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METHODS, TOOLS, AND TECHNOLOGIES

Frontal vehicle illumination via rear-facing lighting reduces potential for collisions with white-tailed deer

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Abstract. Animal–vehicle collisions cause many millions of animal deaths each year worldwide and present a substantial safety risk to people. In the United States and Canada, deer (*Odocoileus* spp.) are involved in most animal–vehicle collisions associated with human injuries. We evaluated a vehicle-based collision mitigation method designed to decrease the likelihood of deer–vehicle collisions during low-light conditions, when most collisions occur. Specifically, we investigated whether the use of a rear-facing light, providing more complete frontal vehicle illumination than standard headlights alone, enhanced vehicle avoidance behaviors of white-tailed deer (*O. virginianus*). We quantified flight initiation distance (FID), the likelihood of a dangerous deer–vehicle interaction (FID ≤ 50 m), and road-crossing behavior of deer in response to an oncoming vehicle using only standard high-beam headlights and the same vehicle using headlights plus an LED light bar illuminating the frontal surface of the vehicle. We predicted that frontal vehicle illumination would enhance perceived risk of deer approached by the vehicle and lead to more effective avoidance responses. We conducted 62 vehicle approaches (31 per lighting treatment) toward free-ranging deer over ~14 months. Although FID did not differ across treatments, the likelihood of a dangerous deer–vehicle interaction decreased from 35% of vehicle approaches using only headlights to 10% of vehicle approaches using the light bar. The reduction in dangerous interactions appeared to be driven by fewer instances of immobility (freezing) behavior by deer in response to the illuminated vehicle ($n = 1$) compared with approaches using only headlights ($n = 10$). Because more deer moved in response to the illuminated vehicle, road-crossing behavior likewise increased when the light bar was on, although these road crossings primarily occurred at FIDs > 50 m and thus did not increase collision risk. Road-crossing behavior was influenced heavily by proximity to concealing cover; deer only crossed when the nearest cover was located on the opposite side of the road. We contend that frontal vehicle illumination via rear-facing lighting has potential to greatly reduce vehicle collisions with deer and other species. Future work should explore fine-tuning the method with regard to the visual capabilities of target species.

Key words: antipredator behavior; collision; lighting; mortality; road ecology; sensory ecology; vehicle; white-tailed deer (*Odocoileus virginianus*).

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Introduction

Animal–vehicle collisions occur frequently across the developed world, pose substantial monetary costs and safety risk to people, and can negatively impact animal populations (Fahrig and Rytwinski 2009, Huijser et al. 2009, Kociolek et al. 2011, DeVault et al. 2013). Because high-speed vehicles are evolutionarily novel, collisions often result from the use of maladaptive avoidance responses by animals, including antipredator behaviors used as surrogates for more appropriate but usually absent vehicle avoidance behaviors (Lima et al. 2015, Blackwell et al. 2016). For example, individual Canada geese (*Branta canadensis*) often run or fly ahead of a truck as if being chased by a predator, rather than move a short distance to the side, away from the vehicle's projected path (Blackwell et al. 2019). Likewise, loose flocks of Canada geese have been observed coalescing into tight groups when directly approached by an aircraft (Blackwell et al. 2012). Also, some birds and mammals fail to adjust their avoidance responses (i.e., increase flight initiation distance [FID]; distance between animal and oncoming threat when escape is initiated) when vehicles approach at unnaturally high speeds, and thus are at a high risk of collision on highways and at airports where high-speed vehicles are common (Blackwell et al. 2014, DeVault et al. 2014, 2015, 2017).

In the United States and Canada, deer (*Odocoileus* spp.) cause most road collisions associated with human injury and death (Huijser et al. 2009). Likewise, deer are the most hazardous wildlife species to aviation: 87% of collisions with white-tailed deer (*O. virginianus*) and 96% of collisions with mule deer (*O. hemionus*) cause damage to the aircraft (DeVault et al. 2011). Importantly, most vehicle collisions with deer and other ungulates (on roads and airport runways) occur at night (Allen and McCullough 1976, Putman 1997, Rodgers and Robins 2006, Biondi et al. 2011), although the precise reasons for the disproportionate number of collisions occurring at night remain unclear. Deer are typically most active at dawn, dusk, and night (Miller et al. 2003), and this increased movement by deer undoubtedly elevates the likelihood of collision during these times. Even so, some authors have suggested that vehicle lighting also contributes to the increased number of collisions occurring during low-light conditions. Vehicle headlights, which are designed to complement the human visual system, might be incompatible with the deer visual system (Dukes 1969, Jacobs et al. 1994), which is adapted to low-light conditions (Dukes 1969, VerCauteren and Pipas 2003, D'Angelo et al. 2008). Specifically, the smaller but intensely bright surface area of the oncoming vehicle most visible to deer at night (i.e., headlights) likely dominates the visual image and could produce a less reliable looming cue (Sun and Frost 1998), which could delay or negate avoidance responses (Blackwell et al. 2014). Also, deer might not associate headlights with an oncoming vehicle and thus be unaware of the threat of collision. Either of these problems encountered by deer conceivably could result in temporary immobility, the freezing-in-the-headlights behavior often observed by motorists. Lastly, humans are less able to avoid vehicle collisions with animals at night than during the day (Sullivan 2011). Irrespective of the causes, it is clear that the development of mitigation measures for reducing deer–vehicle collisions in low-light conditions (i.e., when headlights are necessary for driver safety) should be prioritized by wildlife and transportation professionals.

Most extant mitigation measures designed to reduce vehicle collisions with deer and other wildlife are road-based rather than vehicle-based (Hedlund et al. 2004, Mastro et al. 2008). Road-based mitigation measures include devices and methods intended to influence animal behavior (e.g., roadside reflectors and mirrors, olfactory repellents, hazing) and driver behavior (warning signs, speed limits, animal detection systems), vegetation management and highway lighting designed to increase visibility of wildlife to drivers, and wildlife population regulation (reviewed in Huijser et al. 2007, van der Ree et al. 2015). The demonstrated effectiveness of these road-based mitigation measures ranges widely (D'Angelo et al. 2006, Huijser et al. 2009, Riginos et al. 2018). However, most authors agree the only reliably effective method currently available is roadside fencing (Putman 1997, Hedlund et al. 2004, Mastro et al. 2008), combined with appropriate crossing structures such as overpasses or underpasses (Glista et al. 2009, Huijser et al. 2009). One major problem with road-based

mitigation measures stems from the cost of mitigation (VerCauteren et al. 2006, Huijser et al. 2009) and the unpredictability of crossing locations for animals (Gunson et al. 2011). In other words, it is generally impractical to install fencing or other mitigation measures everywhere wildlife might be present along roads. However, unlike road-based systems, vehicle-based systems are always in the most advantageous location—on the vehicle—to alter wildlife behavior to reduce collisions on roads. A vehicle-based collision mitigation system effective for deer would be a substantial advancement to reduce wildlife mortality and increase driver safety on roads.

