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Bird flight behavior, collision risk and mitigation options at high-speed railway viaducts

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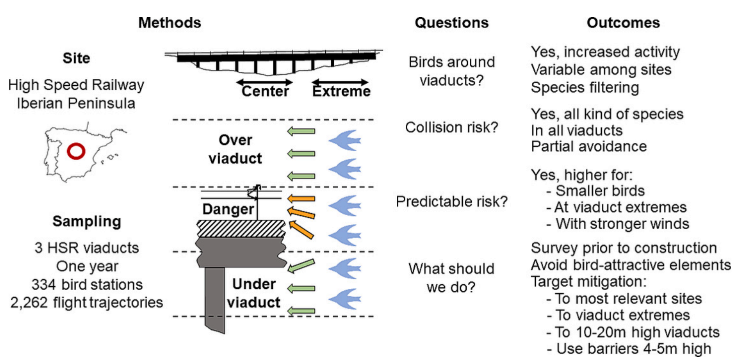
HIGHLIGHTS

- Viaducts attract birds from surroundings, that are then in danger of colliding with trains.
- Small and medium-sized birds are at greater risk of collision.
- Collision risk is maximal at viaduct ends and when it is windy.
- The local bird community composition determines the species involved and the collision risk.
- Anti-birdstrike barriers need to be 4-5 m high.

GRAPHICAL ABSTRACT



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ABSTRACT

High-speed railway (HSR) networks are rapidly expanding and are predicted to continue to grow over coming decades. However, there is scant knowledge of their environmental impacts. Their possible effects on bird mortality, particularly at viaducts, gives especial cause for concern. This work presents the results of a nine-month monitoring of bird activity in the vicinity of three HSR viaducts in Central Spain. The study focused on the effects of the infrastructure regarding bird frequentation of the site and on bird flight activity in the danger zone for collision with passing trains. The findings show (i) that bird communities may differ markedly between sites and (ii) that bird activity increases near the railway together with changes in relative species abundances. Furthermore, (iii) birds show a significant tendency to avoid flying across the danger zone, but (iv) all kinds of birds are at a real risk of collisions with trains at viaducts. The greatest danger is at viaduct extremes rather than in their central section, particularly during gusts of wind and for small or medium-sized birds. It also appears that relatively low viaducts might pose greater risk. In practical terms, these results (i) emphasise the need for thorough prior prospection of bird species present, and their flight patterns, where new viaducts are to be built, (ii) show that there is a real risk of bird collisions with trains at viaducts, which should be mitigated, with particular attention due to viaduct extremes and areas where their height is not much above the surrounding

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vegetation and (iii) strongly indicate the need to minimise viaduct features that may attract birds to them, for example as potential nest sites.

1. Introduction

Railways are among means of transport regarded as having low environmental impact. As such, increasing the extent and use of railway networks are priority objectives of green economy transition politics (Profillidis et al., 2014; EY, 2023). Thus, the European Green Deal (EU, 2019) calls for a 90 % reduction in greenhouse gas emissions from transport by 2050, and it envisages an intensive shift to rail for passenger and freight transport to reduce greenhouse gas emissions. Accordingly, high-speed rail traffic is planned to double in Europe by 2030 and triple by 2050 in comparison with the 2015 scenario, requiring the construction of a high-quality rail network (EU, 2020). The United States similarly plans $80 billion investments in reliable passenger and freight rail services, including the improvement of existing railway corridors and the establishment of new intercity connections (White House, 2021). With this objective, 50 rail corridors connecting US cities <600 miles apart have been identified to implement high speed connections (Amtrak, 2021). Other countries, including China, are also planning extensive high-speed railways (Ascensão et al., 2018). All these proposals regard high-speed railways (HSR) to be the best replacement for medium-haul flights (Profillidis et al., 2014; EY, 2023). Nevertheless, the effects of these infrastructures on ecosystems are poorly understood, other than knowing that they have a low carbon footprint relative to other modes of transport (Borda-de-Água et al., 2017; Popp and Boyle, 2017; St. Clair et al., 2017).

Vertebrate roadkill is one of the most important impacts that roads have on ecosystems (González-Suárez et al., 2018; Teixeira et al., 2020; de Jonge et al., 2022) and it is also a concern with railway lines (García de la Morena et al., 2017; St. Clair et al., 2020). Since railways share several characteristics with roads, they have both been assumed to have similar environmental effects, although investigations have shown differences between them associated with their structural characteristics (e.g., Dornas et al., 2019), and with the type and frequency of the vehicles that use them (Borda-de-Água et al., 2017; Popp and Boyle, 2017). Railway lines present larger embankments and more frequent tunnels and bridges, due to factors such as gradient and curve limitations inherent to their construction. Electrified railway lines also include a diversity of structures such as catenary poles and powerlines. As a result, railway lines may present numerous opportunities for bird species to make use of their structures for feeding, resting, nesting or maintaining territories (Morelli et al., 2014; Mainwaring, 2015). Moreover, since traffic volume is much lower on railways than on roads, railway lines are much less disturbed by noise and human activity and those carrying freight may quite often provide grain spillages, which will also draw in abundant wildlife (St. Clair et al., 2017). Nevertheless, trains often surprise and kill animals that approach lines unaware of the danger (García de la Morena et al., 2017; Dornas et al., 2019; St. Clair et al., 2020).

