarded, was a rotating turbine. Two rotation speeds were used as negative stimuli (8 or 21 rpm), representing the most commonly encountered lower and higher turbine rotation speeds. This limits the risk for a bird being conditioned to avoid a specific rotation speed rather than being conditioned to the stationary turbine. The side of the turbine (i.e., left or right), direction of rotation (i.e., clockwise or counter-clockwise) and rotation speed of the negative stimulus was changed in a pseudo-random order (i.e., the negative stimulus was not presented on the same side or direction of rotation or speed for more than three consecutive trials). To prevent the bird from selecting the turbine based on the noise produced by the rotation (54 ± 1 dB; mean \pm SE; measured with the D cibel X—dB Sonom tre application on a Smartphone), a white noise corresponding to an engine noise was broadcast (58 dB).

A session consisted of 16 trials for doves and 32 trials for hawks. Differences between species are justified by the quantity of food (reward) they can ingest per day. Therefore, for each session, the negative stimulus was presented eight times (four in each direction of rotation: two at 8 rpm and two at 21 rpm) on each side for doves and 16 times (eight in each direction of rotation: four at 8 rpm and four at 21 rpm) for hawks.

Between each trial a black cloth was placed in front of the bird, to prevent it from seeing the stimulus change. The cloth was then removed to let the bird see both turbines and make a choice. To ensure that birds take enough time to observe the two turbines before choosing, the plexiglass door of the dove box was opened only after 20 s. For safety reasons we were not able to implement this procedure for hawks, they could therefore fly directly to one of the two turbines as soon as the black cloth was removed. If the bird chose the positive stimulus, a small amount of food (around 10 seeds for doves and 3 g for hawks) was given to the birds through the dispenser. The experimenter was hiding behind the bird's starting position. At the end of each trial, doves were placed back gently in the box, while hawks returned to the box by themselves. One session per bird was conducted daily for doves, and one to two sessions daily for hawks. When a

bird reached 75% correct choices in four consecutive sessions for doves and 80% correct choices in two consecutive sessions for hawks, we ended the conditioning phase and started the test phase. Initially, the same threshold of 80% of correct choice was chosen for both species (as Haller et al., 2014; Potier, Lieuvain, et al., 2020), but as the number of trials per session was low for doves, we had to decrease this threshold to 75% for this species (as Olsson et al., 2015; White et al., 2007). This threshold still ensures that it is not a random choice (binomial test, $p < .05$).

2.4.2 | Testing phase and data analysis

As for the conditioning phase, one session per day, with 16 trials per session, was conducted with each dove, 5–7 days a week. One to two sessions per day of 32 trials were conducted with each hawk 5 days a week. To ensure that birds were still conditioned, each test session started with four easy trials (negative stimulus rotating at 21 rpm), one on each side and in each direction of rotation. These four easy trials were not considered in our results.

Contrary to McIsaac (2001) and Hodos (2002) who used rotation speeds higher than 40 rpm, we tested five rotation speeds (3, 5, 8, 16, and 21 rpm) (Table 1), reflecting the range encountered in real wind turbines (from 5 to 30 rpm in production and 2–3 rpm after ADS trigger) (Khalfallah & Koliub, 2007). We also tested the maximum speed that our experimental turbines could reach (286 rpm), to determine whether birds can still differentiate it from a stationary one (even if a blur effect may appear). Due to limited time, 21 rpm was tested only for doves under high contrast. Each combination of speed and contrast was presented 32 times (16 times on each side, eight times clockwise and eight times counter-clockwise) and in a pseudo-random order within each session.

Binomial tests were performed with R v. 4.1.2, using a Holm–Bonferroni corrected statistical threshold for each test, calculated with a significance level of $p = .05$. Mean values are presented \pm standard error.

3 | RESULTS

The five doves and three (out of five) hawks were successfully conditioned to the experiment. The conditioning phase duration ranged between 10 and 32 sessions for doves and 9 and 18 sessions for hawks (see Table S2 for information about the number of sessions per bird).

Blade rotation speed (rpm)	Blade-tip linear speed (m.s ⁻¹)	Blade-tip linear speed (deg.s ⁻¹)	Blade-tip retinal image speed (dva.s ⁻¹)
3	0.25	18.24	4.86
5	0.44	31.26	8.34
8	0.70	50.16	13.38
16	1.36	97.32	25.95
21	1.80	128.58	34.29
286	23.94	1714.26	457.17

Note: See Appendix S1 for the retinal image speed calculation.

