WILDLIFE AFTER DARK: A REVIEW OF NOCTURNAL OBSERVATION TECHNIQUES

> *"A luminous blob appeared on a hillside far way and wavered fitfully like a bicycle lamp seen at a distance on a windy night. . . . It swung round a clump of trees about 200 yards away, and came winging, swiftly and silently, towards us. It was a bird . . . every feather of its plumage glittered with tiny points of light, a kind of frosted fire which, without the power to dazzle, was bright enought to illuminate the branches of a tree through which it passed." (Abdulali, 1949).*

Only rarely, as in this account of an owl covered with phosphorescent fungi, do conditions in nature permit the easy observation of nocturnal animals. For this reason, little is known about the activities of most nocturnal mammals, birds, reptiles, amphibians, fishes, and invertebrates. Also lacking are data on the many "diurnal" species that are more active at night than diurnal observers like to assume. Even basic life-history information, such as estimates of parental investment and time-energy budgets, may be suspect unless at least a minimum of nocturnal data is collected. Yet, to observe more than the most overt movements of animals at night the biologist requires some form of nocturnal vision, a requirement not easily met until recently. Advances made in electronics, electro-optics, and other areas during the last few decades now enable researchers to locate and track animals visually at night. The techniques employed fall into two broad categories, viewing instruments and markers.

In this paper we present a comprehensive and critical review of the viewing instruments and markers used to date in nocturnal studies. We provide descriptions, advantages, and disadvantages of each of the techniques and examples of animals on which they have been used. We have attempted to cite all English-language papers published by February 1985 that have new descriptions or evaluations of nocturnal viewing instruments or markers. We have not, however, provided an exhaustive list of studies that merely employed nocturnal techniques originally described in other papers.

VIEWING INSTRUMENTS

Wildlife researchers overwhelmingly depend on their eyes for the collection of data. As much as 95% of the information recorded in the field by most workers is visual (Lehner, 1979), yet human vision is constrained by two limiting factors, the wavelength of electromagnetic radiation and the intensity of that radiation. Human visual perception is confined to wavelengths in the visible band (0.4μ-0.7μ), which represents only a narrow portion of the total light spectrum. Light intensity during a 24-hour period may range from 10^{-6} footcandles (overcast night) to 10^{4} footcandles (bright sunlight). The unaided eye can see with reasonable clarity at an intensity of one footcandle—light in a dimly lit cocktail lounge may be as low as 0.1 footcandle (for those readers requiring an illuminating example). If light intensity is adequate and its wavelength is within the visible portion of the spectrum, visibility is possible without technical assistance. If either or both of these requirements are not met, a nocturnal viewing instrument may permit detailed observations. We describe several such viewing instruments in the following pages. For a more extensive treatment, including non-biological applications, see Fulton and Mason (1981).

BINOCULARS

Although binoculars are not designed specifically for night use, they do facilitate observations under conditions of low light intensity. This is because, in addition to magnifying images, binoculars increase perceived light intensity. Incoming light seems brighter with 8× binoculars, for example, because an image normally filling one-eighth of the observer's field of view now fills the entire field. The relative brightness of binoculars is determined by several design features that affect the amount of light passing through the ocular lens (= eyepiece). Relative brightness may be calculated as follows:

$$\left(\frac{\text{objective lens diameter}}{\text{magnification}}\right)^2 = \text{relative brightness.}$$

The view through 7 × 50 binoculars (relative brightness = 51) is roughly twice as bright as that through 7 × 35 binoculars (relative brightness = 25). Little is gained by increasing the objective lens diameter of 7× binoculars much beyond 50 mm, however, because the exit pupil diameter (objective lens diameter/magnification) of such an instrument is greater than the maximum pupil diameter of the observer (6-9 mm). Light not entering the pupil is, of course, wasted.

In any optical system there is some loss of light intensity due to reflection and refraction (scatter) of incoming light by the lenses. Coated lenses are recommended to reduce reflection to a minimum. Light passing through untreated binoculars loses approximately 5% of its brightness each time it penetrates a lens surface (up to 10 surfaces are commonly used in binoculars). By coating lenses with a molecule-thin layer of magnesium fluoride, light loss can be reduced to 0.5% at each surface. Complete coating of all lens surfaces indicates a quality instrument, one that should display the phrase "fully coated optics." Binoculars bearing the words "coated optics" have only the outer surfaces of the objective and ocular lenses coated; this does nothing to decrease light loss inside the instrument. The amount of light loss due to refraction through binocular lenses depends on the chemical composition of the glass. The best optical grade glass is found only in high quality binoculars.

Workers who desire binoculars that are useful under a variety of field conditions may have to make compromises between relative brightness, size, weight, and other features. Further information on binoculars can be found in Reichert and Reichert (1961), Lehner (1979), Schemnitz and Giles, 1980, and Danylyshyn and Humphreys (1982).

IMAGE CONVERTERS

Image converters are devices that convert nonvisible light such as infrared (IR) into a visible image on a viewing screen. This approach has obvious advantages over that employed for years by field biologists who had no choice but to illuminate a scene with visible light if they wished to make nocturnal observations. For example, Walker (1943) found that elf owls (*Micrathene whitneyi*) eventually habituated to a six-volt lamp illuminating their nest hole in a cactus. