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BEHAVIOUR OF MIGRATING BIRDS EXPOSED TO X-BAND RADAR AND A BRIGHT LIGHT BEAM

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Summary

Radar studies on bird migration assume that the transmitted electromagnetic pulses do not alter the behaviour of the birds, in spite of some worrying reports of observed disturbance. This paper shows that, in the case of the X-band radar 'Superfledermaus', no relevant changes in flight behaviour occurred, while a strong light beam provoked important changes.

Large sets of routine recordings of nocturnal bird migrants obtained using an X-band tracking radar provided no indication of differing flight behaviour between birds flying at low levels towards the radar, away from it or passing it sideways. Switching the radar transmission on and off, while continuing to track selected bird targets using a passive infrared camera during the switch-off phases of the radar, showed no difference in the birds' behaviour with and without incident radar waves. Tracking single nocturnal migrants while switching on and off a strong searchlight mounted parallel to the radar antenna, however, induced pronounced reactions by the birds: (1) a wide variation of directional shifts averaging 8° in the first and 15° in the third 10 s interval after switch-on; (2) a mean reduction in flight speed of 2–3 m s^{-1} (15–30 % of normal air speed); and (3) a slight increase in climbing rate. A calculated index of change declined with distance from the source, suggesting zero reaction beyond approximately 1 km. These results revive existing ideas of using light beams on aircraft to prevent bird strikes and provide arguments against the increasing use of light beams for advertising purposes.

Key words: bird, nocturnal migration, flight, behaviour, light, radar, aircraft collision avoidance, bird strike.

Introduction

The fact that birds have a wider spectrum of sensory capacities than humans (Kreithen, 1979; Beason and Semm, 1991) and are able to orient according to the static magnetic field of the earth (Wiltschko and Wiltschko, 1991, 1996) led to speculation about the potential disturbance of this orientation system by oscillating magnetic fields or by pulsed or continuous electromagnetic fields (Steiner and Bruderer, 1999). Short-term deviations of migratory birds in the neighbourhood of radar transmitters were often associated with the effects of these pulsed microwaves (Poor, 1946; Drost, 1949; Knorr, 1954; Hild, 1971). However, Busnel et al. (1956), trying to repeat Knorr's (1954) observations, failed to find any reaction. Indoor experiments by Kramer (1951) showed no reactions of conditioned birds to the transmission of continuous waves at 520 MHz, while Kreithen and Davis (1995) were able to demonstrate physiological reactions of pigeons to pulsed signals of 1.25 and 2.45 GHz. Eastwood and Rider (1964) found no changes in the directions of migratory birds when aiming an additional strong radar beam at migrating birds observed using surveillance radar. In his comprehensive review of radar ornithology, Eastwood (1967) confirmed the view that radar has no recognizable influence on migrating birds. Wagner (1972), tracking released homing pigeons optically (i.e. steering the antenna of a tracking radar by hand), with the radar transmitter switched on or off for each subsequent pigeon, found a very slight difference in the initial orientation of the two pigeon classes. Heilig (1987), checking a known 'release-site bias' of homing pigeons (characterized by a mean deviation of 90° of initial orientation from the home direction) near the airport of Stuttgart-Echterdingen for the potential influence of the airport radar, found that the release-site bias persisted when both radar systems were out of service for 3 h.

Because studies of bird migration have increasingly made use of radar in the last 10 years, the question whether radar waves have an influence on the flight behaviour of migrating birds is of great importance. In the present study, we first test whether the tracking radar 'Superfledermaus', an ex-military fire control radar used for ornithological research since the late 1960s (Bruderer, 1971, 1997), has any detectable effect on nocturnally migrating birds at close range (i.e. at highest intensities of the electromagnetic fields). We compared birds in four sectors around the radar. In the case of a disturbing or irritating effect, we would expect an increased scatter of directions for approaching birds and directions deviating away from the radar in birds passing the radar sideways. We might also expect differences in climbing rates because birds might try to escape the disturbance by climbing or descending. Birds hesitating on approach may show reduced speeds.

In a second part of the study, we examined some flight paths of tracked birds for the effects of switching the radar transmitter on and off. If the birds are disturbed by the sudden appearance and disappearance of the electromagnetic field, we would expect reactions in their flight behaviour (in direction, horizontal speed, vertical speed and possibly in wingbeat frequency) similar to those provoked by switching on and off a light beam in the third part of the study.

Because of the great importance of visual cues in the life of birds, we expected that birds suddenly confronted with a strong light beam would change their flight behaviour, trying to escape the beam sideways or vertically, and would show uncertainty by slowing down their approach flights and increasing their wingbeat frequency.

