

Reduction of Motion Smear to Reduce Avian Collisions with Wind Turbines

by

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Abstract

Motion smear is the degradation of the visibility of rapidly moving objects. It results from the inability of the retina of the eye to process the high temporal frequencies of stimulation that result from high velocities of retinal-image motion. In the case of wind turbines, motion smear occurs primarily at the tips of the blades, making them deceptively transparent at high retinal-image velocities. Attempts to minimize motion smear must take into account its causes and attempt to reduce the temporal frequency of stimulation of the retina. Anti-motion-smear patterns are designed to do this by not repeating a pattern in one location on a turbine blade at the same location on any other blade. In a three-blade turbine, the temporal frequency of stimulation is thereby reduced by a factor of three.

To simulate turbines in the laboratory, we are using a variable-speed motor to spin an array of three blades with a diameter of 64 cm. The blades with anti-motion-smear patterns are compared with blades that have no patterns or blades with patterns that are not staggered to reduce the temporal frequency of stimulation. Because this apparatus is relatively close to the subject's eye, we are able to simulate retinal-image velocities that would occur in a real environment with wind turbines having diameters of 20 m or more. The subjects used are American kestrels (*Falco sparverius*). Each kestrel is anesthetized and electrodes are inserted under the eyelids in contact with the cornea to record the pattern electroretinogram (PERG) from the retina. The amplitude of the PERG in microvolts is our measure of pattern visibility.

Our current data show that anti-motion-smear patterns produce a higher PERG amplitude, which translates into a higher pattern visibility at a given distance. For example, at a retinal velocity of 120 deg of visual angle/sec, the most effective anti-motion-smear patterns produced PERG amplitudes that were three times the amplitude of the blades with no patterns. Our most recent studies suggest that a single, solid-black blade, paired with two white blades, is the most visible stimulus, possibly because it stimulates a larger area of the retina than striped blades. Even though the anti-motion-smear patterns are more visible at a distance of approximately 25 m than blank blades or blades with unstaggered, repeating patterns, as the bird gets closer to the blades, the retina is unable to process the progressively higher retinal-image velocities and all patterns rapidly lose visibility with decreasing distance.

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Introduction

The development of wind power as a source for the generation of electricity has led to the establishment of wind resource areas such as at Altamont Pass, California, in which thousands of wind turbines have been erected. While generally conceded to be environmentally safe, wind turbines have been reported to be hazardous to flying birds (Howell 1990; Colson & Associates 1995; NRL wind-power meeting proceedings 1994, 1995). The research that is described in this report is designed to take into account what is known from human research on the degradation of the perception of rapidly moving objects and to apply it to the problem of the reduction of avian collisions with wind turbines. An important consideration here, however, is to keep in mind that there are considerable differences between the avian and human visual systems that must be taken into account in designing experiments.

Visual hypotheses to account for collisions. Among various hypotheses to account for avian-turbine collisions based on vision, at least three deserve serious consideration:

1. ***Inability to divide attention between surveying the ground for prey and monitoring the horizon and above for obstacles***. This hypothesis derives from directly substituting our knowledge of human vision for that of avian vision. Humans are foveate animals; we have a 2.5 m fovea (centered in the 5 m macula), which is our area of sharpest vision, with which we search the visual world, like someone searching a dark room with a narrow-beam searchlight. This results from our very low ratio (approximately 1:1) of photoreceptors to ganglion cells in the macular region of the retina. Once outside the macular region, the ratio of receptors to ganglion cells increases progressively to 50:1-100:1 and our visual acuity drops sharply. Birds, on the other hand, and many other animals as well, have universal macularity, which means that they have a low ratio of receptors to ganglion cells (4:1-8:1) out to the periphery of the retina, which means that they maintain quite good acuity even in peripheral vision. (Hodos, Miller and Fite 1991; Hodos 1993). In addition, a specialization of raptors is the presence of two foveal regions; one for frontal vision and one for looking at the ground. Moreover, birds have various optical methods for keeping objects at different distances simultaneously in focus on the retina (Hodos and Erichsen, 1990). Because of these considerations, this seems a most unlikely hypothesis.
2. ***Motion smear: Reduced visibility of the blades, especially at the tips***. As an object moves across the retina with increasing speed, it becomes progressively blurred; this phenomenon is known as “motion smear” or “motion blur” and is well known in human psychophysical research. It results from the fact that the human visual system is sluggish in its response to temporal stimulation; i.e., the visual system summates signals over periods of about 120 msec in daylight (Burr 1980; Bex et al. 1995). The advantage of this summation is that it enhances visual sensitivity, but at the price of the smearing or blurring of moving targets. Some scientists have offered evidence that the human retina has a mechanism for sharpening blurred, moving images (Bex et al. 1995; Hemmett and Bex 1996). Others disagree (Burr and Morgan 1997). Whether or not

birds have such a mechanism is unknown.

The phenomenon of motion smear is apparent at the tips of wind-turbine rotor blades turning at the rate of approximately 35 RPM and higher. The more central regions of the blades do not suffer from motion smear because of their lower velocity. Since both the central regions and the tips are rotating at the same RPM, it seems most likely that the relevant variable is the velocity of the blades at the more peripheral regions. The higher velocity of the blade tip has placed it in the temporal-summation zone in which the retina is sluggish in its ability to resolve temporally separated stimuli, whereas the lower velocities of the more central portions are below the transition point and the individual blades can be seen more or less clearly.

3. ***Angle of approach to the blades.*** A serious problem in attempting to solve the problem of collisions is the absence of data on the angle of approach to the blades at the moment of collision. If the birds are struck while approaching the blades from a direction that is parallel to the long axis of the blade, then the problem of motion smear is compounded by the very small profile of the blades from that line of sight. A solution to this problem must (1) effectively increase the profile of the blades in this orientation and (2) take into account the causes of motion smear.