Because deer behavior in response to vehicles is unpredictable (Blackwell et al. 2014, Pfeiffer et al. 2020), the most effective vehicle-based mitigation system would elicit flight behavior in deer away from roads before vehicles approach deer within a distance that requires some type of evasive maneuver (e.g., braking or swerving) by the driver (Hedlund et al. 2004). Unfortunately, deer whistles, the only widely available vehicle-based device intended to modify deer behavior in response to vehicles (Huijser et al. 2007, Mastro et al. 2008), are completely ineffective (Romin and Dalton 1992, Valitzski et al. 2009). We are aware of only one study evaluating a vehicle-based method or device that showed promise for altering deer behavior in response to an oncoming vehicle. Blackwell and Seamans (2009) found that FIDs of white-tailed deer in response to a vehicle equipped with standard tungsten–halogen headlights were on average 20 m shorter (and thus riskier) than FIDs in response to a vehicle equipped with standard headlights plus a Xenarc high-intensity discharge lamp, a light that better complimented the color vision of white-tailed deer (Cohen et al. 2014). Thus, the manipulation of vehicle lighting appears to hold promise for eliciting earlier avoidance behavior by deer in response to vehicles at night. However, the role chromatic visual stimulus plays in deer response to vehicle approach at night remains unclear (Blackwell and Seamans 2009).

Here, we build upon research by Blackwell and Seamans (2009) by manipulating vehicle lighting in a different way. Specifically, we used a rear-facing light attached to the front of the vehicle to illuminate a larger portion of the vehicle's frontal surface than was visible with headlights alone. Our objective was therefore to evaluate the efficacy of a rear-facing light providing frontal vehicle illumination to reduce dangerous encounters on roads between vehicles and white-tailed deer at night (DeVault et al. 2019). We quantified FID, the likelihood of dangerous interactions (defined below), and road-crossing behavior by deer in response to a vehicle equipped with standard headlights to a vehicle equipped with standard headlights plus the rear-facing light. We hypothesized that light reflected from the frontal surface of the vehicle would provide a more reliable, and perhaps more familiar, looming image to deer approached by the vehicle. We therefore predicted that deer encountered on and near roads at night would reduce immobility behavior and react sooner to an approaching vehicle (i.e., with longer FIDs) when the vehicle was equipped with the rear-facing light, thereby reducing the number of dangerous interactions with the vehicle. Because we expected immobility behavior to decrease with the addition of the rear-facing light, we also predicted that road-crossing by deer would increase because more deer would flee from the path of the approaching vehicle when the vehicle's frontal surface was illuminated.

Methods

Study site

We studied free-ranging white-tailed deer at the National Aeronautics and Space Administration (NASA) Plum Brook Station (PBS) in northern Ohio, USA, near the city of Sandusky. Plum Brook Station is a controlled-access NASA testing facility covering 2200 ha that contains large tracts of undeveloped and managed natural habitats within a larger agricultural and suburban landscape (Bowles and Arrighi 2004). A 2.4-m high chain-link fence surrounds PBS but is permeable to deer in several locations. Undeveloped habitat at PBS is comprised of old fields and grasslands (31%), canopy–dogwood (*Cornus* spp.; 39%), open woodlands (15%), and mixed hardwood forests (11%; Blackwell et al. 2014). Buildings are connected by ~60 km of two-lane roads with relatively low but varying amounts of vehicular traffic (64 km/h speed limit). Most, but not all, roads are bordered by a short-grass

margin ~30 m in width on either side (Blackwell et al. 2014). Estimated white-tailed deer density during the winter of 2018–2019 was 0.52 individuals/ha (United States Department of Agriculture, Wildlife Services, Ohio program, *unpublished data*). Controlled deer hunts occur at PBS several days each year during which hunters are on foot and in vehicles.

Vehicle and light characteristics

We used a 2003 Ford F250 pickup truck for all vehicle approaches. The truck was gray in color with a black plastic grille (Fig. 1). We equipped the truck with a forward-looking infrared (FLIR) camera (PathFinderIR thermal imaging system, FLIR Systems, Goleta, California, USA) mounted to the passenger-side door mirror. The FLIR camera was aimed straight ahead along the road such that deer could be detected at night on or near the road up to ~800 m away, many times further than was possible with vehicle headlights alone. A video monitor located inside the truck on the passenger side provided a real-time video feed from the FLIR camera.

The truck was equipped with two 18 × 15-cm LED headlights each producing 35 watts (3700 lumens) on high beam and a color temperature of 6000–6500 K (Lumen Model SB7601HL-CHR, Lumen, Cranbury, New Jersey, USA). To provide rear-facing illumination to the frontal surface of the vehicle, we attached an LED light bar consisting of 50 3-watt white LED lights producing a total of 15,000 lumens (Havoc Offroad Model 61-40050, Havoc Offroad, Ocala, Florida, USA). Metal brackets were used to attach the light bar to a brush guard mounted on the front of the vehicle. The light bar was approximately level with the hood and aimed downward at a ~45° angle toward the grille so that the light would not be visible to the driver, thereby creating a safety hazard (Fig. 1).

Spectral properties of lighting treatments

We used an Ocean Optics Flame Spectrometer with CC-3-DA cosine corrector (diameter, 7140 μm) with an integration time of 100 ms and Boxcar (width, 0) to quantify absolute irradiance ($\mu W \cdot cm^{-2} \cdot nm^{-1}$) from the two headlights on high beam, the light bar alone, and the headlights in combination with the light bar. We positioned the spectrometer 1.1 m high on a platform with the cosine corrector aimed between the truck headlights; the truck was positioned 57 m away from the spectrometer on a paved road. We made our measurements under dark conditions. We note, however, that by positioning the light bar to face the grille of the truck, light from that device was reflected off of the truck. In other words, our absolute irradiance measure with both light sources comprised direct light from the headlights and light originating from the light bar but reflected from the vehicle. White-tailed deer are dichromatic in that the retina contains three classes of photopigment: a short-wavelength sensitive cone (λ max = 450–460 nm), a middle wavelength-sensitive cone (λ max = 537 nm), and rod pigment (λ max = 497 nm; Jacobs et al. 1994). We report the spectral change with addition of the light bar as the proportional change in flux relative to ultraviolet (300–399 nm), short (400–499 nm), middle (500–599 nm), and long wavelengths (600–699 nm).