Materials and methods

Study area and observation period

Data were collected during a campaign of radar studies on bird migration in the Arava Valley, Israel, 40 km south of the Dead Sea and 140 km north of Elat, 150 m below normal sea level (Bruderer, 1992). The radar, positioned in a flat sand desert, was surrounded by a dam of sand to protect it against echoes from the ground (ground clutter). The dam had a radius of 40 m and was 2.5 m high. Observations lasted from 10 August to 19 September 1992. For a general description of bird migration in the Arava Valley, see Bruderer and Liechti (1995); for the altitudinal distribution, directions and flight behaviour of nocturnal migrants, see Bruderer (1994), Liechti and Bruderer (1995) and Bruderer et al. (1995b). The experiments switching on and off a searchlight mounted parallel to the radar antenna were carried out between 27 August and 17 September 1992, and those switching on and off the radar transmitter were performed on 13 and 14 September 1992.

Radar tracking of low-flying nocturnal migrants

The tracking radar ‘Superfledermaus’ (X-band approximately 9 GHz, 100–150 kW peak pulse power, 60–100 W mean transmitted power, 0.3 μs pulse length, 2082 Hz pulse repetition frequency, 2.2 ° opening angle of the pencil beam) was used to track nocturnal migrants between sunset and sunrise (Bruderer et al., 1995a). A pulse of 100 kW peak power reaching a target at 250 m, 500 m and 1000 m, respectively, produces a power density of approximately 400 W m^{-2}, 100 W m^{-2} and 25 W m^{-2}, respectively. Each bird was tracked for at least 60 s, providing data from at least three intervals of 20 s. Approximately 200 targets per night were searched at random in all directions around the radar. High-level winds were measured by tracking pilot balloons every 4 h. Birds could be tracked down to elevation angles of approximately 4.2 ° and down to a range of approximately 200 m from the radar. Wingbeat patterns, determined according to the echo signatures, were used to identify bird classes and to exclude non-bird targets and flocks from the samples (Bloch et al., 1981; Bruderer, 1997).

Data for the whole autumn season were screened for birds within limited ranges and, within the lowest 300 m above the radar, their tracks were checked for variation in flight behaviour within four sectors around the radar (see Table 1) and with increasing distance from the radar. We calculated the mean direction over the ground (ϕD_g) and the length of the mean vector (**r**, indicating the concentration of directions) as well as the mean angular deviation (± S.D.) according to Batschelet (1981). As additional information to be compared between the four sectors, we calculated an index for the straightness of tracks, $V_{g,tot}/\Sigma V_{g,int}$, and one for the shift in direction $\Sigma\Delta D_g/n-1$ (Fig. 1). V_g (ground speed) is the distance over ground covered by a bird in a given time. $V_{g,tot}/\Sigma V_{g,int}$ is the total vector length of a track divided by the sum of the vectors of its single 20 s intervals; the more a bird changes its direction during the flight, the smaller the total vector compared with the vector sum of the single intervals. $\Sigma\Delta D_g/n-1$ is the sum of all angular differences (positive and negative) in direction over the ground (D_g) between adjacent 20 s intervals divided by the number of intervals minus one. The result is the mean deviation in direction per 20 s interval, which is close to zero if the bird tends not to shift its directions to one side.

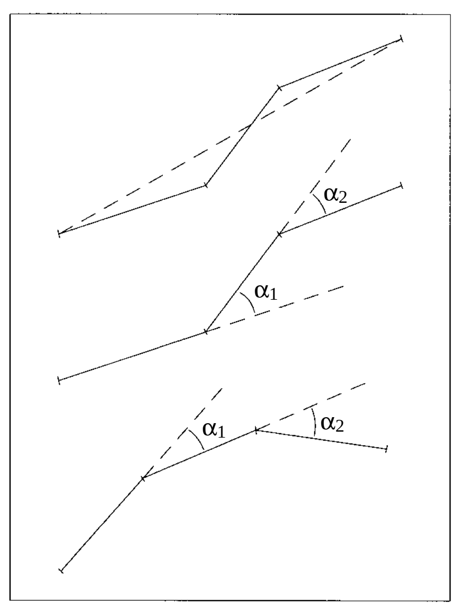

Fig. 1. Graphical explanation of the index for the straightness of a track (upper diagram), where the total vector length of a track is compared with the sum of the individual vector lengths of the available 20 s intervals. The lower two diagrams illustrate the index for the shift in direction; shifts in opposite directions compensate each other, while subsequent shifts in the same direction are summed, indicating a tendency to deviate from the previous track in a specific direction. For further explanation, see Materials and methods.