3.1 | Effect of rotation speed at maximum contrast

All doves were not able to discriminate between turbines that were stationary and those rotating at 3 rpm when the black background was used. However, all of them were able to differentiate the two stimuli at higher rotation speeds (Table 2; Figure 2).

Hawks were able to discriminate between stationary and rotating turbines at every rotation speed if considering a significance threshold of .05, even though several results were very close to the significance threshold. However, when the Holm-Bonferroni correction was applied, only one individual out of the three was able to differentiate the two stimuli at 5 rpm (Table 2; Figure 2).

3.2 | Effect of contrast at different speeds

For doves only, results with the intermediate contrast (dark gray background) were similar to those with the maximum contrast (Table 2; Figure 2). However, under the low contrast condition (light gray background), the majority of doves were able to discriminate between a stationary and a rotating turbine only at speeds higher than 8 rpm (Table 2; Figure 2), even if individual differences were found at each rotation speed (Table 2; Figure 2).

4 | DISCUSSION

To our knowledge, our study is the first to investigate birds' detection of turbine rotation depending on speed and contrast. We found that the detection of rotation differed between species, with hawks being able to differentiate between a stationary and a rotating turbine regardless of rotation speed (except at 5 rpm if considering the Holm-Bonferroni correction), while doves failed at the lowest speed (3–5 rpm, Table 2; Figure 2).

TABLE 1 Rotation speeds and equivalences in linear speeds used in the experiment.

Decreasing contrast between the blades and the background also increased the rotation speed threshold at which a majority of doves perceived the blades as stationary (Table 2; Figure 2).

Both species were able to discriminate between a stationary and a fast-rotating turbine. Hodos (2002) associated a high speed of the image on the retina (expressed in degrees of visual angle per second (dva s⁻¹); Appendix S1) with a motion blur effect. For American Kestrels, a blurring effect would appear when the speed exceeded 200 dva s⁻¹ (corresponding to 125 rpm in our experimental conditions; Appendix S1) (Hodos, 2002). At 286 rpm, our turbine would induce an image speed on the retina of 457 dva s⁻¹ (Table 1; Appendix S1). If the limit of 200 dva s⁻¹ for American Kestrel was also true for doves and hawks, we can assume that a motion blur effect was present at this speed, but that our birds were still able to differentiate between a blurred turbine and a stationary one.

While in our study all hawks were able to detect a rotation speed of 3 rpm, doves were not. It is possible that this 3 rpm threshold varies slightly between individuals and between species. To our knowledge, misestimation of an object's speed has been studied in humans only (Vaziri-Pashkam & Cavanagh, 2008). Below 60 rpm (i.e., 20 rpm in our experiments as turbines have three blades), humans underestimate the rotation speed of an object, which may ultimately lead to an illusion of stationarity at very low speeds (Vaziri-Pashkam & Cavanagh, 2008). Whether this is the case for birds remains to be studied in depth, but our results suggest that it may be the case in birds too, as doves detect the rotation speed of 3 rpm as static. For hawks, the results for the low-speed threshold were less clear and were dependent on the statistical method applied, with values of 3 and 5 rpm close to the significance limit fixed at 0.05. The individual variation of hawks observed at 5 rpm when the Holm-Bonferroni correction was applied could be due to an overcorrection of the significance level (Streiner & Norman, 2011). One explanation could be that the speed threshold for hawks might be very close to

TABLE 2 Percentage of success of birds, confidence interval (CI; in brackets) and *p*-value (*p*; binomial test; in gray when $p \leq$ Holm-Bonferroni threshold).