HSR has special requirements, such as extremely gentle gradients, wide bends and security fencing (UIC, 2015), that enable trains to run at speeds over 250 km/h. The environmental effects of this novel technology are particularly poorly known (Malo et al., 2017). Collisions with birds are among the chief concerns arising from HSR and have given rise to environmental impact assessments and requirements for targeted mitigation measures (Rodríguez et al., 2008). Although initial data on bird mortality at HSR has only been published recently (Malo et al., 2016; García de la Morena et al., 2017), the need for barriers to protect birds at viaducts has been identified for years, given the risk that they may cross flightpaths and produce high mortality (Rodríguez et al., 2008; Zuberogoitia et al., 2015). Studies to date have indeed confirmed that viaducts present high collision risks for birds passing through the area (Godinho et al., 2017; Hu et al., 2020). However, to what extent birds avoid these danger zones and whether barriers are effective in preventing collisions has remained unknown. Knowing this is of paramount importance given the conservation interest of many bird species, the frequency of viaducts along HSR lines and the complexity and expense of fitting them with bird-protection barriers (Ogueta-Gutiérrez et al., 2014).

Bird-strikes at HSR viaducts depend on a series of circumstances, hitherto practically unknown, that result in birds and trains coinciding at one point (Malo et al., 2017). Firstly, HSR presence may change the abundance and species that occur in its vicinity, such that collisions will involve only those species that do not avoid the infrastructure entirely or make some use of it. Those that do avoid the infrastructure will nonetheless suffer loss or degradation of their habitats (Falcao et al., under review), and even population fragmentation if railway avoidance is very strong. The complexity of viaduct construction may strongly influence the species present, through marked avoidance by species most sensitive to human infrastructures and attraction of others by the provision of abundant perches and nest sites (Morelli et al., 2014). Secondly, flight behavior, understood as how birds fly in the presence of the rails, poles and the catenary, is a factor since only those birds that inhabit the viaduct vicinity or cross it in their routine movements run a risk of collision if they traverse within reach of trains or the turbulence that they generate. This danger zone amounts to the 4.5 m gap between the rails and the overhead catenary and its near vicinity (Malo et al., 2017; Niu et al., 2018), where turbulence may buffet birds and/or inflict barotrauma (Grodsky et al., 2011; Dornas et al., 2019). This danger zone if often shielded by anti bird-strike barriers, but construction restrictions usually limit these to 2.5-3 m tall (Ogueta-Gutiérrez et al., 2014) so that the whole gap between the rails and the catenary is not covered effectively. Finally, birds entering the area where they can be hit or damaged by a passing train could potentially react to the approaching vehicle provided that they detect it with enough time for reaction and escape. However, the speed of approaching trains in the case of HSR surpasses the sensory and cognitive capacities of birds (de Vault et al., 2015), and flying across the danger zone can be thus seen as a direct surrogate of death risk in case of temporal coincidence with a train.

This study aimed to determine how birds respond to the presence of HSR viaducts and to better understand the factors conditioning the collision risk incurred by those that fly near them. The starting hypothesis was that (i) although birds generally avoid such infrastructures there are some species that will be more frequent near them because they can use viaducts for nesting, foraging or shelter. A reduction would be thus expected in the number of bird species and individuals flying across viaducts relative to those present in the surroundings at some distance from the infrastructure, along with a qualitative alteration of the bird community. In addition, (ii) birds flying across viaducts should avoid the espace between the rails and overhead wires as well as the smaller gaps between catenary wires, by flying either above or below the whole human infrastructure. Nevertheless, some flights will occur through the danger zone and such crossings should (iii) be most frequent at lower height viaducts and at the extremes of these, where the space below the viaduct is narrower. Lastly, (iv) large bird species should face on average a reduced risk of collision since their lesser maneuvrability (Pennycuick, 1989) makes them less likely to fly between viaduct structures. The answers to all these suppositions would be of great interest for evaluating the effectiveness of the anti-birdstrike barriers that are routinely fitted to HSR viaducts and for improving environmental impact procedures for future railway projects.

2. Methods

2.1. Data collection

The study took place at three viaducts of the Madrid-Segovia high-speed railway line, approximately 20-30 km north of Madrid (Central Spain, Fig. 1A). All three viaducts are protected by 2.5 m solid anti bird-strike barriers. The three sites (localities hereafter) are in quite similar habitat: open pasturelands in shallow valleys crossed by seasonal streams. The dominant habitat is mixed pasture with patches of *Cistus ladanifer*, *Lavandula stoechas* and *Thymus zygis* scrub. The entire zone also has scattered clumps of *Quercus rotundifolia*, *Q. pyrenaica*, *Q. faginea* and *Juniperus oxycedrus*, as well as riparian woods in the valley bottoms dominated by *Fraxinus angustifolia* and *Salix* spp. Viaduct 1 (40°39′8.61"N, 3°43′7.99"O) is 748 m long with a maximum height of 40 m, Viaduct 2 (40°44′57.08"N, 3°44′28.97"O) is 1848 m long and 80 m high in its central portion, and Viaduct 3 (40°46′19.59"N, 3°46′7.54"O) is 702 m long and 35 m high. Locality 1 is in the same valley and close to a landfill, with active dumping areas at approximately 700 m from the viaduct under study. The line began operation in 2007 and at present it sees some 60 trains daily, travelling at 250 km/h in this stretch.

Four sampling points were established per locality for data collection. Two were at the foot of the viaduct itself, one at one extreme and the other in its center (Fig. 1B). Two control points were located at equivalent positions on a line parallel to the railway 500 m away from it. These control points were sited towards the viaduct side whose topography and vegetation most closely matched those of the sampling points at the viaduct itself. In this way the data from each locality was balanced in terms of the viaduct/control and valley center/extreme position factors, and habitat structure was fully comparable between controls and viaduct positions except for the presence of the infrastructure.