Tracking while switching the radar transmission on and off

Parallel to the antenna of the tracking radar, we mounted a passive infrared camera (Inframetrics LORIS IRTV-445L). This thermal-imaging equipment produces no radiation but detects heat differences in the field of view. The field of view is 1.8 ° (in the vertical axis, only 1.45 ° is visible on the television screen). For details of the method, see Liechti et al. (1995). The camera was mounted at the same place as the searchlight depicted in Fig. 2.

Birds flying at low levels were searched by radar in the approach sector; those with flight directions towards the radar were selected for continued tracking. After recording a first representative part of the flight path (40–80 s), the radar transmitter was switched off before the bird had reached its closest point to the radar. The bird target in the cone of view was then tracked by hand for 20–80 s, steering the elevation angle and azimuth drive of the radar antenna manually according to the silhouette visible on the television screen. The radar transmitter was then switched on again, and the procedure was repeated at average intervals of 50 s to compare the behaviour of the bird (direction, vertical speed, horizontal speed) when the radar was switched on.

During infrared tracking, the flight path was not recorded because the range information of the radar was lacking. The comparison was therefore between the mean direction, vertical speed and horizontal speed during complete switch-off intervals and the detailed flight behaviour documented by radar tracks in the switch-on intervals.

Tracking while switching the light beam on and off

As for the infrared camera, we mounted a strong searchlight parallel to the radar antenna (Fig. 2). The core beam of the searchlight had an average opening angle of 3.8 °; it works at 24 V with a 200 W bulb and a reflector of 40 cm diameter. The light intensity was 6 lx at 300 m and 1.5 lx at 600 m.

Searching and radar tracking of the birds was as in the previous experiments. Instead of switching on and off the radar, the birds' flight paths were continuously recorded by radar, while the light beam was switched on after 20–60 s without light. After switching on the light, the bird remained continuously in the light beam for 20–50 s; after switching off the light, radar tracking was continued for 20–50 s. During the light phase, the bird was observed through a telescope (KERN 12.4×100) mounted parallel to the radar antenna (Fig. 2).

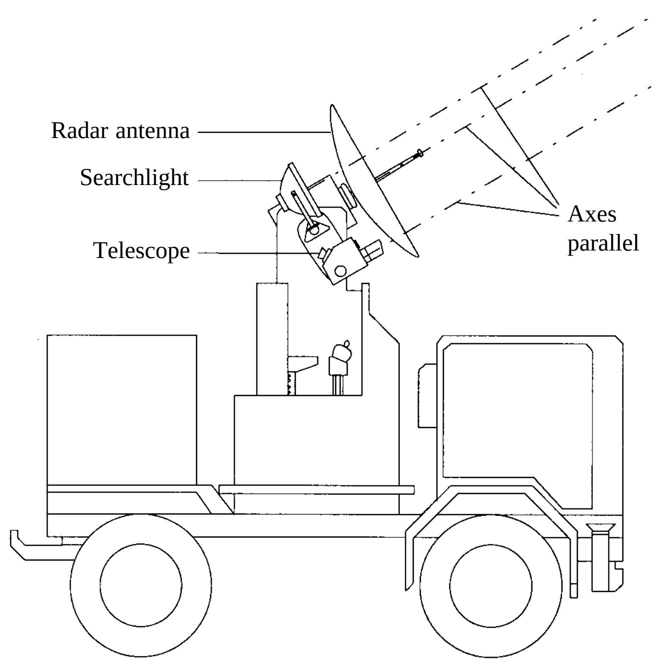

Fig. 2. The tracking radar 'Superfledermaus' with its telescope and an additional strong searchlight mounted parallel to the axis of the parabolic radar antenna. An infrared camera could be mounted instead of the searchlight.

In total, 114 tracks were recorded. Because of variations in the number of intervals per track, we either had to deal with varying sample sizes of intervals previous to, during and after illumination, or we had to reduce the number of tracks to those with equal numbers of intervals. For the detailed analysis, we included only those 56 tracks in which four switch-on intervals and four post-switch-on intervals of 10 s were available. The full sample of 114 tracks was considered for a cross-check of the results. Because the interval immediately before switch-on contained up to 1 s of illumination (as a result of inaccurate synchronisation of tracking intervals and the illumination), we used the first of two pre-switch-on intervals as a reference to be compared with all the following intervals. Because of