The principle of motion-smear reduction. The solution to the problem of motion smear is to maximize the time between successive stimulations of the same retinal region. Any type of pattern applied to the blades that does not take this into account will be ineffective. The typical approach is to apply the same pattern to each blade, which does nothing to maximize the time between successive stimulations of the same retinal region. Our approach is to use different patterns on each blade. The patterns are designed so that a pattern on any given blade region is not repeated on the equivalent region of the other two blades. Thus stimulations per second of any given retinal region are reduced by a factor of three and the time between stimulations is virtually tripled.

Motion smear reduction in frontal approaches to the blades. Fig. 1 shows an anti-motion-smear pattern with the black stripes staggered across the blade in such a way that a given stripe appears in only one location on any of the three blades. In this example, one blade has stripes in locations 1, 4, and 7. Another blade has stripes in locations 3 and 6, and the third blade has stripes in locations 2 and 5.

In our laboratory, we constructed an anti-motion-smear rotor-blade assembly from foam board and mounted it on a variable-speed motor. As the speed of the motor increased, human observers reported that the individual bars at the more peripheral regions of the blade are no longer seen as individual bars, but are gradually replaced by a series of grey, concentric rings that pulsate slightly. The spaces between the rings, however, continue to show the transparency associated with motion smear. The effect is quite dramatic at high tip velocities. Blades on which the bars have been placed at the same location on all blades also show a concentric-ring effect, but not as dramatically as the staggered-pattern blades. Blades that are uniformly white or uniformly black, show the typical

motion-smear effect. We must caution, however, that this is an effect on human observers.

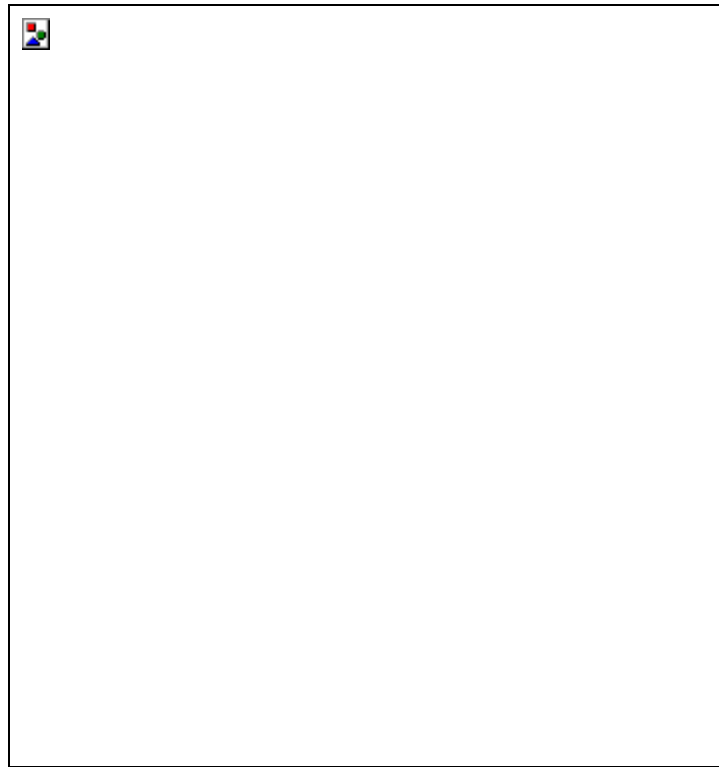


FIGURE 1. An anti-motion-smear pattern. A black bar is not repeated in the same location on either of the two other blades.

Motion-smear reduction in lateral approaches to the rotor blades. The combination of motion smear and a very narrow profile offered by the fast moving tips of rotor blades approached from the side could be quite deadly for a bird. The solution to this problem is a rectangular attachment to the outer tip of the blade. This attachment, which should probably be 0.5 - 0.75 m long and 0.3 m high, and painted black, should be fastened so as to be at right angles to the long axis of the blade (see. Fig. 2). The attachment ideally would be positioned on only one blade to minimize motion smear. Should a single such device have sufficient weight to cause an imbalance of the rotor assembly, additional rectangles could be added to the other two blades for balance. These preferably should be transparent, or at least painted white. We have not yet evaluated the visibility of these lateral anti-motion-smear devices.

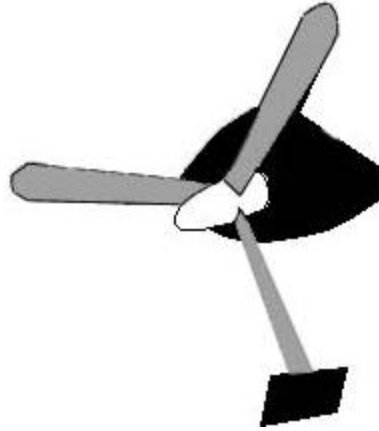


FIGURE 2. A black rectangle affixed to the tip of a single rotor blade.

Retinal images and retinal-image velocities. Retinal-image velocity is calculated from the law of the visual angle, which is illustrated in Fig. 3. As may be seen in this figure, all objects, at whatever distance, that cast the same size image on the retina, subtend the same angle. The angle inside the eye is the same as that from the eye to the object. These angles are called “visual angles” and are the conventional units to describe object size since they are directly related to retinal-image size, which is the only relevant variable for these purposes. In the experiments described below, the tip velocity will be retinal velocity and will be expressed in degrees of visual angle/sec (dva/sec). Degrees of visual angle are calculated as $57.3 \times h/d$, in which h is the object size (height, width, or area), d is the distance, and 57.3 is the conversion factor from radians to degrees. The advantage of these units for laboratory research is that the tip velocity of a rotor blade many meters in length as seen from a distance of 10-20 m can be simulated in the laboratory with a much smaller blade located 0.5-0.6 m from the eye and moving at a much higher RPM rate.