Data collection consisted of recording for 15 min those birds that crossed the viaduct between the investigator and the first three spaces formed by the supporting columns, a sampling width per point of some 150 m. The same procedure was used at the control points, taking an imaginary line at similar height and direction as the viaduct as a reference point and using such features as trees and rocky outcrops as horizontal distance references. These were measured using a laser rangefinder (Leica Rangemaster 900 scan). The number and species of each bird flock (a flock defined as a single bird or a group flying together) was noted at each survey point. The number of birds in each flock was counted or estimated for groups of 20 or more individuals (0.9 % of cases, flock sizes 20–60 birds). At the viaduct points it was noted whether the birds crossed the danger zone, defined as the gap between the rails and the powerlines as well as the area through the catenary cables, or whether they passed above the powerlines or under the viaduct. When birds passed above or under the danger zone, the height in metres at which they did so was also estimated to further explore the data of bird flight at heights close to the viaduct (see explanation below and Fig. 1C).

Not all birds could be identified to species so these were grouped in the cases of vultures (Griffon Vultures *Gyps fulvus* and Monk Vultures *Aegypius monachus*; approximately 66 %:33 %) and kites (Red Kites *Milvus milvus* and Black Kites *M. migrans*; *c.* 90 %:10 %). Gulls were all noted as Lesser Black-backed Gulls *Larus fuscus* although some Black-headed Gulls *Chroicocephalus ridibundus* occur in the area (comprising fewer than 5 % of observations in a parallel independent sampling). Similarly, species smaller than Spotless Starlings *Sturnus unicolor* were grouped as 'small passerines'. Two weather variables were noted at each sampling point: air temperature and windspeed at 1.8 m from the ground, which were measured with a Martin Marten Airflow LCA 6000 anemometer. The number of passing trains was counted in surveys conducted at viaducts but, due to their low frequency (mean ± SD 0.74 ± 0.88 trains by sample; range 0–4; 50.3 % samples without trains) and short duration of crossing events (approximately 2.1 s to cross the section, <8 s to approach 500 m), they have not been included in the data analysis.

Fieldwork took place on days without rain that were not exceptionally windy (weather forecast indicating sustained wind speeds lower than 30 km/h). The decision not to sample during rainy or windy days, reduced our sampling universe of days by <20 %, since according to meteorological data from the area precipitation of >1 mm happens 16 % of days while sustained wind speeds over 30 km/h happen in 4.3 % of days, many of them also rainy (data from Colmenar Viejo meteorological station, Datosclima, 2023). One locality was monitored per day,

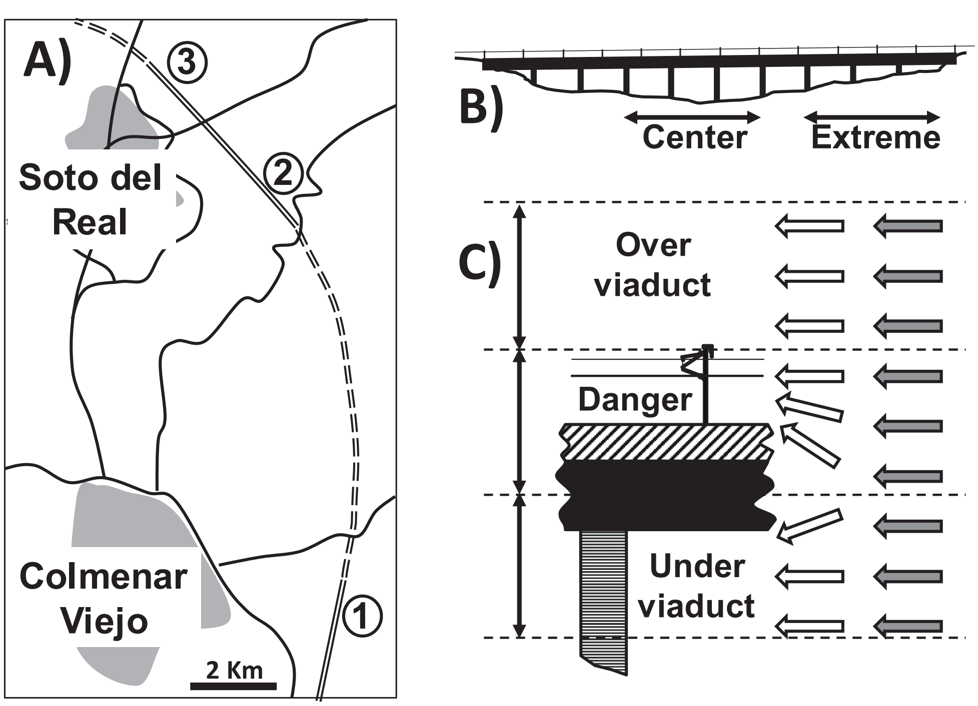

Fig. 1. Configuration of the study sampling of bird flight at viaducts of a high-speed railway (HSR). A) Location of the three HSR viaducts studied in the Madid-Segovia line, the railway shown as a double line, tunnels as broken lines. Nearby localities marked grey, and roads are solid black lines. B) Simplified diagram of a viaduct, showing the three sampled central gaps, corresponding with the deepest zone, and the three sample gaps at the viaduct extreme, where the viaduct is supported on the valley slope. C) Profile of a section of a viaduct and catenary showing expected flight paths of approaching birds (solid arrows). In case that birds did not avoid the danger zone, it would be expected to observe slight modifications of their flight paths to avoid colliding with the viaduct, but the frequency of observed crossings (empty arrows) should be equivalent in the three 8 m sections defined by this study (vertical arrows on the left).

between 10.00 and 14.00 h approximately. After 15 min at one survey point observation switched to another, the order of visits alternating to ensure that each point was monitored at different times of the morning. By this means each survey point was monitored twice on each of 42 days of data collection (except one point not sampled one day), between April and December 2018 (20 days in spring-summer and 22 in autumn). In total 334 15-min samples of flying birds were obtained.