Table 1. *Comparison of four sectors around the radar with respect to the mean direction and mean angular deviation (ϕD_g) of tracks, concentration of directions (**r**), vertical speed (V_z), total vector length divided by the sum of vector length per interval of each track ($V_{g,tot}/(\Sigma V_{g,int})$, mean shift in direction between intervals ($\Sigma\Delta D_g/n-1$)*

Sector	N	ϕD_g (degrees)	**r**	V_z (cm s^{-1})	$V_{g,tot}/\Sigma V_{g,int}$ (%)	$\Sigma\Delta D_g/n-1$ (degrees per 20 s)
Approach 300–30 °	282	177±44	0.702	−4±55	99.6	−1±15
Flight-off 120–210 °	237	171±37	0.788	8±53	99.6	−1±12
Passing W 210–300 °	282	167±42	0.736	−5±68	99.2	0±8
Passing E 30–120 °	250	172±52	0.582	1±52	99.4	−1±15

Values are means ± S.D.
Only birds below 300 m above ground level, no other restrictions.

Table 2. *Comparison of four sectors around the radar as in Table 1, but restricted to migrants with track directions of 165±45°*

Sector	N	ϕD_g (degrees)	**r**	V_z (cm s^{-1})	$V_{g,tot}/\Sigma V_{g,int}$ (%)	$\Sigma\Delta D_g/n{-}1$ (degrees per 20 s)
Approach 300–30°	217	178±17	0.954	−9±51	99.7	0±4
Flight-off 120–210°	206	171±20	0.941	11±52	99.7	0±5
Passing W 210–300°	172	169±19	0.943	−4±68	99.6	−1±6
Passing E 30–120°	175	174±20	0.939	0±43	99.8	0±4

Values are means ± S.D.

interference with ground clutter at low flight levels, only a few targets (N=19) provided sufficiently good wingbeat patterns to allow pre- and post-switch-on analysis of wingbeats. To check for a potential decrease in response with increasing distance, the changes in ground speed (km h^{-1}), direction (degrees) and climbing rate (dm s^{-1}) from the reference interval to the first interval after switch-on were summed to form an index of change in flight behaviour. The same index was calculated for the difference between the third-last and second-last intervals before switch-on. Both indices were tested for variation with distance, using all 114 tracks.

Results

Radar tracking of low-flying nocturnal migrants

Neither of the hypotheses on increased variation of directions or vertical speeds due to evasive action by the birds with respect to the radar beam was supported by the flight data for birds tracked at levels below 300 m; this was true when all tracks were included (Table 1) and when the flight directions of the birds were restricted to ±45° around the mean direction of 165° prevailing at these low levels (Table 2). There is no significant difference in the mean directions from the four sectors, the mean directions to the west and east of the radar are not shifted away from the radar and the variance of track directions is not increased in the approach sector to the north. There are no significant differences in the mean and variation of vertical speeds from the different sectors, and the standard deviations cover a range (approximately ±50 cm s^{-1}) that is within the normal variation of 'horizontally' flying birds. The straightness of tracks is not reduced in the approach sector, and there are no signs of increased directional shifts to either side of the radar or in the approach sector compared with flight-off. When calculating a regression for the straightness of all available tracks below 600 m above ground level and track directions of 120–240° (N=2159) *versus* distance from the radar, we found no correlation. A scattergram of climbing rates *versus* distance showed no distance-dependent trends.

Tracking while switching the radar transmission on and off

The longest of 21 recorded tracks was that of six heron-type birds flying past the radar at an altitude of slightly more than 1000 m. Fig. 3 shows the projection of the whole flight path (eight intervals with the radar switched on and the flight path recorded; seven intervals with the radar switched off and no recordings of the flight path). There was no recognizable change in any flight variable either when the birds flew towards the radar or when the radar was switched on.