Field methods

We established a 24.7-km route on paved roads through various habitats at PBS and drove the length of this route once during every night of data collection. Adhering to the preplanned route reduced the likelihood of double sampling deer on the same evening. We also restricted our observations to a single approach on straight and level roads where our treatment was potentially visible to deer ≤1 km in distance on the same road. We generally attempted to collect data during one night every two weeks between 26 February 2018 and 17 April 2019, but we postponed data collection during inclement weather (we only attempted data collection when roads were dry and wind speed <10 km/h) and weeks when controlled deer hunts were conducted.

Our data collection methods roughly followed Blackwell and Seamans (2009) and Blackwell et al. (2014). Our first vehicle approach was conducted with the light bar on (providing frontal vehicle illumination); thereafter, we alternated vehicle approaches between lighting treatments (light bar on vs. light bar off). High-beam headlights were used for every vehicle approach. A driver (always TLD) and observer (TWS or BFB) were present each night of data collection. Beginning 30 min after sunset at the start of the route, we quickly accelerated to 60 km/h and set the

Fig. 1. A Ford F250 pickup truck was used for 60 km/h approaches toward white-tailed deer at night. An LED light bar was attached to a brush guard on the front of the vehicle and aimed rearwards, illuminating the vehicle's frontal surface. Images show the light bar off (top) and on (bottom) in evening/low-light (left) and nighttime/very low-light (right) conditions. The vehicle's high-beam headlights are on in all images.

vehicle's cruise control to maintain that speed. The observer continuously focused on the live feed from the FLIR camera on the video monitor. When a stationary deer or contiguous group of deer was detected on the road or within 3 m of the road edge, the observer alerted the driver. At that time, the observer dropped a cloth bag filled with gravel from the passenger-side window of the moving vehicle to mark the starting point of the approach, and both driver and observer noted the position of the deer relative to the road. The observer then dropped additional bags from the window at the moment when each deer in the group initiated an avoidance response, defined as a behavior that would take an individual deer away from the road (i.e., to avoid collision), or flight away from its initial off-road position across the road. The observer recorded data for up to five deer in a group. We rapidly slowed the vehicle to avoid potential collision when we approached deer to within roughly 20 m without an avoidance response by the deer. We collected data only for (initially) stationary deer because we could not determine for moving deer when they began their avoidance response. The driver maintained vehicle speed at 60 km/h until every member of a group initiated their avoidance response, the truck was forced to slow or stop to avoid collision, or the truck reached the point perpendicular to the original position of the individual or group (i.e., the end of the approach).

After each vehicle approach, we stopped the truck to measure environmental data, the start distance (distance between vehicle and deer when deer were first detected with the FLIR), and flight initiation distances (FIDs). We measured ambient light intensity, wind speed, and

air temperature at the initial position of the deer. Ambient light intensity (μmol·m^{-2}·s^{-1}) was measured with a Li-COR LI-250 Light Meter and LI-190SA Quantum Sensor (LI-COR Biosciences, Lincoln, Nebraska, USA). We measured air temperature and wind speed with a Kestrel 4500 Pocket Weather Tracker (Nielson-Kellerman, Boothwyn, Pennsylvania, USA). We measured start distance and FIDs with a Bushnell Yardage Pro 1000 Laser Ranging System (Bushnell, Overland Park, Kansas, USA) and later corrected measurements for forward momentum of the bags dropped from the moving truck (Blackwell et al. 2014). When an individual deer failed to react to the vehicle approach as described above (i.e., remained immobile), FID was recorded as 0 m. We also measured distance to concealing cover (shrub vegetation or trees that could conceal a standing adult deer) from the initial position of the individual or center of the group. For deer initially detected within 3 m of the road edge (i.e., not on the road surface), we noted whether the nearest concealing cover was across the road or on the same side of the road as the deer's initial position. Data collection ended each night when the investigators reached the end of the preplanned route. The Animal Care and Use Committee of the United States Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center approved all procedures used in this study (QA-2891). No animals were struck by the vehicle or otherwise injured during this study.

Defining dangerous interactions with deer

Most automobile accidents associated with wildlife that result in human injury occur when drivers swerve to miss the animal and subsequently lose control of the vehicle or collide with other vehicles or objects (Allen and McCullough 1976, Rowden et al. 2008). Thus, as stated above, the ideal vehicle-based collision mitigation system for deer would elicit flight behavior in the animal away from the road before the driver feels compelled to perform an evasive maneuver. In a study quantifying a driver's ability to detect deer at night, Mastro et al. (2010) found that most drivers failed to see deer decoys along roads until they were within 50 m of the decoys, even though they were expecting to see them at some point along the road course (see Rumar 1990 for similar findings). As such, a deer vacating the vicinity of the road with an FID > 50 m would not elicit an evasive maneuver by the driver because in this scenario the driver likely would be unaware of the deer's existence. Moreover, when designing road projects, Fambro et al. (1997) recommended that planners expect drivers traveling at 60 km/h to require 82.5 m to perceive an object in the road and stop in time to avoid it. Thus, it is unlikely that most drivers would be able to avoid a deer first detected 50 m away and in the path of the vehicle (see also guidance from the U.S. Department of Transportation, National Highway Traffic Safety Administration, https://one.nhtsa.gov/nhtsa/Safety1nNum3ers/august2015/S1N_Aug15_Speeding_1.html). We therefore set an a priori threshold for a dangerous interaction with deer at an FID of 50 m. By our definition, an observed FID ≤ 50 m would represent a dangerous interaction because a driver might strike the deer or actively try to avoid it (including an immobile deer with FID = 0) and possibly crash, whereas an observed FID > 50 m would pose no threat because the deer would flee from the road before being detected by the driver.

Statistical analyses

We calculated the mean FID for each group of deer encountered during vehicle approaches (rather than for individual deer) because of interdependence among individuals (Lingle and Wilson 2001). Thus, each vehicle approach was treated as an experimental unit, although we also report road-crossing behavior for individual deer. We present mean ± SE unless indicated otherwise.