2.2. Data analysis

Two linear mixed models were employed to determine which factors affect the number of birds that cross viaducts. These used number of flocks and number of individuals seen in 15 min of observation as response variables (log-transformed to better fit normality assumptions) and sampling point as random variable to account for repetitive sampling. Three categorical factors were included as fixed explicative variables: locality (3 levels), presence of infrastructure (control vs. viaduct) and position in valley bottom or on valley slope (center vs. extreme). Temperature and wind speed were included as fixed continuous variables. To obtain the best model, saturated models were constructed that included the sampling point random factor, all the categoric factors and continuous variables for analysis. Subsequently, those explicative variables that were non-informative, according to Akaike Information Criteria (ΔAIC<2, Burnham and Anderson, 2002) and parameter significance, were eliminated. Residuals of final models were checked for their normality and for the absence of trends across explanatory variables, and the increase in explicative capacity (ΔAIC) relative to the corresponding null model with random factors only used as an informative criterion of the models (Mac Nally et al., 2018).

Multivariate analyses employing constrained ordination techniques (Leps and Smilauer, 2003) were used to investigate whether birds that frequent viaducts are a random sub-sample of the species in the vicinity or whether differentiating features emerge. Redundancy analysis (RDA) was selected after establishing with a detrended correspondence analysis that the beta diversity of the samples was not high (gradient length < 4.0, Leps and Smilauer, 2003). An exploratory RDA was first performed with the ambient variables and locations, in order to establish the relative weight of factors 'locality', 'infrastructure' and 'position' (center vs. extreme) in the observed bird community. Then, the particular effects of variables 'viaduct/control' and 'center/extreme' were tested by means of RDAs with locations as fixed covariables (Leps and Smilauer, 2003). All analyses were carried out at the level of observation point, with centered and standardized response and explanatory variables. Significances were calculated using Monte Carlo simulations with 9999 replicates and the relevance of detected trends was further evaluated in terms of the total variance explained by them.

Two approximations were used to determine how flying birds tackle crossing viaducts that they encounter and the factors that determine their risk of death there. A χ^2 test was used to find whether the subset of birds that approach in flight the structure of the viaduct itself avoid the danger area, comparing the frequency of observed crossings through three 8 m vertical sectors. These sectors comprised crossings just below the viaduct, through the danger zone or just above the highest catenary cable, expected frequencies being that one third of crossings would be through each sector in case of no aversion to viaduct presence (Fig. 1C). A Bonferroni correction (Rice, 1989) was applied, given that three tests of observed vs. expected frequencies were performed.

In addition, to establish whether birds of different sizes show different preferences for particular flight zones when crossing a viaduct, two binomial mixed-effects regression models were performed using all data, with 'flight zone' as categoric response variable for each observed flock. These analyses were modelled in each case with the response variables 'danger zone/other' and 'under viaduct/other'. As with the mixed models explained above, saturated models were fitted first and later simplified, so that the final models obtained only include significant variables. The absence of overdispersion in the final models was checked as well as the lack of trends across explanatory variables in their residuals. With a view to aiding understanding of the results, the definitive models were used to calculate probabilities applying them to different situations, using these to obtain simple interpretations (e.g., the probability of flight through the danger area doubles under situation 'A') based on probability ratios.

Multivariate analyses were carried out with CANOCO 4.5 (Leps and Smilauer, 2003) and all other statistical analyses with the lme4, lmerTest and MuMIn packages (Kuznetsova et al., 2017; Barton, 2019; Bates et al., 2014), within Rstudio® 3.4.2. software (R Core Team, 2022).

3. Results

In total, 5822 individuals were recorded in 2262 observations of flying birds over the nine-month study period at the12 survey sites in three locations. Of the latter, 56.1 % were in the viaduct zones and 43.9 % in the control zones (6 survey sites in both cases). At the viaducts the number of observations was always slightly higher at the valley extreme (52.4 %) than in the valley center (47.6 %). At all viaducts only a minority of observations were of birds that crossed the danger zone (range 5–10 % of flocks and 4–19 % of birds). When birds did cross the danger zone ($n = 87$ bird flocks), some 50 % did so between the catenary cables. Risky flights were observed for all kind of birds, from small passerines to large raptors like kites and vultures.

Similar models were obtained both for the number of individuals and the number of flocks that included the locality, presence/absence of viaduct and temperature as factors determining bird flight in the area (Table 1). In both cases, the inclusion of fixed factors in the models notably improved their informative capacity only with the sampling point random factor (ΔAIC -49.0 and − 63.3, respectively). According to the models, the number of observations and of birds was significatively greater in the presence of viaducts (Mean ± SD of observed data: 7.7 ± 4.6 flocks/sample and 21.7 ± 19.3 individuals/sample) than at the control points (6.0 ± 3.4 flocks/sample and 13.2 ± 14.5 individuals/sample), and the number of flocks and individuals observed was greater with lower temperatures (in autumn). In addition, more flocks and individuals were consistently observed at locality 1 (10.9 ± 3.9 flocks/sample and 30.4 ± 22.0 individuals/sample) than at locality 2 (5.6 ± 2.6 flocks/sample and 14.4 ± 10.9 individuals/sample) or 3 (4.1 ± 1.9 flocks/sample y 7.5 ± 7.0 individuals/sample). Wind speed and position at the valley center or on the extreme were not significant.