Species	Wind turbine's background	Individual	Rotation speed (rpm)					
			3	5	8	16	21	286
			Success (%), <i>p</i> (95% CI)	Success (%), <i>p</i> (95% CI)	Success (%), <i>p</i> (95% CI)	Success (%), <i>p</i> (95% CI)	Success (%), <i>p</i> (95% CI)	Success (%), <i>p</i> (95% CI)
Harris's hawks	Black	Dali	72, .020 (53–86)	69, .050 (50–84)	88, <.001 (71–96)	84, <.001 (67–95)	-	84, <.001 (67–95)
		Gypsyie	69, .050 (50–84)	69, .050 (50–84)	72, .020 (53–86)	78, .002 (60–91)	-	72, .020 (53–86)
		Lancelot	78, .002 (60–91)	84, <.001 (67–95)	69, .050 (50–84)	94, <.001 (79–99)	-	69, .050 (50–84)
Domestic doves	Black	White	56, .597 (38–74)	72, .020 (53–86)	91, <.001 (75–98)	97, <.001 (84–100)	78, .002 (60–91)	75, .007 (57–89)
		Blue	69, .050 (50–84)	75, .007 (57–89)	78, .002 (60–91)	97, <.001 (84–100)	97, <.001 (84–100)	81, .001 (64–93)
		Red	59, .377 (41–76)	69, .050 (50–84)	94, <.001 (79–99)	91, <.001 (75–98)	94, <.001 (79–99)	78, .002 (60–91)
		Yellow	66, .110 (47–81)	94, <.001 (79–99)	88, <.001 (71–96)	94, <.001 (79–99)	91, <.001 (75–98)	94, <.001 (79–99)
		Green	41, .377 (24–59)	91, <.001 (75–98)	72, .020 (53–86)	100, <.001 (89–100)	94, <.001 (79–99)	75, .007 (57–89)
Dark gray	Dark gray	White	66, .110 (47–81)	94, <.001 (79–99)	97, <.001 (84–100)	94, <.001 (79–99)	-	84, <.001 (67–95)
		Blue	63, .215 (44–79)	81, .001 (64–93)	78, .002 (60–91)	91, <.001 (75–98)	-	91, <.001 (75–98)
		Red	56, .597 (38–74)	75, .007 (57–89)	84, <.001 (67–95)	84, <.001 (67–95)	-	84, <.001 (67–95)
		Yellow	72, .020 (53–86)	84, <.001 (67–95)	97, <.001 (84–100)	84, <.001 (67–0.95)	-	88, <.001 (71–96)
Light gray	Light gray	Green	72, .020 (53–86)	88, <.001 (71–96)	75, .007 (57–89)	84, <.001 (67–0.95)	-	78, .002 (60–91)
		White	47, .860 (29–65)	75, .007 (57–89)	56, .597 (38–74)	84, <.001 (67–0.95)	-	56, .597 (38–74)
		Blue	53, .860 (35–71)	59, .377 (41–76)	78, .002 (60–91)	81, .001 (64–0.93)	-	81, .001 (64–93)
		Red	50, 1.000 (32–68)	66, .110 (47–81)	66, .110 (47–81)	84, <.001 (67–0.95)	-	84, <.001 (67–95)
		Yellow	66, .110 (47–81)	81, .001 (64–93)	88, <.001 (71–96)	75, .007 (57–0.89)	-	75, .007 (57–89)
Green	47, .860 (29–65)	50, 1.000 (32–68)	69, .050 (50–84)	59, .377 (41–0.76)	-	66, .110 (47–81)		