We first examined the fixed effects of observer, season, and air temperature on mean group FID via a linear mixed-effects model (PROC MIXED; SAS 9.2, Cary, North Carolina, USA). Although our experimental design reduced the chance we would collect observations on the same individuals during one night, we used the "repeated" statement with subject = observation date (R-side effect) and an autoregressive covariance structure to control for repeated observations. We assumed a Gaussian distribution and used residual maximum likelihood as our estimation method and Kenward-Roger degrees of freedom.

We assessed model residuals relative to a Gaussian distribution. We found no effects of observer, season, or air temperature (see Results), and thus proceeded with an analysis of treatment (headlights and light bar off vs. headlights and light bar on) on mean group FID. Similar to the aforementioned model, we used a linear mixed-effects model, assumed a Gaussian distribution, identified observation date as the subject of a repeated effect, and used residual maximum likelihood as our estimation method and Kenward-Roger degrees of freedom.

In addition, we modeled the likelihood that deer responded with an FID ≤ 50 m (i.e., a dangerous interaction). We used a generalized linear mixed-effects model (PROC GLIMMIX; SAS 9.2) with lighting treatment as the fixed effect. As before, we included observation date as our repeated effect. We entered the distance to concealing cover, the location of the nearest concealing cover relative to the deer (i.e., a categorical variable of the same or opposite side of the road), deer group size, and start distance of the approach as G-side random effects. We assumed that individuals might respond later to vehicle approach if concealing cover was nearby, on the same side of the road, with increasing group size, and with decreasing start distances. We scored responses for which FID ≤ 50 m as1 (a dangerous interaction) and FID > 50 m as 0. As such, we assumed a binomial distribution, selected a logit link function, and used residual pseudo-likelihood as our estimation method and designated Kenward-Roger degrees of freedom.

Finally, we modeled the likelihood that at least one individual in a group crossed the road in front of the vehicle. Deer initially observed on the road (as opposed to within 3 m of the road edge) were not included in road-crossing analyses. Once again, we used a generalized linear mixed-effects model with treatment as the fixed effect. We included observation date as our repeated effect and the location of the nearest concealing cover and start distance of the approach as G-side random effects. We assumed that individuals would be more likely to cross the road if the nearest concealing cover was across the road from the animal's position. Further, we assumed that increasing the start distance of the approach would contribute to greater likelihood of crossing. Similar to our previous analysis, we scored road-crossing responses as 1 and no crossing as 0. Again, we assumed a binomial distribution, selected a logit link function, and used residual pseudo-likelihood as our estimation method and designated Kenward-Roger degrees of freedom.

Results

When used in combination with the headlights, the light bar contributed to a mean increase of 1.5–24.6% in absolute irradiance across the preselected wavelength ranges (Table 1, Fig. 2). Notably, the contribution of the light bar to spectra detectable by white-tailed deer (short and middle wavelengths) increased on average by ~8% (Table 1, Fig. 2).

We completed 62 vehicle approaches toward deer (31 per lighting treatment) during 26 nights of data collection ($\bar{x}$ = 2.4 approaches/night; SD = 2.1; max = 7). No vehicle approaches toward deer were conducted during four of those nights due to a lack of opportunities (i.e., no stationary deer observed within 3 m of road edge). On average, we collected data every 17.7 nights (SD = 9.9) during the study period. Ambient light measurements made immediately following vehicle approaches were always zero, with the exception of one reading of 0.01 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and one reading of 0.02 $\mu mol \cdot m^{-2} \cdot s^{-1}$. We therefore omitted ambient light measurements from our statistical models.

Across the 62 vehicle approaches, 37 involved single deer, the maximum deer group size was six, and the mean group size was 1.70 ± 0.13.

Table 1. Proportional change in absolute irradiance ($\mu W \cdot cm^{-2} \cdot nm^{-1}$) relative to ultraviolet (300–399 nm), short (400–499 nm), middle (500–599 nm), and long wavelengths (600–699 nm) between lighting treatments on a Ford F250 pickup truck used to approach white-tailed deer at night.

Wavelength	$\bar{x}$ change in flux	SD
300–399	0.246	0.532
400–499	0.145	0.428
500–599	0.015	0.015
600–699	0.096	0.096

Note: The lighting treatments are high-beam headlights only vs. high-beam headlights in combination with an LED light bar reflecting light from the frontal surface of the vehicle.

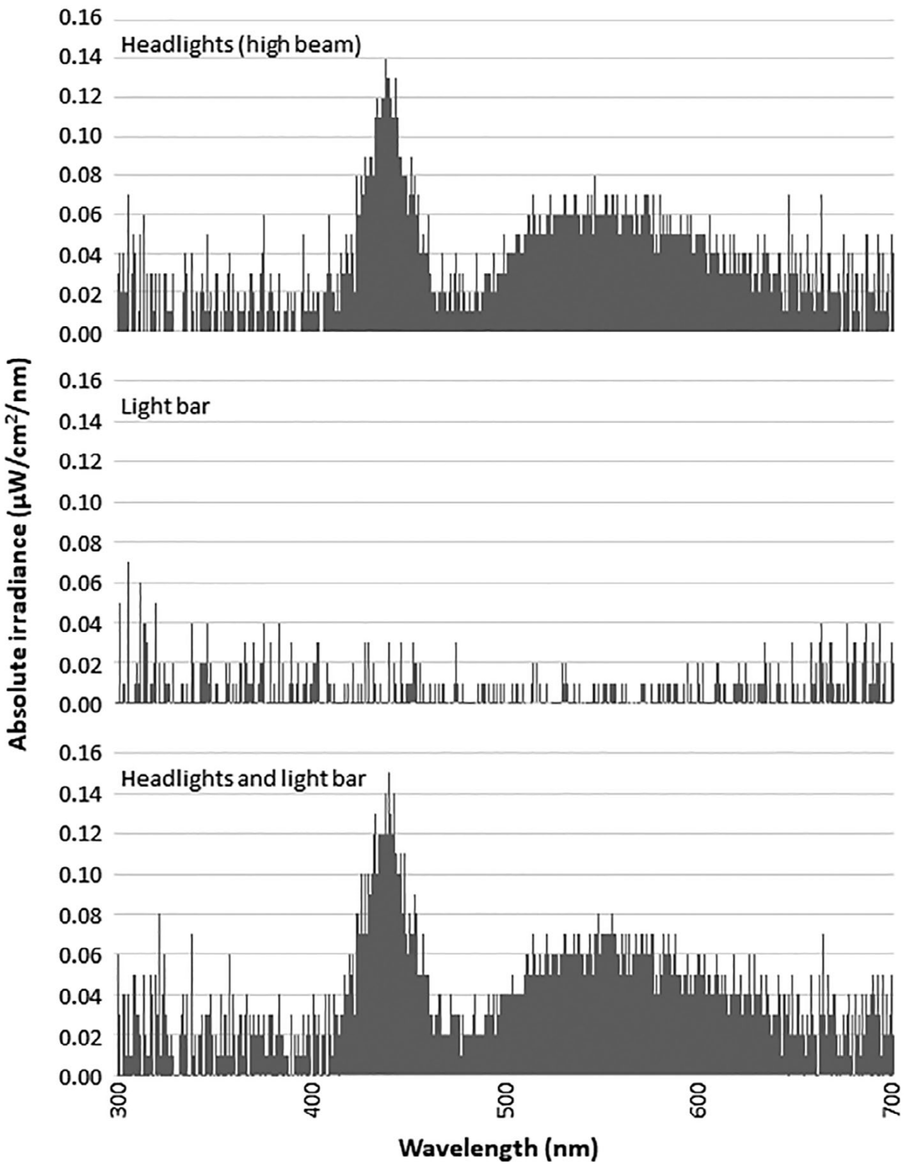

Fig. 2. Absolute irradiance from light sources on a Ford F250 pickup truck (measured at 57 m from the truck) used for 60 km/h approaches toward white-tailed deer at night. Data are shown for direct light from headlights on high beam (top), light reflected from the frontal surface of the vehicle but originating from an LED light bar (middle), and the headlights in combination with the LED light bar (bottom). Measurements were made under dark conditions.

Start distances ranged from 114 to 808 m with a mean of 399 ± 20.7 m. We collected FID data for 100 of 105 total deer approached with the vehicle. Of those 100 deer, only four were initially observed on the road. As indicated above, we found no effect of observer, season, or air temperature on deer group FID (Table 2). Immobility behavior (group FID = 0) was observed during 10 vehicle approaches with only standard headlights, compared with only one vehicle approach when the light bar was on (Fig. 3). The mean FID of deer groups approached with only

Table 2. Type 3 statistics for fixed effects from a linear mixed-effects model analysis of mean group flight initiation distance of white-tailed deer in response to vehicle approach at night.

Response variable	Numerator df	Denominator df	*F*	*P*
Observer	1	24.2	2.96	0.098
Season	1	22.2	0.76	0.393
Air temp.	28	12.3	1.13	0.426

Note: See text for details on the experimental design and analyses.

standard headlights was 134.1 ± 23.8 m, whereas the mean FID of deer when the light bar was on was 173.0 ± 22.2 m. Our model indicated no effect of treatment on group FID ($F_{1/53.7} = 0.59$, $P = 0.447$).

Eleven of 31 (35.5%) vehicle approaches using only headlights were categorized as dangerous interactions (FID ≤ 50 m), compared with 3 of 31 (9.7%) dangerous interactions when the light bar was on (Fig. 3). Our model would not converge with location of concealing cover, group size, or start distance as random effects; the model converged when including cover distance only, although cover distance did not contribute significantly to the model (residual pseudo-likelihood test of covariance parameter: df = 2, $\chi^2 = 0.45$, $P = 0.650$). During approaches using only headlights, deer were more likely (based on least-squares means, 36% vs. 10%) to delay response indicating a dangerous interaction (i.e., FID ≤ 50 m) compared to approaches with the light bar on ($F_{1/51.7} = 4.47$, $P = 0.039$).

We observed 25 vehicle approaches during which at least one deer in the group crossed the road in front of the vehicle ($n = 60$ approaches considered; during two vehicle approaches, the only deer observed were initially standing on the road). For vehicle approaches using only headlights, at least one deer in the group crossed the road in front of the vehicle during 11 of 30 (36.7%) vehicle approaches, compared with 14 of 30 (46.7%) approaches when the light bar was on. Our model failed to converge when we included start distance; we therefore used location of the nearest concealing cover as the only random effect, which contributed to the likelihood of crossing (residual pseudo-likelihood test of covariance parameter: df = 2, $\chi^2 = 5.32$, $P = 0.046$). Considering model likelihood based

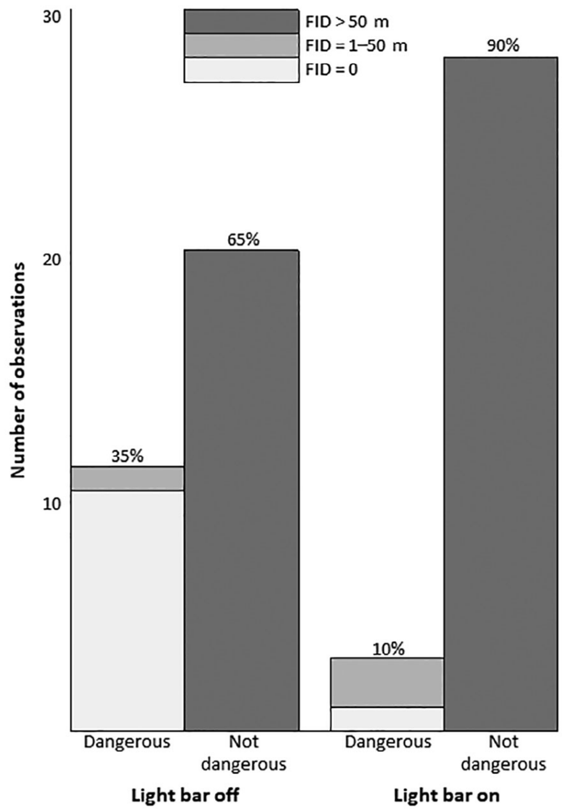

Fig. 3. Number of dangerous vs. not dangerous vehicle interactions with white-tailed deer at night based on group flight initiation distance (FID). Vehicle approaches were conducted with high-beam headlights only ($n = 31$) or with high-beam headlights in combination with a rear-facing LED light bar reflecting light from the frontal surface of the vehicle ($n = 31$). Deer–vehicle interactions were considered dangerous when mean group FID ≤ 50 m.