The multivariate analysis results showed that there are differences between the bird assemblage observed near viaducts and in the control zones, and between the valley extremes and valley centers, although the principal source of variation in the data was associated with sampling localities. Thus, the RDA with all the explicative variables (Fig. 2) shows that the three effects analyzed were significant ($p < 0.001$) and that 26 % of the variance in the bird data is explained by the locality effect, with 3 % explained by viaduct presence and around 1 % by position in the valley center or extreme (arrow sizes in Fig. 2 depicting it). The second RDA, controlling for the sampling locality effect, established that both presence of the infrastructure (viaduct/control) ($F = 11.8$; $p < 0.001$) and position in the valley (center/extreme) ($F = 6.2$; $p < 0.001$) are highly significant for the bird assemblage. The importance of viaduct presence among species for which the global RDA gave an explicative capacity >5 % (Table 2) was especially evident in six cases: Rock Dove *Columba livia*, Spotless Starling, Iberian Magpie *Cyanopica cooki*, Barn Swallow *Hirundo rustica* and small passerines, which had higher flight frequencies near viaducts; whereas Common Buzzards *Buteo buteo* avoided them. Differences were also detected between valley center and extremes in four cases: Rock Dove, Iberian Magpie and Eurasian Magpie *Pica pica* were most active in the central part of valleys, whereas kites were most often seen in the slope zones ('extreme' position). Finally, variation in abundance of vultures, kites and Northern Ravens *Corvus corax* was almost entirely associated with differences among sampling

Table 1
Results of the explicative models for the number of observations of bird flocks (left) and the total number of individuals (right) seen flying at three study locations close to viaducts of a high-speed railway line. Locality_1 and Position_control used as reference levels for categorical variables. Note that models were built with log-transformed data.

	Number of observations			Number of birds		
	parameter±SE	t	p	parameter±SE	t	p
Intercept	1.12 ± 0.04	28.9	<0.001	1.53 ± 0.06	24.5	<0.001
Locality_2	−0.26 ± 0.04	−6.7	<0.001	−0.29 ± 0.06	−4.7	<0.001
Locality_3	−0.39 ± 0.04	−9.9	<0.001	−0.58 ± 0.06	−9.1	<0.001
Position_viaduct	0.08 ± 0.03	2.6	0.023	0.20 ± 0.05	3.9	0.002
Temperature	−0.007 ± 0.001	−5.5	<0.001	−0.015 ± 0.002	−7.1	<0.001

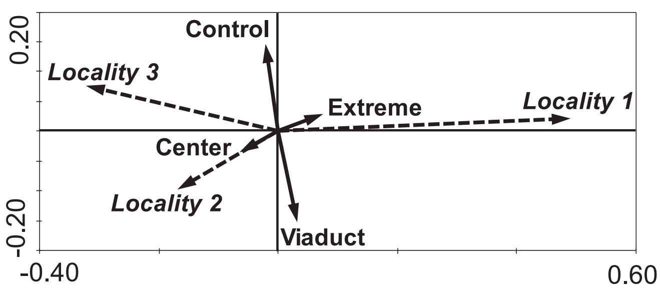

Fig. 2. Result of the ordenation of observations of flying birds on axes 1 and 2 of the RDA, showing trends associated with study site effects (dashed arrows) and the explanatory variables 'viaduct/control' and 'valley center/extreme' (solid arrows). RDA axes 1 and 2 explain some 28.9 % of the data variance and accumulate 95.5 % of the information of the explicative variables. Arrow lengths reflect the relative explicative capacity of each variable.

Table 2
Explicative capacity of the variables 'locality', ubication 'viaduct/control' and position 'viaduct centre/extreme' according to the RDA of bird species abundance in the vicinity of viaducts. Only species for which ten or more observations were obtained are shown. The detected tendency of abundance relative to viaduct proximity vs. control (↑, increase; ↓, decrease) or position in the valley (U, greater in centre; \ greater in the extreme) is shown for species for which >1.5 % of the total variation in abundance is explained by environmental variables.

	Number of observations	Explained variance (%)	Share of explained variance (%)		
			Site	Viaduct	Position
Buteo buteo	50	5.5	60.0	↓ 34.4	5.6
Columba livia	154	23.3	28.8	↑ 62.5	U 8.7
Corvus corax	22	6.1	99.5	0.5	0.0
Corvus corone	17	1.9	61.8	32.8	5.4
Cyanopica cooki	65	10.0	25.1	↑ 30.2	U 44.7
Gyps fulvus + *Aegypius monachus*	574	55.5	97.8	0.1	2.1
Hirundo rustica	14	4.12	41.3	↑ 43.4	15.3
Larus fuscus	17	4.02	65.9	33.6	0.5
Milvus spp.	416	33.9	94.0	1.3	\ 4.7
Pica pica	84	7.6	16.8	12.4	U 70.8
Sturnus unicolor	96	12.5	46.4	↑ 52.6	1.0
Small passerines	710	7.3	31.8	↑ 52.4	15.8

localities.

Regarding the behavior of the subset of birds that approached viaducts at altitudes close to the danger zone (see Fig. 1C, $n = 449$ flocks), there was a significant tendency for them to avoid crossing through that zone (19.4 %; $\chi2 = 16.6$; 2 degrees of freedom; $p < 0.001$). Instead, there was a greater than expected tendency for birds to fly within the 8 m above the catenary (50.1 %; $\chi2 = 15.1$; 2df.; $p < 0.001$), whereas the frequency of flights just under the danger zone did not differ from that expected by chance (30.5 %; $\chi2 = 0.56$; 2df.; $p = 0.45$).