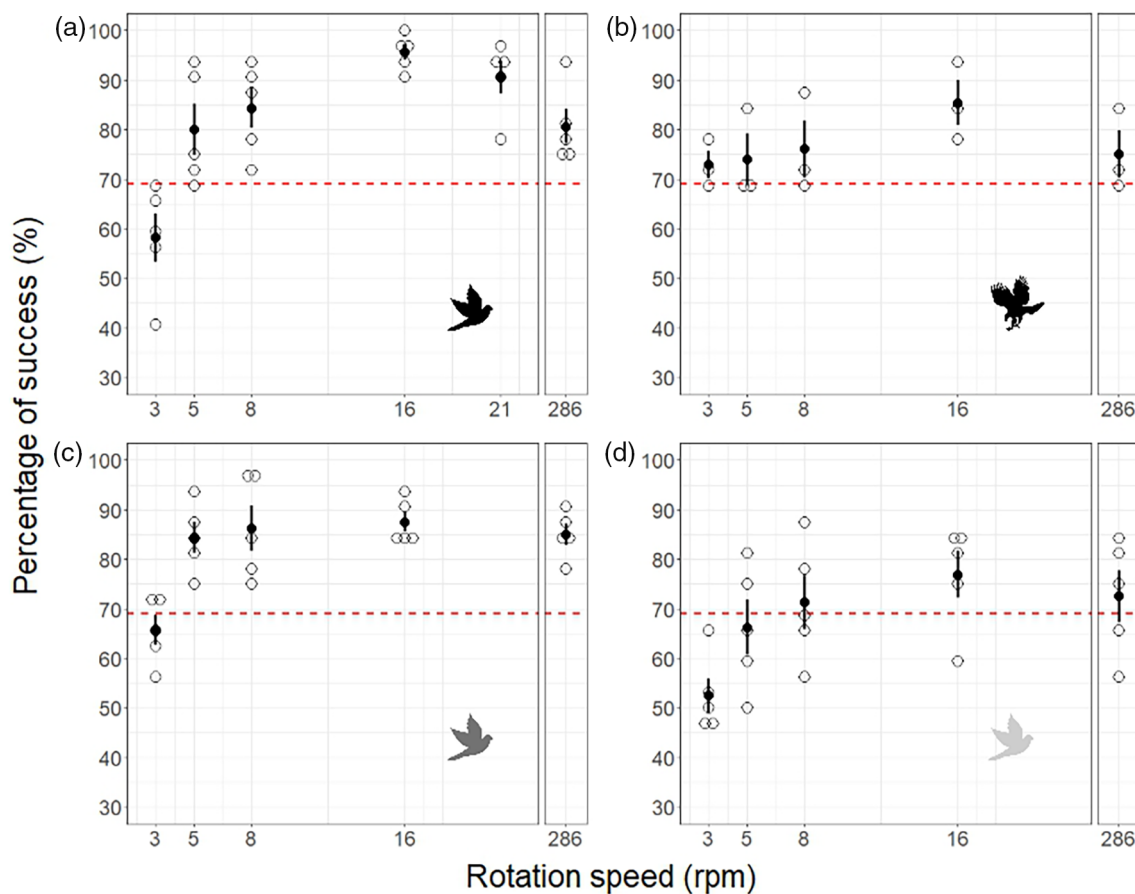


FIGURE 2 Percentage of success of birds depending on rotation speed for domestic doves (a, c, d) and Harris's hawks (b) with a black background (a, b), a dark gray background (c) or a light gray background (d). Mean values (\pm SE) are given in black and individual values in white circles surrounded by black. The red line represents the threshold of detection (binomial test, $p < .05$).

3 rpm, but more experiments with more birds would be needed to find an absolute value for this threshold. Another possible explanation for the difference between hawks and doves' results might be that ambient luminosity in the hawks' indoor experiment was 2,000 times lower than for the doves' outdoor experiment. In humans, the perceived rotation speed is negatively correlated with luminosity only at high speed (Vaziri-Pashkam & Cavanagh, 2008). Because in our experiment differences between hawks and doves appeared at low speeds, our result may not be due to differences in luminosity.

In humans, speed underestimation increases with lower contrast; as a consequence, the apparent stationarity threshold is higher at low contrast (Campbell & Maffei, 1981). This appeared to be the case in doves too, as threshold detection was at a higher rotation speed (5 rpm) under the low contrast condition. In humans, the contrast sensitivity is higher when an object is stationary than when it is rotating, but once in motion, the contrast sensitivity is positively correlated to rotation speed (Campbell & Maffei, 1981). As a consequence, under the

low contrast condition our stationary turbine may be detectable by doves, but invisible when rotating, especially at low speeds. Our research did not address the question of whether doves can detect a rotating wind turbine with low contrast to its surroundings, but this issue is essential to understand birds' behavior toward wind turbines in the real world. We can assume that a bird's behavior in front of a perceived stationary wind turbine would not be the same if the wind turbine was not perceived at all, hence an experiment examining this issue would be crucial for improving bird conservation.

While ADSs slow down wind turbines at about 3 rpm, our study showed that this speed may be counterproductive for some bird species, as found in doves. Even a regulation speed of 5 rpm may not be detected as different from stationary if the contrast between the wind turbines and the background is low. Furthermore, to our knowledge, there are no studies on the ability of birds to predict rotational movement. As this movement does not occur in nature, we can assume that birds are not able to predict the path of the blades. Thus, even if the turbine is

perceived as rotating, if birds are not able to predict the rotational movement, they will not be able to predict the risk. Our results dramatically show the need for more studies on the way regulation speed is detected by birds and whether it effectively reduces collisions, to help decision-making, especially as birds vary greatly in their visual and motor abilities which enable them to avoid collisions (reviewed in Martin, 2017).