on least-squares means, at least one deer in a group was more likely (19.2% vs. 2.4%) to cross the road when the light bar was on compared with vehicle approaches using only headlights ($F_{1/42.8} = 6.34$, $P = 0.016$). For individual deer, 18 of 46 (39.1%) crossed the road in front of the vehicle using only headlights, compared with 24 of 50 (48.0%) when the light bar was on. However, considering only individual deer with FID > 0 (those individuals showing an avoidance response), 18 of 32 (56.3%) crossed the road when using only headlights, compared with 24 of 49 (49.0%) individual deer when the light bar was on (Fig. 4). In other words, when deer

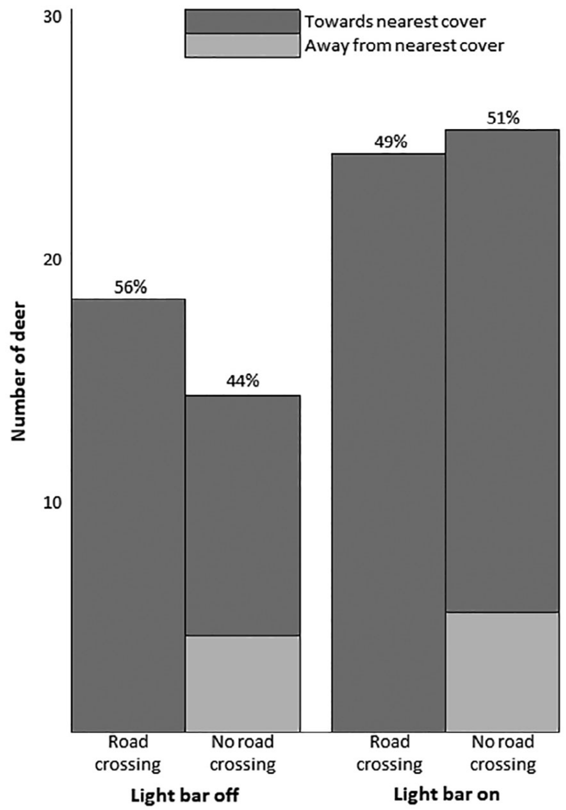

Fig. 4. Road-crossing by white-tailed deer in response to vehicle approach at night. Vehicle approaches were conducted with high-beam headlights only (n = 31) or with high-beam headlights in combination with a rear-facing LED light bar reflecting light from the frontal surface of the vehicle (n = 31). Here, data for individual deer that reacted to the vehicle (i.e., FID > 0) are shown across vehicle approaches. Deer were detected with a FLIR camera up to 808 m from the approaching vehicle and recorded as crossing the road when they first were found stationary, standing < 3 m from the road edge, and crossed the road in front of the approaching vehicle. Cover is defined as vegetation capable of concealing a standing adult deer.

initiated escape, the likelihood of crossing did not appear to differ between treatments.

Across all vehicle approaches, mean distance to cover was 19 m (SD = 36). No individual deer initially detected off the road (≤3 m of the road edge) that exhibited avoidance behavior in response to the vehicle (n = 81) crossed the road in front of the vehicle when the nearest cover was on the same side of the road as the deer. In other words, when deer crossed the road, they always moved toward the nearest concealing cover, irrespective of the lighting treatment (Fig. 4). Of the 14 individual deer with FID > 0 that moved away from the road rather than across it when the vehicle was using only headlights, four (28.6%) moved away from the nearest cover (Fig. 4). Similarly, 5 of 25 (20.0%) individual deer with FID > 0 that moved away from the road when the light bar was on moved away from the nearest cover (Fig. 4).

Discussion

We predicted that white-tailed deer approached at night would reduce immobility behavior and react with longer FIDs when the vehicle headlights were augmented with a rear-facing light bar illuminating the frontal surface of the vehicle. Although immobility behavior was reduced (10 vehicle approaches resulting in group FID = 0 with the light bar off vs. one with the light bar on), our model indicated no difference in group FID between lighting treatments. Similarly, Blackwell and Seamans (2009), working at the same location, observed a modest increase in FID when adding a high-intensity discharge lamp to standards headlights, but a significant increase in likelihood of response of deer at >94 m when using the combined lighting treatment. Blackwell et al. (2014), again working with the same population, found that FID was not dynamically adjusted with start distance and was highly variable within the population. Each of these studies included mean start distances that fell within the zone of awareness for white-tailed deer (<500 m; see Stankowich and Coss 2005) and thus were likely minimally influenced by FID of individuals initially unaware of the vehicle approach. We therefore suggest that vehicle lighting influences perceived risk by deer more so by changing the likelihood of escape initiation than by yielding distinct differences in FID by treatment.

Although we found no difference in FID across treatments, the likelihood of a dangerous interaction was reduced when the light bar was used. Specifically, model results indicated that vehicle approaches without frontal illumination were 3.6 times more likely to result in a dangerous interaction with deer than vehicle approaches using the light bar. This reduction in dangerous

interactions appeared to be driven primarily by the decrease in immobility behavior by deer when the light bar was on (Fig. 3). Blackwell et al. (2012) found that Canada geese reacted sooner to aircraft they were better able to detect based on their visual system. Other authors likewise have suggested that certain types of vehicle lighting could enhance visual tracking of vehicles by birds and potentially could reduce bird–vehicle collisions (Blackwell and Bernhardt 2004, Blackwell et al. 2009, Doppler et al. 2015, Goller et al. 2018). Although fewer data are available on mammal responses to vehicle lighting (Blackwell and Seamans 2009), we suggest that the more extensive illumination of the vehicle via the light bar in our study might have provided more information on the approaching threat, thereby enhancing perceived risk, reducing immobility behavior, and decreasing the likelihood of a dangerous interaction.

We found support for our prediction that road-crossing behavior by deer would increase with the addition of the light bar, ostensibly because more deer reacted (i.e., moved in response) to the approaching vehicle when the vehicle's frontal surface was illuminated. However, once deer began to move in response to the vehicle, they did not cross more often when the light bar was on (Fig. 4). Also, the increased likelihood of movement (and thus road-crossing behavior) when the light bar was on did not appear to increase the risk of collision, because most road crossings occurred well before the 50-m threshold defining a dangerous interaction (Fig. 3). In these cases, the driver likely would not have been aware the deer crossed the road.