The adjusted model for probability of bird flock crossings of the danger zone shows that for the whole sample (2262 flocks) this is independent of study locality, but it is associated with position within the viaduct (center/extreme), bird size and windspeed (Table 3, ΔAIC -15.3 regarding the null model of random effects). This probability increases at viaduct extremes and with stronger winds, and it is lower for the largest birds. Fig. 3A shows model outputs based on estimations for different plausible situations (see precise features in Table S1). According to the model, the probability of crossing through the danger zone varies between 0.1 % and nearly 22 %, the principal difference being related to bird size. In all situations, medium-sized birds have a probability of risky flight some 4.7 times that of large birds. Small birds incur a risk about 30 times that of large birds. In addition, the expected percentage of danger zone flights is between 2.0 and 2.3 times greater at viaduct extremes than in their centres, and it increases 1.6 times with winds of 1.17 m/s (the mean observed wind speed) relative to calm conditions, and 2.6–3.0 times in windier conditions (2.5 m/s; corresponding to c.a. the 2.5 % of the observed stronger winds during sampling).

Lastly, the adjusted model of probability of cross-flight under viaducts shows that this depends on sampling locality, position (center/extreme) within the viaduct and bird size (Table 3, ΔAIC -25.8 regarding the null model of random effects). This probability was greater at locality 2, coinciding with the highest (and longest) viaduct, at viaduct centers and for small and medium-sized birds. According to the modelled probabilities for different situations (Fig. 3 and data in Table S2), the proportion of flights beneath viaducts varies within the range 81–96 % for medium-sized and small birds, and 3–17 % for large birds. These ranges reflect that for small birds there is limited variation in probability of underflying viaducts between localities (5–10 %) and between viaduct positions: 5–15 % being more likely in the center than

Table 3
Results of binomial models explicative of the probabilities of bird transit through the danger zone for collisions with train or catenaries, and below the viaducts of a high-speed railway line. Note that negative parameters increase the probability of the modelled event, and positive ones reduce it.

	Flight through the risk area			Flight under viaducts		
	parameter ±SE	Z	p	parameter ±SE	Z	p
Intercept	6.78 ± 1.53	4.4	<0.001	2.59 ± 1.38	1.9	0.061
Locality_2	–	–	–	−1.00 ± 0.28	3.6	<0.001
Locality_3	–	–	–	−0.39 ± 0.27	1.4	0.151
Position_extreme	−0.85 ± 0.28	3.1	0.002	0.94 ± 0.22	4.3	<0.001
Bird size_mid	−1.56 ± 1.67	0.9	0.349	−4.85 ± 1.89	2.6	0.010
Bird size_small	−3.55 ± 1.66	2.1	0.032	−4.57 ± 1.90	2.4	0.016
Wind speed	−0.44 ± 0.19	2.4	0.017	–	–	–

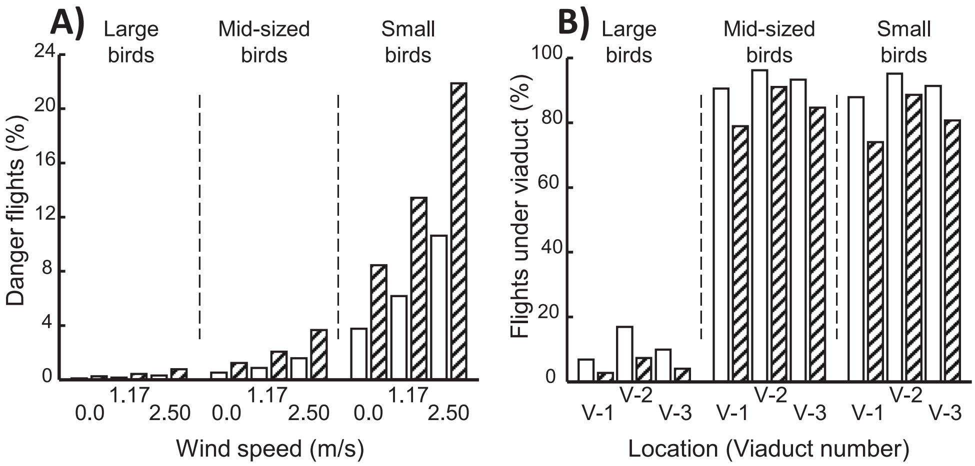

Fig. 3. A) Model-estimated percentages of birds flying through the danger area of HSR viaducts according to bird size, wind speed and section of the viaduct (center, empty bars vs. extreme, hatched bars). Bird-size classes correspond to wingspans ≤40 cm (small), 41-100 cm (mid-sized) and > 100 cm (large). Selected wind speeds correspond to calm, mean measured wind speed during sampling and the threshold for the ≈2.5 % higher wind speeds measured during sampling. B) Model-estimated percentages of birds flying under three HSR viaducts according to location (viaduct number), bird size and section of the viaduct (center-extreme). Viaduct numbers follow nomenclature in Fig. 1. Bird-size classes and sections of viaduct indicated as in panel A.

at the extreme. For large birds, the probability of underflying the lowest viaducts is only 0.4–0.6 of that of underflying the highest viaduct; and 2.3–2.4 times more likely under the viaduct centre than under its extreme.

4. Discussion

The results offer an initial insight into bird flight patterns in the vicinity of high-speed train viaducts and establish that only some prior hypotheses are supported. In general, it is found that bird flight frequency increases near viaducts due to some species making use of the structures. Furthermore, although birds generally avoid flying where they are at risk of collision with trains or catenaries, some do cross the danger area. This behavior is associated with certain variables, so that it is possible to identify appropriate protective measures that should be employed on high-speed railways. Our results also show the presence of a large variability in the analyzed process in terms of differences among sites, bird species and numbers, a fact which is associated with large variances in the dataset and hinders explanatory capacities of models. Anyhow, models show some relevant tendencies across sites which can be used to guide mitigation.