The proportions used in our experimental mini wind turbines mimicked a scenario where a bird would be standing 187.5 m away from a 100 m diameter wind turbine. However, the bird's perception of the turbine may change as it came closer. As a result, a turbine perceived as stationary at 187 m may be perceived by the bird as rotating at 50 m, just as the reverse can be true. However, understanding how birds perceive wind turbines at a distance is still relevant as they must decide whether to continue flying toward the turbine or change direction to avoid it before entering the rotor-swept area, and the likelihood of a collision increases as birds approach the turbine. The perception of a stationary wind turbine while it is rotating, or the underestimation of the actual speed, could impact the bird's decision to enter the rotor-swept zone. If birds adapt their behavior according to the perceived rotation speed, the action to slow down the blade speed might encourage the bird to fly through the rotor-swept zone despite the risk. Such a phenomenon of wrong decisions induced by the misperception of the quality of the environment recalls the problem of ecological and evolutionary traps (Robertson et al., 2013). In this theory, animals take wrong decisions because they still use cues for certain habitat quality, inherited by natural selection which shaped their perception of the world, while human activities altered habitat quality without modifying the cues. When triggering a slow-down of blades at 3 rpm, ADS could send a "wrong cue" of stationarity to birds, hence acting as an evolutionary trap, as other human-made structures (Demeyrier et al., 2016; Lorne & Salmon, 2007; Vlaschenko et al., 2019). To efficiently prevent collisions while considering all species and all environmental conditions, a precautionary principle should be that ADS target regulation speed should be a fast and true stop at 0 rpm.

Our study highlighted also the importance of high contrast for rotation speed detection. Painting one blade in black, as proposed by McIsaac (2001), Hodos (2002) and applied by May et al. (2020), increases the contrast between the wind turbine and the background. This may be a promising solution to reduce avian collision with wind turbines as the bird's rotation speed perception might be better under high contrast conditions.

However, our study may have misestimated birds' abilities to see rotations as our birds were trained to focus

on the turbine, whereas in the wild, birds would scan the surroundings for their daily life (searching for food, defending territory, migrating, etc.) without necessarily paying attention to the wind turbine. As self-motion may alter the neuronal pathways of vision, an additional misestimation may be due to the fact that birds were perched when making their decision and were not in flight (Frost, 2010). Our study should be repeated with flying birds to highlight the actual detection of turbines' rotation while approaching.

Although further studies are needed to understand how birds see rotations and how we can improve wind turbine detection, our results highlight for the first time the potential impact of wind turbine rotation on blade detection by birds, and thus possibly on avian collision risk.

AUTHOR CONTRIBUTIONS

Constance Blary, Francesco Bonadonna, Simon Potier and Olivier Duriez designed the study. Constance Blary, Elise Dussauze and Simon Potier performed the experiment. Constance Blary and Elise Dussauze analyzed the data. Constance Blary wrote the manuscript with contributions from all authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data used for analyses are available at <https://data.indores.fr/>.