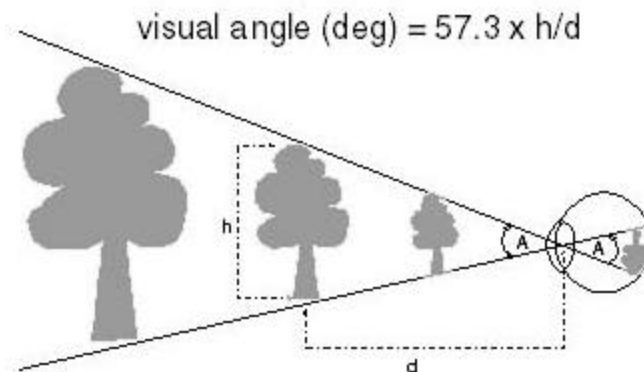


FIGURE 3. The law of the visual angle. Objects of different sizes and distances that subtend the same

angle will cast the same size image on the retina. Angles A and A' are the same.

In addition to the type, location and configuration of the stimuli, the question of which is the relevant motion variable to consider is important. As discussed above, simple RPM most likely is not a relevant variable because it is the same for both the peripheral and central regions of the blades, yet the perceptual effects of the same RPM on each region are very different. This is because the central and peripheral regions of the blades are moving at different velocities. As is well known in human visual perception, however, the actual velocity of stimulus (the rotor blades in this case) typically is irrelevant; what is crucial is the velocity of the image of the blade as it sweeps across the retina of the eye. As the bird approaches the rotor blades, the size of their retinal image increases just as a photographic image increases in size as the camera approaches the subject (Fig. 4). This means that as the bird approaches the rotor blades, its retinal velocity increases because the tip of the blade must cover a greater distance in the same time. This is related to the phenomenon of “motion parallax”(Goldstein, 1984), which we can observe by looking out the side window of a rapidly moving train or car; objects close to the window race by with great speed and have considerable motion smear, while distant objects move by at a more leisurely pace and remain sharply in focus. Therefore the proper way to express the velocity of the rotor tips is in units of retinal-image velocity, which take into account the distance as well as the size of the object.

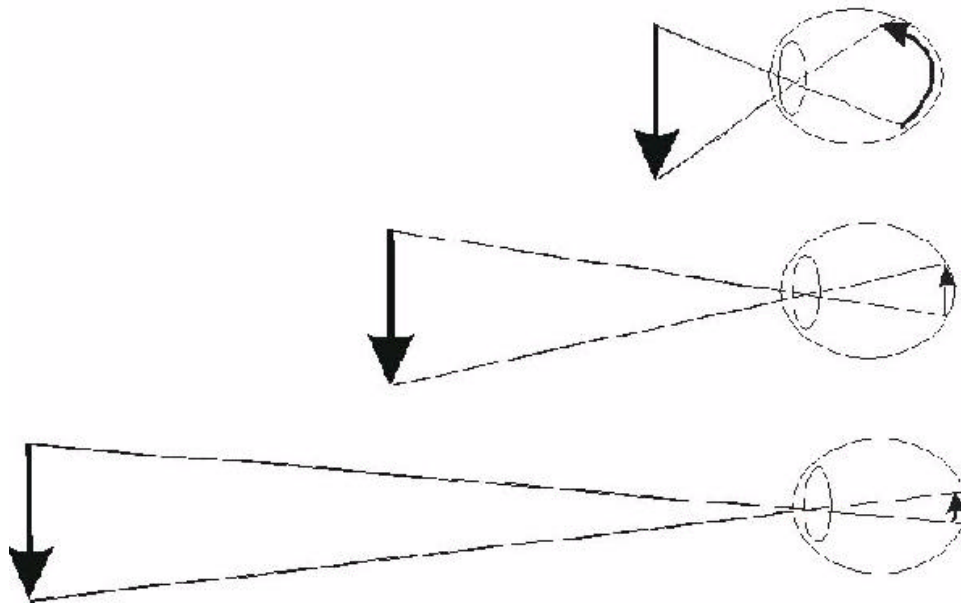


FIGURE 4. As an object moving perpendicularly to the axis of the eye, such as a turbine blade, gets closer to the eye, as when a bird is flying towards the blade, its visual angle increases and the image of the blade must cover a larger area of the retina in the same period of time; i.e., its retinal-image velocity increases.

The foregoing discussion should make several points clear to the reader: (1) The RPM of the blades tells nothing about the velocity of the image of those blades as they sweep across the retina of the eye, and hence their visibility, unless one takes into account the distance. (2) Beyond a certain point, the visibility of a constant-RPM blade will decrease as the observer approaches the blades due to motion smear. (3) Even though our stimulus display is minuscule in comparison to the absolute size of a wind-turbine rotor, because of the very short viewing distance, the retinal image sizes and retinal velocities are comparable.

The pattern electroretinogram. Behavioral psychophysical methods to determine the optimal parameters of the patterns to minimize motion smear are extremely slow, time consuming and labor intensive. A more rapid method, that has been used for psychophysical purposes is the pattern electroretinogram or PERG (Fitzke et al. 1984, 1985a,b; Hodos et al. 1985; Porciatti et al. 1991) which is generated whenever there is a local contrast change on the retina, such as would be produced by a black bar moving across the retina. The PERG is generated when the retinal area goes from lighter to darker as the leading edge of the bar enters it and again when it goes from darker to lighter as the trailing edge exits it. Similar effects would be achieved by the images of rotating blades as they passed a given retinal area. Blank rotor blades should generate a lower PERG amplitude than striped blades because they have a lower contrast against the background than do the stripes, which have nearly 100% contrast. In this case, contrast is defined as $(L_L - L_D / L_L + L_D) \times 100$, in which L_L is the luminance of the brighter area and L_D is the luminance of the dimmer area. The pattern electroretinogram has been used to measure visual acuity, contrast sensitivity, and a variety of other psychophysical indicators.