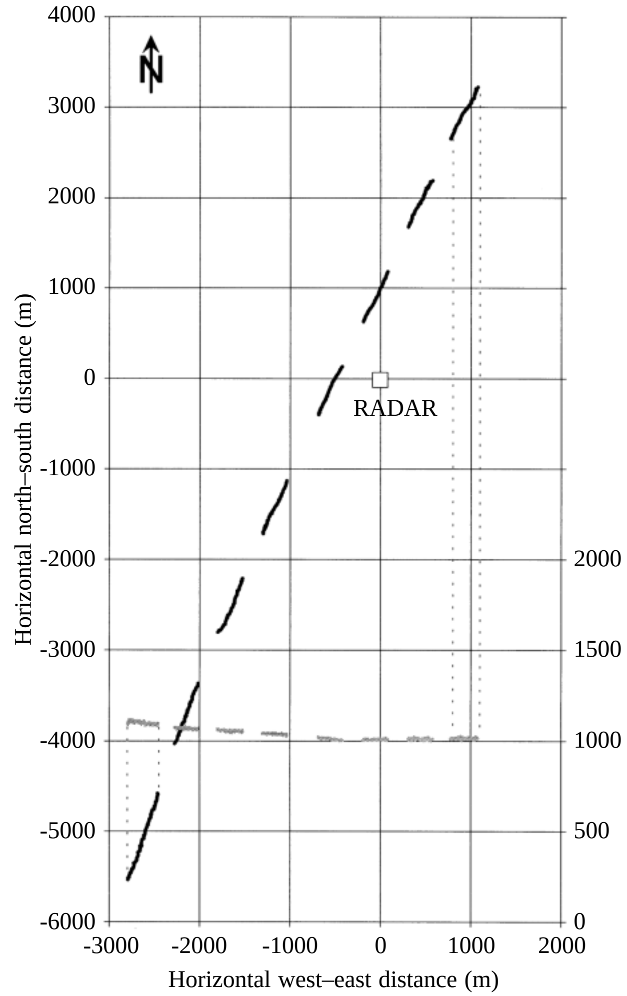

Fig. 3. Horizontal (black lines) and vertical (grey lines) projections of the radar-tracked flight path of six heron-type birds flying slightly more than 1000 m above the Arava Valley (13 September 1992). Horizontal coordinates and altitudinal scales have their origin at the radar. The flight path was only recorded when the radar transmitter was on; when the birds were tracked using infrared, no recording of the flight path was possible (range information lacking). In the first and last recorded intervals, the horizontal and vertical projections are connected by fine dashed lines.

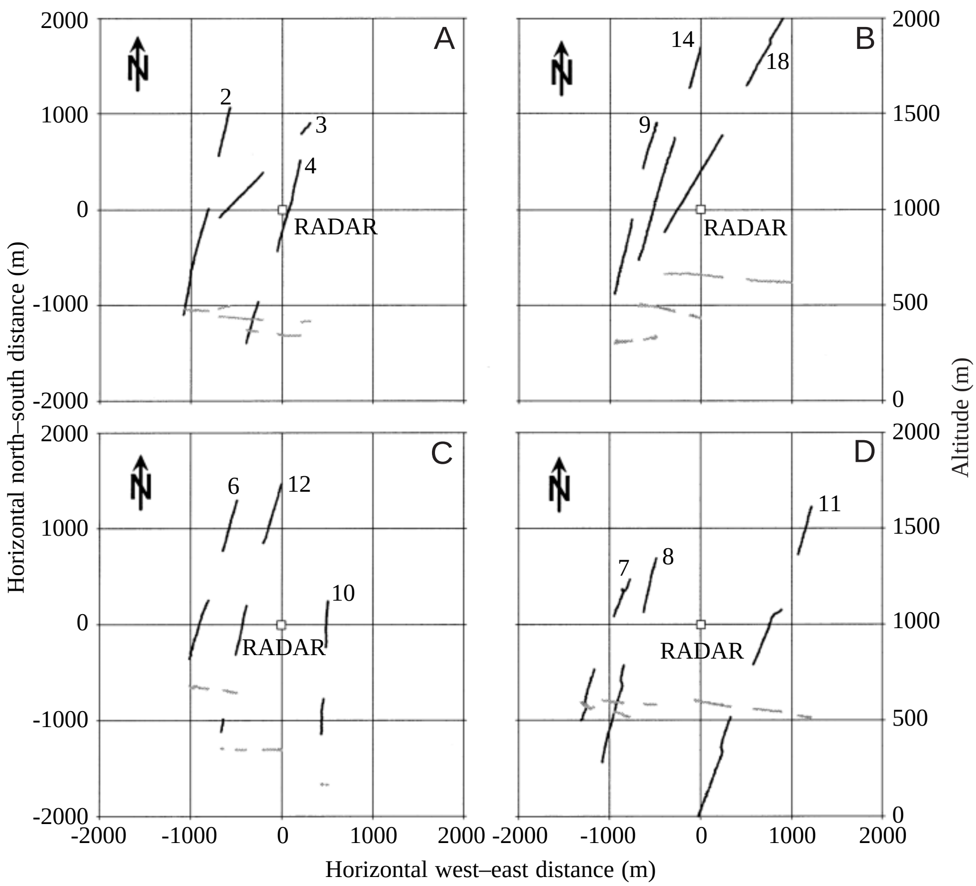

Fig. 4. Same presentation as Fig. 3. (A) Tracks 2, 3 and 4: single birds recorded on 13 September 1992; (B) tracks 9, 14 and 18: single birds recorded on 13 September 1992; (C) single birds recorded on 14 September 1992; track 6, small wader; track 10, small passerine; track 12, waterbird; (D) tracks showing irregularities in the flight paths; tracks 7 and 8, small waders; track 11, three herons.