We also found that road-crossing behavior was influenced by proximity of the nearest concealing cover. Once deer began to move in response to the vehicle, they crossed the road only when the nearest concealing cover was across the road (Fig. 4). This finding provides another example of a maladaptive use of antipredator behavior for vehicle avoidance (DeVault et al. 2015, Lima et al. 2015). Deer receive no benefit from concealing cover when attempting to avoid a vehicle, even though the location of cover with respect to the deer appears to strongly influence the decision of whether to cross the road in front of the vehicle. Even so, this tendency by deer to flee toward concealing cover potentially could be incorporated into roadside vegetation management planning to reduce deer–vehicle collisions (Blackwell et al. 2014). For example, in areas where deer densities are high, it might be beneficial to maintain short grass in medians of divided highways instead of trees or shrubs to reduce crossings toward the median in response to vehicle approach.

Although our results clearly indicate that illumination of the frontal surface of the vehicle influenced avoidance behavior of deer in response to an oncoming vehicle, we did not investigate which characteristics of the light affected the behaviors we observed. Was deer behavior influenced by the difference between lighting treatments in spectral composition or the area illuminated? Given that spectra detectable by white-tailed deer increased by only about 8% with the addition of the light bar (Table 1, Fig. 2), we suspect that the area illuminated by the light bar (i.e., much of the frontal surface of the vehicle as opposed to only vehicle headlights) was primarily responsible for the differences in behavior we observed across lighting treatments. Moreover, the efficacy of frontal vehicle illumination for reducing dangerous interactions between wildlife and vehicles potentially could be enhanced by fine-tuning characteristics of the light reflected from the vehicle to better match the visual system of deer (VerCauteren and Pipas 2003, Cohen et al. 2014) or other targeted species (Blackwell et al. 2009, 2012, Doppler et al. 2015, Goller et al. 2018). In our study, we used a white LED light bar reflecting light from a mostly black frontal vehicle surface (Fig. 1). Future work should investigate whether differences in wavelength, intensity, or spatial arrangement of light used for illuminating the frontal surface of vehicles improve avoidance behaviors and therefore reduce the likelihood of an animal–vehicle collision. Also, our method could be explored in similar applications, including wildlife collisions with aircraft, trains, and wind turbine blades.

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Literature Cited

Allen, R. E., and D. R. McCullough. 1976. Deer-car accidents in southern Michigan. Journal of Wildlife Management 40:317–325.

Biondi, K. M., J. L. Belant, J. A. Martin, T. L. DeVault, and G. Wang. 2011. White-tailed deer incidents with U.S. civil aircraft. Wildlife Society Bulletin 35:303–309.

Blackwell, B. F., and G. E. Bernhardt. 2004. Efficacy of aircraft landing lights in stimulating avoidance behavior in birds. Journal of Wildlife Management 68:725–732.

Blackwell, B. F., T. L. DeVault, E. Fernández-Juricic, E. M. Gese, L. Gilbert-Norton, and S. W. Breck. 2016. No single solution: application of behavioural principles in mitigating human-wildlife conflict. Animal Behaviour 120:245–254.

Blackwell, B. F., T. L. DeVault, T. W. Seamans, S. L. Lima, P. Baumhardt, and E. Fernández-Juricic. 2012. Exploiting avian vision with aircraft lighting to reduce bird strikes. Journal of Applied Ecology 49:758–766.

Blackwell, B. F., E. Fernández-Juricic, T. W. Seamans, and T. Dolans. 2009. Avian visual configuration and behavioural response to object approach. Animal Behaviour 77:673–684.

Blackwell, B. F., and T. W. Seamans. 2009. Enhancing the perceived threat of vehicle approach to white-tailed deer. Journal of Wildlife Management 73:128–135.

Blackwell, B. F., T. W. Seamans, and T. L. DeVault. 2014. White-tailed deer response to vehicle approach: evidence of unclear and present danger. PLOS ONE 9:e109988.

Blackwell, B. F., T. W. Seamans, T. L. DeVault, S. L. Lima, M. B. Pfeiffer, and E. Fernández-Juricic. 2019. Social information affects Canada goose alert and escape responses to vehicle approach: implications for animal-vehicle collisions. PeerJ 7:e8164.

Bowles, M. D., and R. S. Arrighi. 2004. NASA's nuclear frontier: the Plum Brook reactor facility. Monographs in Aerospace History 33:150–151.

Cohen, B. S., D. A. Osborn, G. R. Gallagher, R. J. Warren, and K. V. Miller. 2014. Behavioral measure of the light-adapted visual sensitivity of white-tailed deer. Wildlife Society Bulletin 38:480–485.

D'Angelo, G. J., J. G. D'Angelo, G. R. Gallagher, D. A. Osborn, K. V. Miller, and R. J. Warren. 2006. Evaluation of wildlife warning reflectors for altering white-tailed deer behavior along roadways. Wildlife Society Bulletin 34:1175–1183.

D'Angelo, G. J., A. Glasser, M. Wendt, G. A. Williams, D. A. Osborn, G. R. Gallagher, R. J. Warren, K. V. Miller, and M. T. Pardue. 2008. Visual specialization of an herbivore prey species, the white-tailed deer. Canadian Journal of Zoology 86:735–743.

DeVault, T. L., J. L. Belant, B. F. Blackwell, and T. W. Seamans. 2011. Interspecific variation in wildlife hazards to aircraft: implications for airport wildlife management. Wildlife Society Bulletin 35:394–402.

DeVault, T. L., B. F. Blackwell, and J. L. Belants, editors. 2013. Wildlife in airport environments: preventing animal–aircraft collisions through science-based management. Johns Hopkins University Press, Baltimore, Maryland, USA.

DeVault, T. L., B. F. Blackwell, and T. W. Seamans. 2019. Frontal vehicle illumination to reduce animal-vehicle collisions. U.S. Patent Application #16/668,253, filed October 30, 2019. United States Patent and Trademark Office, Alexandria, Virginia, USA.

DeVault, T. L., B. F. Blackwell, T. W. Seamans, S. L. Lima, and E. Fernández-Juricic. 2014. Effects of vehicle speed on flight initiation by turkey vultures: implications for bird–vehicle collisions. PLOS ONE 9:e87944.

DeVault, T. L., B. F. Blackwell, T. W. Seamans, S. L. Lima, and E. Fernández-Juricic. 2015. Speed kills: ineffective avian escape responses to oncoming vehicles. Proceedings of the Royal Society B 282:20142188.