Methods

Subjects. The subjects were seven American kestrels (*Falco sparverius*) on loan from the Patuxent Wildlife Research Center of the US Department of the Interior, Laurel, MD. The birds were housed in the laboratory for 3-4 days per week and returned to their large, outdoor flight cages at the Patuxent Center at all other times for fresh air and exercise.

Apparatus. The PERG was recorded and analyzed by an ENFANT electrophysiology system (Neuroscientific Corp., Farmington, NY). This instrument is capable of presenting a wide range of visual stimuli on a video display monitor and recording, amplifying, displaying, and analyzing electrical potentials such as those generated by the PERG. Among the analytical techniques available on this instrument are signal averaging, curve fitting, variable high-pass and low-pass filtering, various regression analyses, Fourier analysis of frequency components, and others.

To produce the simulated blade stimuli, a variable-speed motor was fitted with 32 cm-long rotor blades made from 5 mm-thick white foam board. These were displayed against a background of the same material to provide a worst-case, minimal-contrast situation between blades and the background. Additional sets of blades of the same material also were prepared with black stripes positioned according to variations on the principle displayed in Fig. 1. The diameter of the circle formed by the outer tips of the blades (64 cm), at a viewing distance of 60 cm, formed a retinal image that subtended a visual angle of 61.1 $^{\circ}$. The birds, however, saw only the lower half of this

circle, so the angular subtense of the display that they saw was approximately 30.6m. This would be the same size retinal image as a 20 m diameter rotor would make at a distance of 19 m.

Procedure. In order to record the PERG, the animal was anesthetized with 20% chloral hydrate (365 mg/kg, IM) and its head was placed in a rigid metal head holder. All pressure points were treated with local anesthetic. Platinum electrodes (0.5 mm diameter) were inserted in each lower eyelid so that the electrode made good contact with the cornea, just below the pupil. Care was taken not to obscure the pupil. A third electrode was inserted in the skin of the scalp to serve as a ground. One eye was covered with a black patch and the electrode in this eye served as the indifferent electrode. This technique is minimally invasive and the anesthesia depth is lighter than that required for major surgery.

Velocity parameters of the blades. Eight blade velocities ranging from 36 to 134 RPM were used in the experiment. Table 1 shows the blade velocities in RPM, m/sec, and deg/sec, the velocity of the retinal image in degrees of visual angle per sec (dva/sec).

TABLE 1. Blade velocities used in experiment

A. Blade Velocity (RPM)	B. Blade -tip Velocity (m/sec)	C. Blade -tip Velocity (deg/sec)	D. Blade -tip Retinal-image Velocity (dva/sec)
36	1.2	216	115
48	1.6	288	153
56	1.9	336	179
66	2.2	396	211
80	2.7	480	256
96	3.2	576	307
105	3.5	630	336
134	4.5	804	428

Do these stimulus parameters realistically model what would occur in the field? A 20 m diameter rotor has a circumference of 62.8 m. At 70 RPM, the tip velocity is 4,398 m/min or 263,894 m/hr or 264 km/hr (165 mph). 4,398 m/min also equals 73.3 m/sec. Its retinal-image velocity, however, depends on the distance at which it is viewed (see above). At a distance of 36.5 m it will have a retinal-image velocity of 115 dva/sec, which is the equivalent of the retinal-image velocity of our 64 cm-diameter stimulus at 36 RPM (Column D in the table). At a distance of 9.8 m, however, the 20 m rotor will have a retinal-image velocity of 428 dva/sec, which is the same as our

134 RPM stimulus.

Table 2 describes the series of patterns that was used in the studies reported here. The baseline against which all blade patterns is compared with is the noise condition, which is the measure of biological noise and ambient electrical noise. The amplitude of the PERG is judged not only in terms of its absolute amplitude in nV , but also in its relationship to the noise level. The higher the signal-to-noise ratio, the more visible the moving images on the retina are. The standard of comparison for the relative visibility of any striped pattern is the PERG amplitude of the blank blades, which are intended to simulate the typical, unpatterned, wind-turbine blade array. Our initial preliminary observations suggested that a way to deal with the different velocities of the central and peripheral regions of the blade would be to have thick stripes between the center of the blade and the hub, and thin stripes between the center of the blade and the tip. We also investigated anti-motion-smear patterns made up only of thin stripes and only of thick stripes. Finally, we attempted the simplest type of anti-motion-smear design; i.e., a single black blade, paired with two blank blades, as illustrated in Figure 5.

TABLE 2. Summary of the blade patterns

Pattern type	Description
Noise	both eyes covered; no visual stimulation
Blank	white blades without stripes
Non-staggered (thin)	the same thin-stripe pattern on each blade
Staggered thin	anti-motion-smear; thin stripes
Staggered (thick and thin)	anti-motion-smear; thick stripes from center of blade to hub; thin stripes from center to tip
Single-blade (thin)	anti-motion-smear; thin stripes on one blade; two blades blank
Single-blade (thick and thin)	anti-motion-smear; thick stripes from center of blade to hub; thin stripes from center to tip on one blade; two blades blank
Single-blade (solid black)	anti-motion-smear; one blade solid black; two blades blank.