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REFERENCES

- Campbell, F. W., & Maffei, L. (1981). The influence of spatial frequency and contrast on the perception of moving patterns. *Vision Research*, 21, 713–721. [https://doi.org/10.1016/0042-6989\(81\)90080-8](https://doi.org/10.1016/0042-6989(81)90080-8)
- Cavanagh, P., Tyler, C. W., & Favreau, O. E. (1984). Perceived velocity of moving chromatic gratings. *Journal of the Optical Society of America. A*, 1, 893–899. <https://doi.org/10.1364/JOSAA.1.000893>
- Demeyrier, V., Lambrechts, M. M., Perret, P., & Grégoire, A. (2016). Experimental demonstration of an ecological trap for a wild bird in a human-transformed environment. *Animal Behaviour*, 118, 181–190. <https://doi.org/10.1016/j.anbehav.2016.06.007>
- Drewitt, A. L., & Langston, R. H. W. (2006). Assessing the impacts of wind farms on birds: Impacts of wind farms on birds. *Ibis*, 148, 29–42. <https://doi.org/10.1111/j.1474-919X.2006.00516.x>
- Frost, B. J. (2010). A taxonomy of different forms of visual motion detection and their underlying neural mechanisms. *Brain, Behavior and Evolution*, 75(3), 218–235. <https://doi.org/10.1159/000314284>
- Ghim, M. M., & Hodos, W. (2006). Spatial contrast sensitivity of birds. *Journal of Comparative Physiology. A*, 192, 523–534. <https://doi.org/10.1007/s00359-005-0090-5>
- Haller, N. K., Lind, O., Steinlechner, S., & Kelber, A. (2014). Stimulus motion improves spatial contrast sensitivity in budgerigars (*Melopsittacus undulatus*). *Vision Research*, 102, 19–25. <https://doi.org/10.1016/j.visres.2014.07.007>
- Hodos, W. (2002). *Minimization of motion smear: Reducing avian collision with wind turbines; period of performance: July 12, 1999–August 31, 2002*. National Renewable Energy Laboratory. <https://doi.org/10.2172/15004460>
- Hodos, W., Ghim, M. M., Potocki, A., Fields, J. N., & Storm, T. (2002). Contrast sensitivity in pigeons: A comparison of behavioral and pattern ERG methods. *Documenta Ophthalmologica*, 104(1), 107–118. <https://doi.org/10.1023/A:1014427615636>
- Hodos, W., Leibowitz, R. W., & Bonbright, J. C., Jr. (1976). Near-field visual acuity of pigeons: Effects of head location and stimulus luminance. *Journal of the Experimental Analysis of Behavior*, 25(2), 129–141. <https://doi.org/10.1901/jeab.1976.25-129>
- IPCC. (2022). Climate change 2022: Mitigation of climate change.
- Khalfallah, M. G., & Koliub, A. M. (2007). Suggestions for improving wind turbines power curves. *Desalination*, 209, 221–229. <https://doi.org/10.1016/j.desal.2007.04.031>
- Kitano, M., & Shiraki, S. (2013). Estimation of bird fatalities at wind farms with complex topography and vegetation in Hokkaido, Japan. *Wildlife Society Bulletin*, 37, 41–48. <https://doi.org/10.1002/wsb.255>
- Kunz, T. H., Arnett, E. B., Erickson, W. P., Hoar, A. R., Johnson, G. D., Larkin, R. P., Strickland, M. D., Thresher, R. W., & Tuttle, M. D. (2007). Ecological impacts of wind energy development on bats: Questions, research needs, and hypotheses. *Frontiers in Ecology and the Environment*, 5, 315–324. [https://doi.org/10.1890/1540-9295\(2007\)5\[315:EIOWED\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2007)5[315:EIOWED]2.0.CO;2)
- Land, M. F., & Nilsson, D. E. (2012). *Animal eyes*. Oxford University Press.
- Land, M. F. (1999). Motion and vision: Why animals move their eyes. *Journal of Comparative Physiology. A*, 185, 341–352. <https://doi.org/10.1007/s003590050393>
- Lee, J., & Zhao, F. (2021). *GWEC global wind report 2021*. Global Wind Energy Council.
- Lind, O., Sunesson, T., Mitkus, M., & Kelber, A. (2012). Luminance-dependence of spatial vision in budgerigars (*Melopsittacus undulatus*) and Bourke's parrots (*Neopsephotus bourkii*). *Journal of Comparative Physiology. A*, 198, 69–77. <https://doi.org/10.1007/s00359-011-0689-7>
- Lorne, J. K., & Salmon, M. (2007). Effects of exposure to artificial lighting on orientation of hatchling sea turtles on the beach and in the ocean. *Endangered Species Research*, 3(1), 23–30. <https://doi.org/10.3354/esr003023>
- Marques, A. T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M. J. R., Fonseca, C., Mascarenhas, M., & Bernardino, J. (2014). Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. *Biological Conservation*, 179, 40–52. <https://doi.org/10.1016/j.biocon.2014.08.017>
- Martin, G. R. (2017). *The sensory ecology of birds*. Oxford University Press.
- Martin, G. R., Portugal, S. J., & Murn, C. P. (2012). Visual fields, foraging and collision vulnerability in gyps vultures: Vision and culture collisions. *Ibis*, 154, 626–631. <https://doi.org/10.1111/j.1474-919X.2012.01227.x>
- Marx, G. (2017). *Le parc éolien français et ses impacts sur l'avifaune: Etude des suivis de mortalité réalisés en France de 1997 à 2015*. LPO France.
- May, R. F., Hamre, Ø., Vang, R., & Nygård, T. (2012). Evaluation of the DTBird video-system at the Smøla wind-power plant. Detection capabilities for capturing near-turbine avian behaviour. NINA report.
- May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., & Stokke, B. G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution*, 10, 8927–8935. <https://doi.org/10.1002/ece3.6592>
- McClure, C. J., Rolek, B. W., Dunn, L., McCabe, J. D., Martinson, L., & Katzner, T. (2021). Eagle fatalities are reduced by automated curtailment of wind turbines. *Journal of Applied Ecology*, 58(3), 446–452. <https://doi.org/10.1111/1365-2664.13831>
- McIsaac, H. P. (2001). Raptor acuity and wind turbine blade conspicuity. Proceedings of national avian-wind power planning meeting IV (PNAWPPM-IV), p. 59–87.
- Olsson, P., Lind, O., & Kelber, A. (2015). Bird colour vision: Behavioural thresholds reveal receptor noise. *The Journal of Experimental Biology*, 218(2), 184–193. <https://doi.org/10.1242/jeb.111187>
- Pääkkönen, A. K., & Morgan, M. J. (1994). Effects of motion on blur discrimination. *Journal of the Optical Society of America A*, 11, 992. <https://doi.org/10.1364/JOSAA.11.000992>
- Potier, S., Lieuvain, M., Pfaff, M., & Kelber, A. (2020). How fast can raptors see? *The Journal of Experimental Biology*, 223, jeb209031. <https://doi.org/10.1242/jeb.209031>
- Potier, S., Mitkus, M., & Kelber, A. (2018). High resolution of colour vision, but low contrast sensitivity in a diurnal raptor. *Proceedings of the Royal Society B*, 285, 20181036. <https://doi.org/10.1098/rspb.2018.1036>