DeVault, T. L., T. W. Seamans, B. F. Blackwell, S. L. Lima, M. A. Martinez, and E. Fernández-Juricic. 2017. Can experience reduce collisions between birds and vehicles? Journal of Zoology 301:17–22.

Doppler, M. S., B. F. Blackwell, T. L. DeVault, and E. Fernández-Juricic. 2015. Cowbird responses to aircraft with lights tuned to their eyes: implications for bird-aircraft collisions. Condor: Ornithological Applications 117:165–177.

Dukes, T. W. 1969. The ocular fundus of normal white-tailed deer (*Odocoileus virginianus*). Bulletin of the Wildlife Disease Association 5:16–17.

Fahrig, L., and T. Rytwinski. 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecology and Society 14:21.

Fambro, D. N., K. Fitzpatrick, and R. J. Koppa. 1997. Determination of stopping sight distances. NCHRP Report 400. Transportation Research Board, National Research Council, Washington, D.C., USA.

Glista, D. J., T. L. DeVault, and J. A. DeWoody. 2009. A review of mitigation measures for reducing wildlife mortality on roadways. Landscape and Urban Planning 91:1–7.

Goller, B., B. F. Blackwell, T. L. DeVault, P. E. Baumhardt, and E. Fernández-Juricic. 2018. Assessing bird avoidance of high-contrast lights using a

choice test approach: implications for reducing human-induced avian mortality. PeerJ 6:e5404.

Gunson, K. E., G. Mountrakis, and L. J. Quackenbush. 2011. Spatial wildlife-vehicle collision models: a review of current work and its application to transportation mitigation projects. Journal of Environmental Management 92:1074–1082.

Hedlund, J. H., P. D. Curtis, G. Curtis, and A. F. Williams. 2004. Methods to reduce traffic crashes involving deer: What works and what does not. Traffic Injury Prevention 5:122–131.

Huijser, M. P., J. W. Duffield, A. P. Clevenger, R. J. Ament, and P. T. McGowen. 2009. Cost-benefit analyses of mitigation measures aimed at reducing collisions with large ungulates in the Unites States and Canada: a decision support tool. Ecology and Society 14:15.

Huijser, M. P., P. McGowen, J. Fuller, A. Hardy, A. Kociolek, A. P. Clevenger, D. Smith, and R. Ament. 2007. Wildlife-vehicle collision reduction study. Report to Congress. U.S. Department of Transportation, Federal Highway Administration, Washington D.C., USA.

Jacobs, G. H., J. F. II Deegan, J. Neitz, B. P. Murphy, K. V. Miller, and R. L. Marchinton. 1994. Electrophysiological measurements of spectral mechanisms in the retinas of two cervids: white- tailed deer (*Odocoileus virginianus*) and fallow deer (*Dama dama*). Journal of Comparative Physiology A 174:551–557.

Kociolek, A. V., A. P. Clevenger, C. C. St. Clair, and D. S. Proppe. 2011. Effects of road networks on bird populations. Conservation Biology 25:241–249.

Lima, S. L., B. F. Blackwell, T. L. DeVault, and E. Fernández-Juricic. 2015. Animal reactions to oncoming vehicles: a conceptual review. Biological Reviews 90:60–76.

Lingle, S., and F. Wilson. 2001. Detection and avoidance of predators in white-tailed deer (*Odocoileus virginianus*) and mule deer (*O. hemionus*). Ethology 107:125–147.

Mastro, L. L., M. R. Conover, and S. N. Frey. 2008. Deer-vehicle collision prevention techniques. Human-Wildlife Conflicts 2:80–92.

Mastro, L. L., M. R. Conover, and S. N. Frey. 2010. Factors influencing a motorist's ability to detect deer at night. Landscape and Urban Planning 94:250–254.

Miller, K. V., L. I. Muller, and S. Demarais. 2003. White-tailed deer (*Odocoileus virginianus*). Pages 906–930 *in* G. A. Feldhamer, B. C. Thompson and J. A. Chapman, editors. Mammals of North America: biology, management and conservation. Second edition. Johns Hopkins University Press, Baltimore, Maryland, USA.

Pfeiffer, M. B., R. B. Iglay, T. W. Seamans, B. F. Blackwell, and T. L. DeVault. 2020. Deciphering interactions between white-tailed deer and approaching vehicles. Transportation Research Part D 79:102251.

Putman, R. J.. 1997. Deer and road traffic accidents: options for management. Journal of Environmental Management 51:43–57.

R. van der Ree, D. J. Smith, and C. Grilos editors. 2015. Handbook of road ecology. Wiley-Blackwell, West Sussex, UK.

Riginos, C., M. W. Graham, M. J. Davis, A. B. Johnson, A. B. May, K. J. Ryer, and L. E. Hall. 2018. Wildlife warning reflectors and white canvas reduce deer-vehicle collisions and risky road-crossing behavior. Wildlife Society Bulletin 42:119–130.

Rodgers, A. R., and P. J. Robins. 2006. Moose detection distances on highways at night. Alces 42:75–87.

Romin, L., and L. B. Dalton. 1992. Lack of response by mule deer to wildlife warning whistles. Wildlife Society Bulletin 20:382–384.

Rowden, P., D. Steinhardt, and M. Sheehan. 2008. Road crashes involving animals in Australia. Accident Analysis and Prevention 40:1865–1871.

Rumar, K.. 1990. The basic driver error: late detection. Ergonomics 33:1281–1290.

Stankowich, T., and R. G. Coss. 2005. Effects of predator behavior and proximity on risk assessment by Columbian black-tailed deer. Behavioral Ecology 17:246–254.

Sullivan, J. M. 2011. Trends and characteristics of animal-vehicle collisions in the United States. Journal of Safety Research 42:9–16.

Sun, H., and B. J. Frost. 1998. Computation of different optical variables of looming objects in pigeon nucleus rotundus neurons. Nature Neuroscience 1:296–303.

Valitzski, S. A., G. J. D'Angelo, G. R. Gallagher, D. A. Osborn, K. V. Miller, and R. J. Warren. 2009. Deer responses to sounds from a vehicle-mounted sound-production system. Journal of Wildlife Management 73:1072–1076.

VerCauteren, K. C., M. J. Lavelle, and S. E. Hygnstrom. 2006. A simulation model for determining cost-effectiveness of fences for reducing deer damage. Wildlife Society Bulletin 34:16–22.

VerCauteren, K. C., and M. J. Pipas. 2003. A review of color vision in white-tailed deer. Wildlife Society Bulletin 31:684–691.