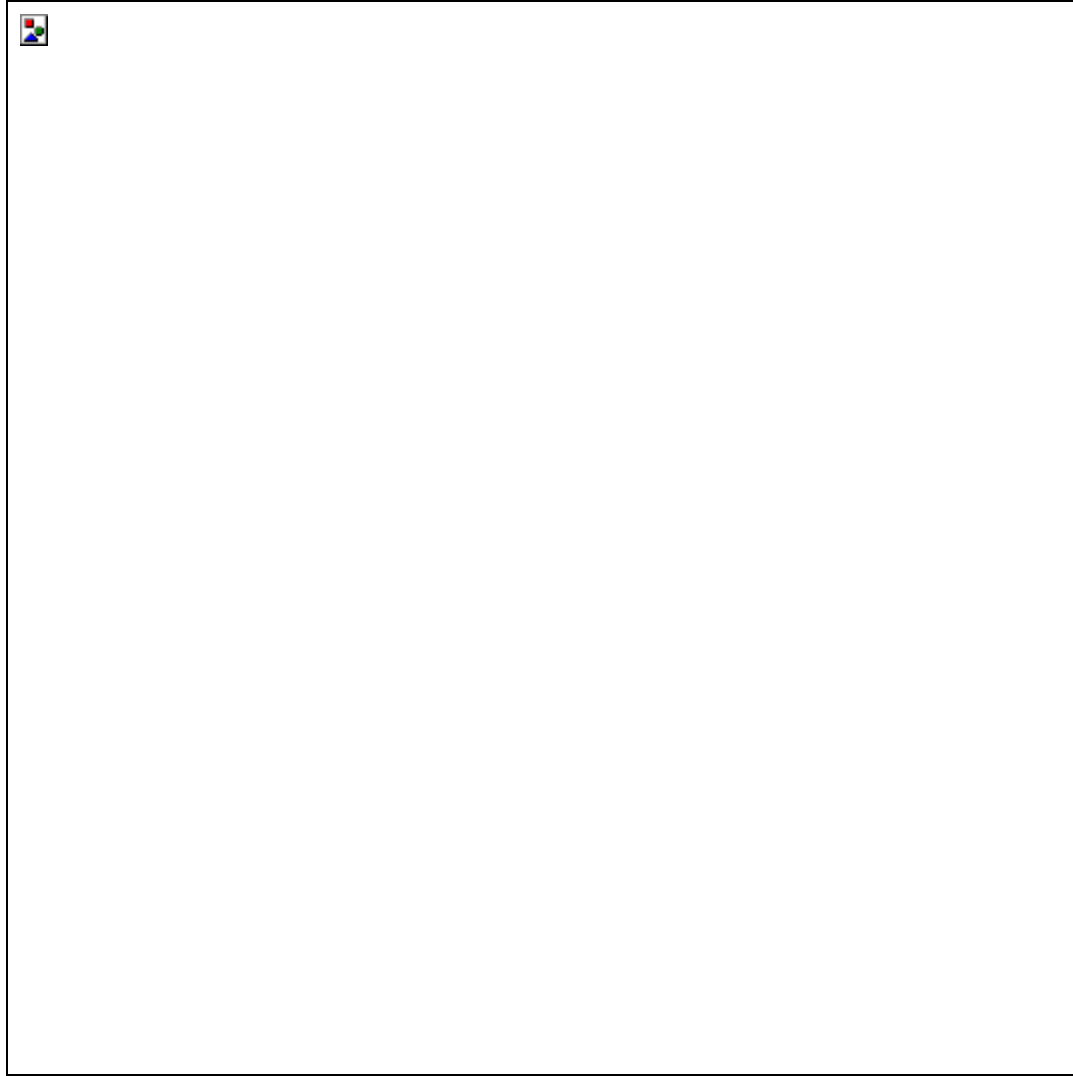


FIGURE 5. The single, black blade, anti-motion-smear pattern.

Refractive studies and visual acuity. Before conducting any visual experiments, it is vital to carry out a preliminary study of the refractive state of the eye. By determining which corrective lens gives the highest visual acuity (the precise equivalent of an optometric examination), we are assured that the image of the stimulus display is in focus on the retina. The PERG is used for this procedure as well. The method is based on the observation that PERG amplitude decreases as the spatial frequency of a grating stimulus increases. By increasing the spatial frequency (decreasing the width of the bars and spaces) until the PERG amplitude reaches the noise level, an estimate of visual acuity can be obtained (Porciatti et al. 1991). Such a refractive study was carried out on each kestrel.

Results

Refractive state and visual acuity. Our results collected thus far from seven kestrels indicate that the mean refractive state is $+0.07$ diopters ± 0.07 s.e.m., which indicates that for this population of young, adult kestrels, no effective refractive error was found. The mean visual acuity was 20.6 cycles/dva ± 2.7 s.e.m. These data were collected, however, while attempting to establish the optimum position on the retina for best acuity and not all data points were from the optimum region. The data from this optimal retinal location in five kestrels indicate that mean acuity was 23.2 cycles/dva, which corresponds to an acuity of $20/26$ on the Snellen eye chart, common to optometry and ophthalmology offices, on which $20/20$ equals normal human visual acuity. The best bird, however, had an acuity of 33.5 cycles per degree of visual angle, corresponding to $20/18$ on the Snellen chart.

PERG results with rotating blades. We have collected data from four kestrels using the following stimuli: (1) blank blades; (2) blades with thin stripes in our staggered pattern; (3) blades with thick stripes in our staggered pattern; (4) no stimulus; i.e., the eyes are covered so that they cannot see the blades or anything else. Fig. 6 shows the mean results of seven recording sessions with each of the four types of stimulus configuration. The figure plots the mean amplitude ($n = 7$) of the pattern electroretinogram (PERG) in nV as a function of the velocity of the retinal image of the blade as it sweeps across the retina. Retinal velocity is in degrees of visual angle per second (dva/sec). Later in this report, we will translate retinal velocity into practical terms that are of relevance to a bird approaching a moving wind turbine.