The other 20 tracks comprised only 2–3 phases of tracking by radar and 1–2 phases of tracking by the passive infrared camera (radar switched off). Fifteen of these showed straight flight paths, indicating no reaction to the experimental situation (eight examples are shown in Fig. 4A–C). Five flight paths (25 %), two of them twice, showed some irregularities in direction during the tracking phase (three examples shown in Fig. 4D and track 18 in Fig. 4B). In only one case (track 11) did this directional change immediately follow the switch-on of the radar. To check whether such variation in direction also occurs at a lower intensity of the electromagnetic field, we checked 100 randomly selected flight paths at ranges of more than 2 km from the radar, but at equally low levels as for the experimental birds (i.e. below 600 m). Twenty-seven of these 100 tracks showed irregularities in direction comparable with that in Fig. 4D; there was, however, no complete circle among them. We cannot, therefore, exclude the possibility that the complete circle in Fig. 4D (track 7) may be a reaction to the incident radar waves; however, in general, there was no marked increase in the number of irregularities in the flight paths with decreasing distance.

Tracking while switching the light beam on and off

Representative examples showing the influence of the light beam on migrating birds are given in Fig. 5A,B, while Fig. 6A–C demonstrates the reactions of 56 birds tracked during directly comparable time intervals. Fig. 5 demonstrates the wide variation of possible reactions, which poses some problems for the statistical analysis. In 25 % of the birds, there was no obvious reaction; in 54 % of the cases, the main reaction was shifting away from the light source, 11 % shifted towards it, 7 % showed mainly climbing or descent, and 3 % primarily decreased speed.

Change in direction (Fig. 6A)

The difference between the first interval after switch-on and the reference was a mean shift in direction of 8±10 ° (mean ± S.D., N=56). The reactions in the second interval after switch-on were very inconsistent: while some birds increased their deviation from their previous track, others over-compensated for the previous deviation, leading to increased variation but to only a moderate additional change in mean direction. The same trends continued in the third interval after switch-on; in the fourth interval with illumination, variation and deviation from the reference direction decreased. This decrease continued after switch-off, but the birds had still not fully returned to the pre-treatment direction 40 s after switch-off.

Change in ground speed (Fig. 6B)

Mean ground speed dropped by approximately 2 m s^{-1} after illumination and variation more than doubled. Similar to the reaction in direction, variation increased in the second interval

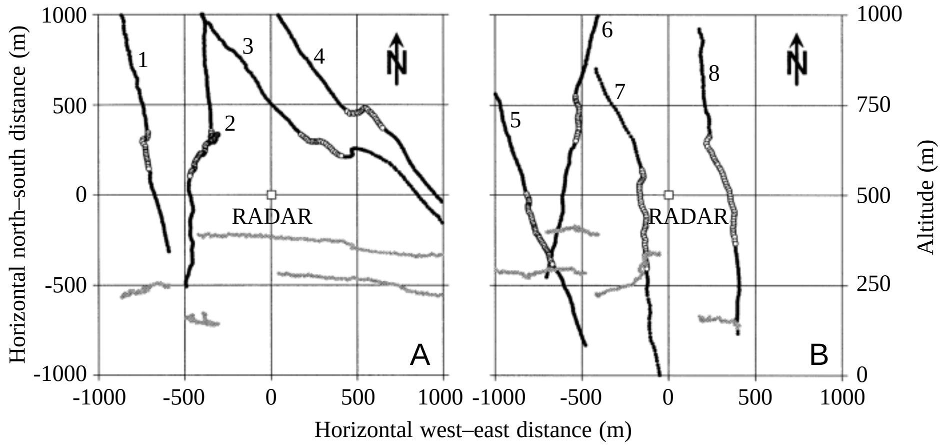

Fig. 5. (A,B) Same presentation as in Figs 3 and 4. Typical examples of radar-recorded flight paths of birds temporarily illuminated by a strong searchlight. Phases with illumination are marked by superimposed rings in the horizontal tracks. Tracks 1 and 4 deviate away from the light source; track 3 deviates and shows a notable reorientation movement after switch-off; track 2 stops, turns through 360° and continues on an irregular flight path; track 5 loses altititude briefly at switch-on and then continues normally; tracks 6 and 8 shift towards the light source; track 7 is climbing slightly before switch-on, but climbs steeply and continues its flight 100 m higher.

after switch-on. Variation and deviation then tended to decrease until switch-off. Variation remained high after switch-off, while mean speed returned to normal.