- Potier, S., Mitkus, M., & Kelber, A. (2020). Visual adaptations of diurnal and nocturnal raptors. *Seminars in Cell & Developmental Biology*, 106, 116–126. <https://doi.org/10.1016/j.semcdb.2020.05.004>
- Robertson, B. A., Rehage, J. S., & Sih, A. (2013). Ecological novelty and the emergence of evolutionary traps. *Tree*, 28(9), 552–560. <https://doi.org/10.1016/j.tree.2013.04.004>
- Streiner, D. L., & Norman, G. R. (2011). Correction for multiple testing: Is there a resolution? *Chest*, 140(1), 16–18. <https://doi.org/10.1378/chest.11-0523>
- Thaxter, C. B., Buchanan, G. M., Carr, J., Butchart, S. H. M., Newbold, T., Green, R. E., Tobias, J. A., Foden, W. B., O'Brien, S., & Pearce-Higgins, J. W. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society B*, 284(1862), 20170829. <https://doi.org/10.1098/rspb.2017.0829>
- Vlaschenko, A., Kovalov, V., Hukov, V., Kravchenko, K., & Rodenko, O. (2019). An example of ecological traps for bats in the urban environment. *European Journal of Wildlife Research*, 65(2), 20. <https://doi.org/10.1007/s10344-019-1252-z>
- Vaziri-Pashkam, M., & Cavanagh, P. (2008). Apparent speed increases at low luminance. *Journal of Vision*, 8(16), 1–12. <https://doi.org/10.1167/8.16.9>
- White, C. R., Day, N., Butler, P. J., & Martin, G. R. (2007). Vision and foraging in cormorants: More like herons than hawks? *PLoS One*, 2(7), e639. <https://doi.org/10.1371/journal.pone.0000639>
- Zimmerling, J. R., Pomeroy, A. C., d'Entremont, M. V., & Francis, C. M. (2013). Canadian estimate of bird mortality due to collisions and direct habitat loss associated with wind turbine developments. *ACE*, 8, art10. <https://doi.org/10.5751/ACE-00609-080210>

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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