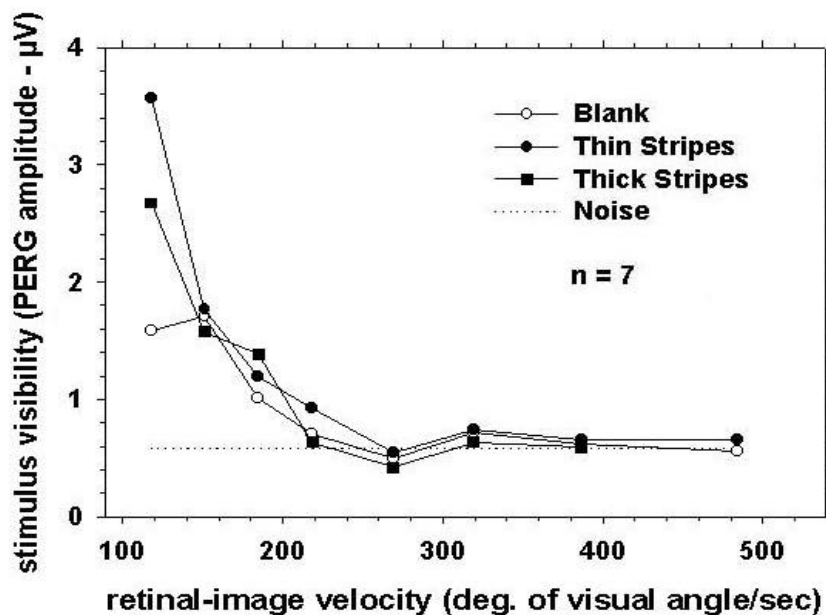


FIGURE 6. PERG amplitudes as a function of retinal-image velocity for four stimulus types.

In the figure, the dotted line indicates the average PERG amplitude when the eyes are closed, which represents the level of biological noise and hence no visibility. We are assuming here that visibility varies linearly with the PERG amplitude that is above the noise level. Thus, doubling the amplitude above the noise level represents a doubling of visibility. Our noise level is approximately 0.6 nV . If PERG amplitude above noise varies linearly with visibility, then for blank blades, the visibility at 118 dva/sec is about 1.0 (1.6 nV minus 0.6 nV). By about 185 dva/sec the visibility has dropped in half, and by about 220 dva/sec it has dropped to zero (i.e., to the noise level). In contrast, the thick stripes have a visibility of 2.05 (2.6 nV minus 0.6 nV) at 118 dva/sec, whereas the thin stripes have a visibility of 3.0 (3.6 nV minus 0.6 nV) at the same retinal-image velocity. Thus we can say that the thin, staggered stripes have a visibility that is approximately three times greater than the blank blades at 118 dva/sec. The next higher speed that we used was 150 dva/sec. At this retinal velocity, all the patterns performed equally poorly, depending on your perspective. At 220 dva/sec, thick stripes and the blank blades have achieved zero visibility, while the thin stripes have a slight (but probably meaningless) visibility advantage of 0.4. Thereafter, all the stimuli are essentially have no visibility as individual blades, but rather appear as a blur or smear.

What does this mean in practical terms? Fig. 7 gives some idea. In this figure, the X-axis has been changed to represent distance from the eye. We can make this conversion because for any moving stimulus, the retinal-image velocity increases linearly as the distance to the eye decreases. In this figure, we have made this conversion for a hypothetical 20-m diameter turbine rotating at 45 RPM. The figure shows that at distances from the stimulus of 23 m, the three types of stimuli are clearly different, but the difference is gone when the distance shortens to 18 m and closer. By 12 m, the visibility of all the patterns has dropped effectively to zero.

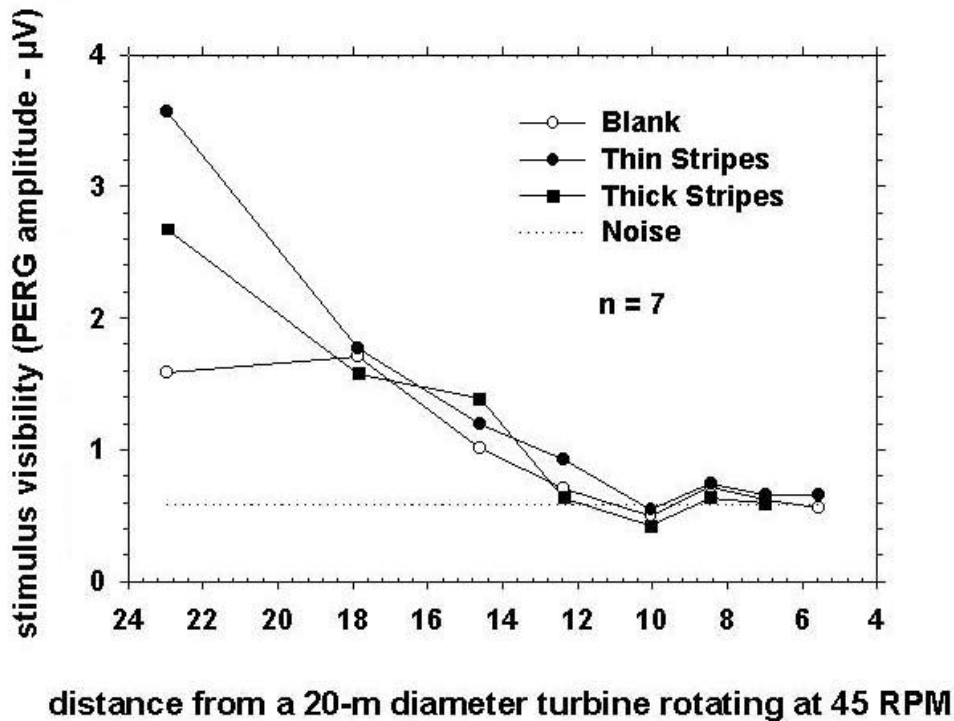


Figure 7. Blade visibility as a function of distance from a hypothetical 20-m diameter turbine rotating at 45 RPM in the field.