Change in climbing rate (Fig. 6C)

The vertical speeds showed only minor variation. Vertical speeds of $\pm 0.5\,m\,s^{-1}$ are quite normal during nocturnal migration (Bruderer et al., 1995b). There is, however, some consistency in the observed variation, indicating a tendency for an increased climbing rate when approaching the radar and a slight decline after switching off the light.

The result was the same for all three parameters when the whole sample of 114 tracks (with varying lengths of tracking phases) was considered for comparison. The fact that all three variables tended to shift towards the switch-on behaviour during the last pre-switch-on interval is due to inaccurate triggering of the radar recording intervals and manually switching on the light beam in response to a telephone-transmitted command from the radar operator: in several cases, the light was actually on for a fraction of a second within the last pre-switch-on interval.

Change in wingbeat frequency

Only 19 echosignatures provided comparable sequences before and after switch-on. Seven of these showed no reaction. Among the 12 birds with reactions, one showed a decrease in frequency of 8 %, and all the others showed increases in wingbeat frequency of between 8 and 20 % (mean 13 %).

Index of change as a function of distance

The sum of changes in ground speed ($km\,h^{-1}$), direction (degrees) and climbing rate ($dm\,s^{-1}$) between the reference interval and the first interval after switch-on, plotted against distance from the radar at the moment of switch-on, declined steeply with distance, but there was no corresponding distance-dependent change in the index derived from the third-last and second-last intervals before switch-on. Beyond 1 km, the difference between the two indices disappeared, suggesting that the birds no longer reacted to the light.

Discussion

This study shows that the beam of a strong searchlight influenced the flight behaviour of migrating birds, whereas the beam of an X-band tracking radar did not. With respect to radar ornithology, the results prove that, at least in the case of our X-band tracking radar, the instrument used to study bird migration does not provoke any measurable changes in the behaviour of the birds. The disturbing effect of the light beam provides arguments against the increasing use of light beams for advertising purposes (attracting people to places of interest), and it may revive suggestions that light beams (e.g. landing lights) should be used to alter the flight paths of birds in front of approaching aircraft.

With respect to radar waves, our results corroborate previous tests which revealed no measurable reactions either in free-flying migrants (Busnel et al., 1956; Eastwood and Rider, 1964) or in experimental in-door flights (Kramer, 1951). Reports of the reactions of mainly large birds to radar (Poor, 1946; Drost, 1949; Knorr, 1954; Hild, 1971) do not include experiments, but, these observations of unexpected behaviour in birds suggest that particular combinations of wavelength, pulse repetition frequency and bird size may provoke reactions that were not recorded in the above-mentioned experiments. Laboratory experiments by Kreithen and Davis (1995), and observations suggesting that pigeons fly lower and slower when homing towards an active 150 kW radio transmitter (6.1–21.8 MHz) than in the absence of a transmission (Steiner and Bruderer, 1999), indicate that some electromagnetic fields can be detected by the birds.

Chickens and rabbits roaming in the close vicinity of our radar (20–50 m away) never showed any visible reaction when the radar beam was aimed at them, in accordance with the results of Drost (1949). Large migrating birds (raptors, herons, ducks) showed only rare reactions when the radar was aimed at them on approach at short distance (50–200 m). Considering that no reaction was observed when tracking the birds from behind, the few approach reactions were considered to be caused by the visible movement of the antenna towards the bird. In only one case since the start of our radar observation in 1967 did we observe a sudden, notable change in the flight