In the first instance, a major variability among locations stands out, thought this affects the number and species of flying birds detected but neither to the tendency of birds to occur more frequently near viaducts nor to the proportion of flights through the danger zone. This location effect strongly emerges in models of the number of flocks or individuals observed, as well as in the relative abundance of species revealed by the multivariate analysis. Bird abundance declines between the locality 1, the most southerly study site which is close to an urban landfill dump, and further north, along with a partial change in species present. For example, vultures, kites, Common Buzzards and Lesser Black-backed Gulls were notably abundant at locality 1. In contrast, Ravens and Spotless Starlings appeared mainly at locality 2, Carrion Crows *Corvus corone* occurred both at localities 2 and 3, and Barn Swallows were at locality 3. Local variation in bird species present and their abundance is well known and very much needs to be borne in mind when developing the environmental impact evaluation of such infrastructures as high-speed railways (Carrete et al., 2012; Northrup and Wittemyer, 2013; Godinho et al., 2017). In this case, the concentration of large numbers of birds around urban landfill sites and their risk of colliding with running trains adds to other causes for concern like the increased danger of collisions with aircraft and human infrastructures, or the health risks that arise from them (Baxter and Robinson, 2007; Cook et al., 2008; Martínez-Abraín et al., 2012).

In any event, viaducts give rise to increased bird flight activity in their vicinities, and to changes in the species involved on a very local scale. Collisions with trains are a real danger, as a result. As quite often observed along railway lines (Wiacek et al., 2015), more individual birds occur near viaducts than in more distant areas, because of viaducts offering new structural features together with fairly limited disturbance (Li et al., 2010; Morelli et al., 2014; Hu et al., 2020). Viaducts stand out literally, being elevated above the surrounding landscape and offering abundant perches for courtship, surveillance or hunting as well as cavities or potential nest-sites (Meunier et al., 1999; Mainwaring, 2015; Malo et al., 2017). For example, during our fieldwork Rock Doves, Ravens, Spotless Starlings, Barn Swallows and House Sparrows *Passer domesticus* all nested on these viaducts and both Red and Black Kites and Eurasian Magpies searched them for carcases. Given that trains pass at long intervals and extremely rapidly, the very intense disturbance that they cause is brief and the noise does not affect birds as much as the much more continuous disturbance associated with roads (Rheindt, 2003; Palomino and Carrascal, 2007; Polak et al., 2013). Despite this, some species (e.g., Common Buzzard, Table 2) avoid the vicinity of viaducts, so that it is possible to speak of there being an interspecific filter among species that fly around viaducts that depends both on the species composition of the local bird community and on the individual responses of attraction or repulsion shown by species encountering the infrastructures (Meunier et al., 1999; Pearce-Higgins et al., 2009). Among these filters there stands out the effect of carcase availability on scavengers, similar to that involving roadkill on motorways (Planillo et al., 2015, 2018), that may encourage birds to engage in very risky flight behavior (Cuthill and Guilford, 1990). This attraction effect to the infrastructure by the provision of a resource, followed by increased mortality, seems to be widespread in railways as exemplified by large mammals using them as easy-movement corridors or as feeding sites due to the presence of grain spillages (St. Clair et al., 2020), as well as by birds perching on the infrastructure instants before being overrun by high-speed trains (García de la Morena et al., 2017).

Our results thus show that there exists a degree of collision risk arising from the attraction of birds by the infrastructure and by their only partial avoidance of the danger zone. Most birds that cross viaducts fly risk-free above or below the infrastructure (Godinho et al., 2017; Hu et al., 2020), and this study found that many gain height to avoid traversing the area of risk, showing a repulsion response like the one described by Luzenski et al. (2016) for a power line. Nevertheless, a minimum of 5 % of crossings (15–20 % in some cases) happen through the gap between the rails and the catenary or through the catenary cables (*c.* 50 % of risky crossings). In either case, birds that cross when a train is passing will almost certainly be killed by collision or loss of flight control, given that the turbulence generated by a high-speed train travelling at 250-300 km/h comprises strong positive and negative pressure waves that span a few meters (Niu et al., 2018). The high speed most probably impedes any direct reaction of birds to an approaching train based on visual cues (de Vault et al., 2015), but it may be possible that they are alerted about this danger by the noise and the vibration of the catenary cables and take flight. This type of response by birds perched on the cables or railway line posts has been observed on occasions (pers. obs.) but it may result in either increased or reduced collision risk depending on the timing and direction of flight (García de la Morena et al., 2017; Fernández-Juricic et al., 2018). In line with the idea of unavoidable crashing of birds with approaching trains, and with the wide set of bird species detected in this study crossing the danger area, first estimates of bird mortality in HSRs point to a generalized problem that affects most or all bird species living in traversed landscapes, with a higher relevance for species that use the infrastructure for perching feeding or nesting (Malo et al., 2016; García de la Morena et al., 2017; Herranz et al., 2021).

Risky behavior is associated with bird size and whether crossing occurs at the center or extremes of viaducts. Small birds are some 30 times more likely to incur risk than large birds, and five times more likely to do so than medium-sized ones (Table S1). This is because the small birds that frequent viaducts have relatively small home ranges that include the infrastructure, which they traverse or use habitually. In the present case, the meadows and copses under the viaducts are good feeding grounds for various small bird guilds, such as granivores, insectivores and small raptors (Barbaro et al., 2014; Morelli et al., 2014). In contrast, large birds cross the area during far-ranging movements between feeding and resting areas and these generally avoid crossing the danger zone by minor alterations of flightpath. Such large birds, moreover, glide more often and tend to be less maneuverable than small birds (Pennycuick, 1989), and hence tend to fly higher and avoid manmade constructions (Godinho et al., 2017). Nevertheless, during the fieldwork we repeatedly saw both Red and Black Kites (wingspans 1.62 m and 1.37 m respectively, SEO, 2020) searching for food over the railway line (see also Planillo et al., 2015), even crossing it between the catenary cables. Kites have low wing loadings and tend to glide close to the ground for long periods in search of prey or carrion, a habit that also makes them prone to colliding with aircraft (Fernández-Juricic et al., 2018). This observation also points to the need of gathering larger datasets with a finer species resolution, as well as detailed behavioural records, to understand differences in the risk associated to different species and ecological traits not explored here like flight mode, wing load or feeding strategy.