Fig. 8 shows the full range of patterns that we have tested thus far. At present, these visibility data have been collected only at a retinal-image-velocity of 120 dva/sec. At present, we have data from three recording sessions from three kestrels. We plan to have data from at least five sessions from each of five kestrels before attempting a statistical analysis to determine which patterns differ significantly from any of the others. Pattern 1 represents the noise condition (eyes covered) and, as in Figures 1 and 2, constitutes the baseline against which other patterns are compared. In these experiments the average noise amplitude was approximately 0.5 μV . Pattern 2 indicates the PERG amplitude of three blank blades, which have a visibility of about 0.9 (μV above noise). Patterns 3 and 4 had visibilities of about 1.4. Pattern 3 was a single blade pattern with thick and thin stripes and pattern 4 was a three-blade pattern with unstaggered stripes. The latter is a blade type that is in experimental use in the Altamont wind area. Pattern 5 had thick and thin stripes staggered in an anti-motion-smear configuration. Its visibility was 2.0, which is slightly more than double that of the blank blades. Pattern 6 had the same thin stripes as pattern 4, but on only on a single blade, which conforms to the anti-motion-smear principle. It had a somewhat better visibility of 2.3 (μV above noise). Pattern 7, which was a single, solid black blade with two blank blades, had a visibility of 2.5. Pattern 8 was the staggered, thin-stripe, anti-motion-smear pattern that was used to collect the data in Figs. 5 and 6. It proved to be the most effective stimulus with a visibility of 2.7 (μV above noise).

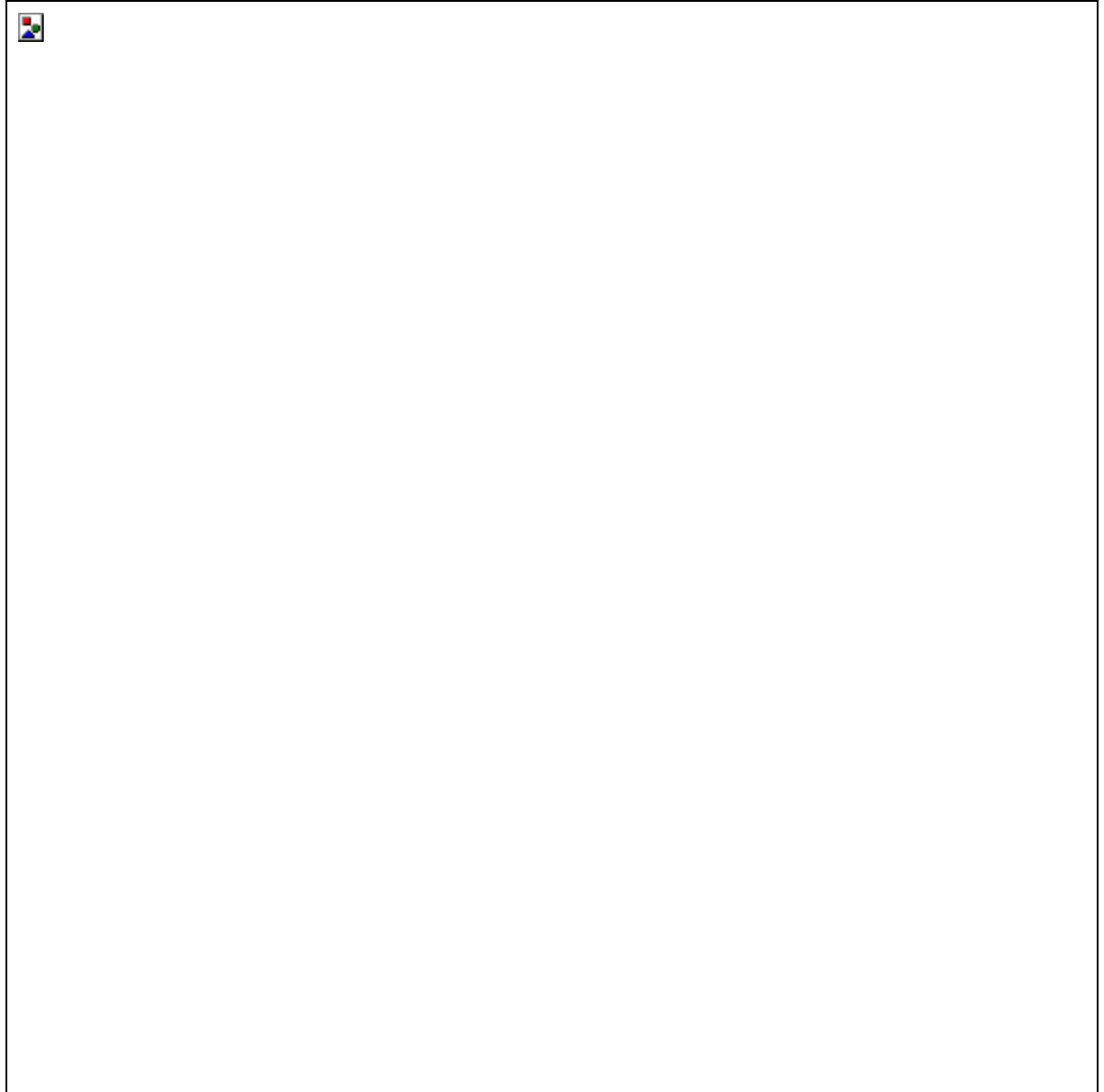


FIGURE 8. Visibility of seven blade patterns relative to the “noise” condition (pattern 1), which is also represented as a horizontal line.