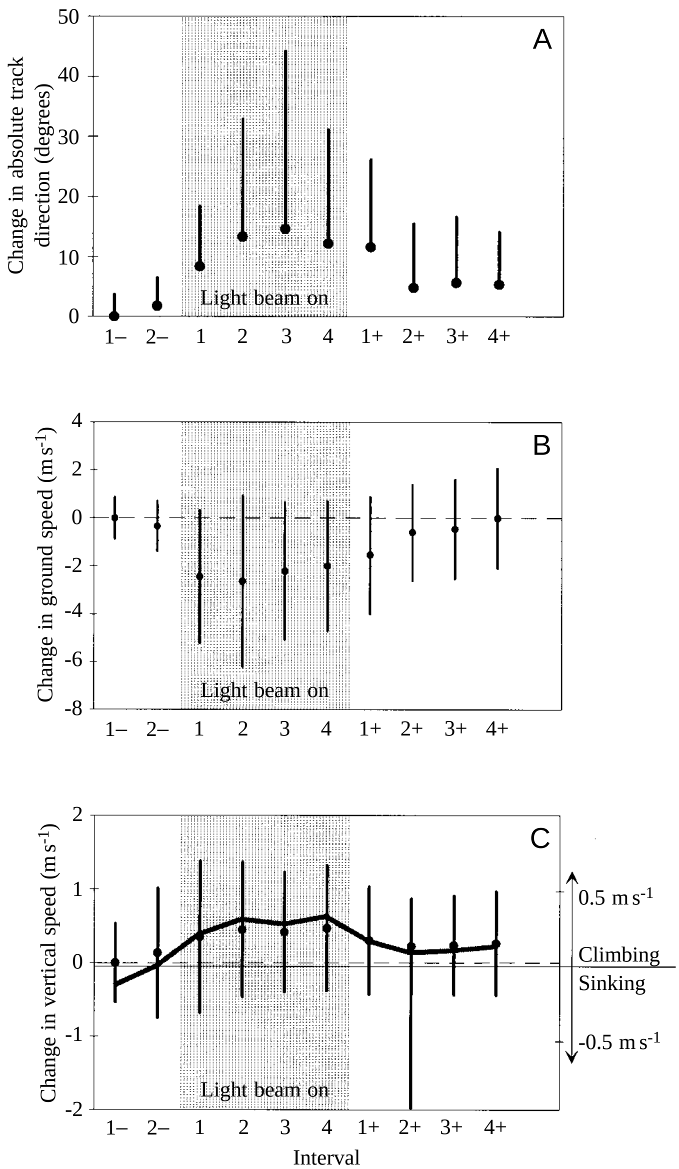

Fig. 6. Mean changes in three flight variables of 56 birds during two intervals of 10 s before switching on the searchlight (1–, 2–), four intervals during switch-on (1–4), and four intervals after switch-off (1+ to 4+). (A) Absolute track direction; (B) ground speed; (C) vertical speed. Values are means ± S.D. The reference line (dashed) corresponds to the mean climbing rate (0.01 m s^{-1}) during the first pre-switch-on interval (1–). The thick line in C indicates the mean climbing rate (right scale).

behaviour of migrating birds that might have been caused by the influence of the radar waves. On 17 September 1974 at 18:05 h, a flock of 21 grey herons (*Ardea cinerea*) crossed the alpine pass Hahnenmoos. They flew in perfect V-formation at an altitude of approximately 1000 m above the radar, which was positioned next to the pass at 1920 m above sea level. Approximately 300 m after they had passed the radar, the beam was aimed at them and tracking was initiated. Immediately after lock-on, the V-formation disintegrated. After flying in circles, the disorganized flock continued, climbing slightly, in its previous southwesterly direction. At 2.3 km from the radar station, the birds had reached 1100 m, they again flew three horizontal circles, and re-established their V-formation. After another 2.5 km, having reached an altitude of 1300 m relative to the radar station, they again flew some horizontal (non-thermal) circles, then shifted to horizontal flight towards west-southwest, probably as a reaction to the course of the mountain ridges to the south and the course of the valley below.

Our data on the disturbing effects of visible light confirm earlier experiments by Larkin et al. (1975). Using the telescope mounted parallel to the light beam, the birds were often seen hovering briefly and then trying to escape from the beam sideways. The brief period of hovering contributed to the measured reduction in ground speed, but was not its main reason, because the speed in the following switch-on interval was still low, tending towards normal only from the third switch-on interval onwards. The reduction in ground speed of 2–3 m s^{-1} is a significant (15–30 %) fraction of normal migratory air speed (Liechti and Bruderer, 1995). The observed shifts in direction are considerable, particularly since the direction had not completely returned to normal 40 s after switch-off.

We are grateful to all the volunteers working at the radar station and to the Israeli Ministry of Communication for enabling us to carry out this study in Israel. Herbert Stark was part-time leader of the radar station in the Arava Valley and performed the light experiments. The radar and the spotlight were provided by the Swiss Army, the infrared equipment by the Israeli Ministry of Communication; financial support for the development of the recording equipment was from the Swiss National Science Foundation (currently grant no. 31-43242.95). We thank M. Kestenholz, I. Steiner, B. Naef-Daenzer and the referees for valuable suggestions for improving the paper.

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