Regarding mitigation measures, it is noteworthy that viaduct extremes are about twice as dangerous as their central sectors, given that more birds cross at viaduct ends where the ground and vegetation are closer. This results both from the local flights of small birds mentioned above and from the soaring of large birds above the vegetation making use of orographic uplift to reduce flight costs (Duerr et al., 2012; Lanzone et al., 2012; Shamoun-Baranes et al., 2016). The latter is fairly well exemplified by kites and vultures, which were recorded 61 % and 27 % more often over the valley flanks than in the central sectors of viaducts. Furthermore, in the case of kites, 13.6 % of flights at viaduct extremes were through the danger zone as opposed to only some 3.4 % of those in the central sectors. Underflying by kites comprised 6.4 % of observations at viaduct ends but 21.8 % of those in the central sectors. This emphasises the threat that viaducts may pose, both for gliding raptors that hunt over the tree canopy and find themselves at viaduct ends during their hunting flights, and also for those that take advantage of valley slope upcurrents (e.g., Barrios and Rodríguez, 2004).

The danger posed by viaducts is also weather dependent, being greater when it is windy. Wind can cause difficulties for flying birds, especially to gliders, often leading them to fly lower and thus more likely to collide with infrastructures (Shamoun-Baranes et al., 2006; Lanzone et al., 2012). Although rainy or very windy days were avoided during this study, elevated wind speed was associated with a higher frequency of flights through the danger zone. A similar situation might arise with dense fog if poor visibility made it harder for birds to avoid viaducts or catenaries, and it would be worth investigating the question in areas prone to fog or under strong winds (Wang et al., 2015, see however Barrios and Rodríguez, 2004).

To conclude, this study shows that railway viaducts pose a danger to birds, which may be killed if they encounter a passing train. However, the observed behavior patterns suggest improvements in mitigating this problem along the tens of thousands of kilometers of new railway lines planned globally (Ascensão et al., 2018; EU, 2020; Amtrak, 2021; EY, 2023). In the first instance, given the degree of inter-site variation, the environmental impact surveys preceding the construction of such infrastructures should ensure that the bird community that inhabits or uses the area is fully documented. This is necessary to determine which species may be affected and to detect whether there are local circumstances such as communal roosts, flightpaths or hunting areas of especially vulnerable species (Godinho et al., 2017; Hu et al., 2020). Such investigations conducted at the local scale will allow measures to be taken where the cost to effectiveness ratio of mitigation is lowest (Gunson and Teixeira, 2015). In addition, since viaducts themselves attract certain species that may end up being killed, as far as possible viaducts should not incorporate features, such as potential nestholes or ledges, that will draw birds in. It must be remembered that although such species, e.g., feral Rock Doves, may be of low conservation importance, their carcases may well attract species of problematic conservation status, such as the Red Kite, which is 'Near threatened' on a European scale (IUCN, 2021).

Moreover, installing anti bird-strike barriers may be advisable along all or part of viaducts, depending on local circumstances. This study has shown that traditional, 2.5 m high barriers (present on the three viaducts studied), do not prevent some birds from crossing the danger zone. It may be necessary to install 4-5 m high barriers to cover most of the gap between the rails and the powerlines, though they should be built of poles or other discontinuous material to reduce their wind load. These structures actually work as visual cues since they can be cross-flighted by birds, but they seem effective for mid- and large-sized birds (Zuberogoitia et al., 2015; Herranz et al., 2021). Moreover, it is advisable to attach flappers, spirals, or other markers to the overhead wires to increase their visibility for birds and further promote overflights (Ferrer, 2012). Such enhanced protection will be most important in areas much frequented by birds, and at viaduct extremes rather than in the centres. Protecting viaduct ends should be a priority if the vulnerable species include raptors or other soaring birds that make use of valley upcurrents, or the small birds that may inhabit the habitats around the viaduct extremes. Also, although this study did not detect particular risks associated with viaduct height, it may be that 10-20 m high viaducts, such as those that cross rivers or floodplains (e.g., Hu et al., 2020), may be more dangerous to birds than the 40-80 m high viaducts typical of montane regions, since the former more closely resemble the viaduct extremes studied here. It may well be that maximum bird activity at viaducts over rivers occurs at the viaduct centres (Godinho et al., 2017), a possibility that needs investigation. Conversely, the proportion of bird flights that occur under viaducts is higher at high viaducts, reducing the collision risk for birds that fly just over the vegetation.

Finally, it is emphasised that knowledge of bird mortality on high-speed railway lines remains extremely limited and this study is just a first approach to fill this large gap of knowledge, focused on viaducts and with a limited set of sampling locations and bird species. Thus, it is not yet possible to evaluate the importance of viaducts as potential hotspots for bird deaths relative to mortality along the (far lengthier) embanked stretches of the lines (Godinho et al., 2017; Malo et al., 2021). Furthermore, bird species not crossing the railways or strongly avoiding their proximities could suffer population fragmentation, an issue which deserves investigation.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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