Discussion

Refraction and visual acuity. Our data indicate that the seven kestrels were free of refractive errors that could have affected their vision. In addition, we determined that under the conditions of our experiment, the average visual acuity of the five from which we had the optimal measurements was 23.2 cycles/dva. The best bird of these five had an acuity of 33.5 cycles/dva. Published behavioral data from a single kestrel by Hirsch (1982), indicate an acuity of 40 cycles/dva. We recently have reported elsewhere (Hodos et al. 2000), however, that the PERG underestimates visual acuity by approximately 79% as compared to acuity determined by behavioral methods. Increasing 23.2 cycles/dva by 79% indicates an acuity of 41 c/dva, comparable to the

behavioral result reported for this species by Hirsch (1982). The acuity of our best kestrel (33.5 cycles/dva) increased by 79% would be approximately 60 cycles/dva.

PERG studies of blade patterns. An ideal visual deterrent for avian-turbine collisions is one that continues to provide high visibility as the bird gets closer and closer to the whirling blades. Our analysis of the problem from the velocity detection literature and from our own experiments, reported here, indicate that the physiology of the retina will not permit such a situation. Beyond a certain point, the velocity of the retinal images of the blades sweeping across the retina will overwhelm the retina's ability to keep up. The initial effect will be a smearing or blurring of the image of the blades, and finally their complete transparency, which could appear as an illusory safe place to fly, with deadly consequences for the bird. Our findings indicate that for a hypothetical turbine with a 20-m diameter blade circumference and rotating at 45 RPM, our anti-motion smear patterns are quite visible at distances of about 23 m. By 18 m, however, visibility has dropped sharply and no blade pattern, of those we have tested, has an advantage. By 12 m, visibility has effectively dropped to zero as motion smear and transparency become the dominant visual events.

How useful is good blade visibility at 23 m? A kestrel with the wind at its back could safely maneuver at about 25 m (M. Morrison, personal communication). Closer than that, however, the bird would be at risk for not being able to avoid the blades should a sudden wind gust push it forward. Moving closer to the blades to about 14.5 m, the blank blades have lost 50% of their visibility at 23 m, and by 12 m, all the blade patterns have become totally blurred. Good visibility at a distance of approximately 23 m would seem to be a useful deterrent, if low tip visibility is a factor in collisions. On the other hand, since the blade tips at distances of 10-12 m and closer appear to be transparent blurs, the birds might interpret them as being "safe"; i.e., as the bird gets closer, the threatening looking blades disappear and the bird might feel safe in approaching closer or even trying to fly through the transparent visual smear.

The results of our comparison of different blade patterns, while not yet complete, is highly suggestive that the thin-stripe, staggered, anti-motion-smear pattern is the most visible of any that we tested. Its visibility (mV above noise) was 2.7, which is three times the visibility of the blank blades. (0.9). This is what the anti-motion-smear principle would predict. Not far behind was the single black blade with a visibility of 2.5, which almost certainly will not be statistically different from the 2.7 of the thin, staggered stripes. We now have to determine whether these patterns will maintain their superiority at distances shorter than 18 m.

Additional laboratory research. The optimal color of the blade patterns is a variable that needs to be investigated. The human motion-smear literature suggests that if color is important, it probably would be only be so at the lower velocities (Burr et al. 1998); this, however, would have to be investigated in the avian eye, which is much more specialized for color-vision processing than the human eye. In particular, we need to determine whether color offers any advantage over black in increasing visibility at the shorter distances and will shortly be beginning some studies on this question. Finally, we will be evaluating the optimal size, shape, and color of devices to deter lateral approaches to blades.

Applications to the wind-power industry. The finding that anti-motion-smear patterns increase the visibility of turbine blades at distances at which raptors could safely maneuver away from them should be of interest to the industry. These data, however, only apply to conditions of bright illumination. We have no idea at present to what extent these stimuli retain their improved visibility under sub-optimal viewing conditions, such as mist, rain, etc. Nor will they (or any other visual pattern, for that matter) retain their visibility once the animal gets close enough for the retinal-image velocity to exceed 200 dva/sec, at which point the bird's retina has passed the limit of its ability to process temporally changing stimuli. Nevertheless, such patterns are worth testing in the field to determine whether the visibility advantages they offer will reduce avian mortality. The finding that a single, solid-black blade, paired with two blank blades is a highly visible stimulus could have useful economic consequences for wind power companies that have an interest in testing this type of deterrent, as there would be no requirement for the precision application of stripes in specific positions on each of three blades.

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General Discussion

Dr. Hodos initiated the general discussion following his presentation by asking the group, “What do wildlife biologists think about this?”

One respondent suggested the use of strobes mounted on the hub of the turbine to “freeze” the moving image, giving the appearance that the blade is moving more slowly (and therefore becomes more visible). Another participant pointed out that this would not help a bird avoid the blades, “because the bird would not see the blade where it actually is.”

One participant asked Dr. Hodos how well he expected his laboratory findings to carry over into the field, given the greater complexity of the natural world. Dr. Hodos acknowledged the difference, but noted that, “once the bird is 15 to 20 meters away [from the turbine] ...there probably isn’t much of the natural world left that it is viewing.”

Dr. Hodos agreed that it might be interesting to run the experiment with different blade widths. As to whether a larger turbine rotating more slowly would be beneficial from the standpoint of visibility to birds, he noted that it is the tip velocity and the distance that are the critical factors, not the RPM. However, the bird “might be able to get closer” to a slower-moving turbine.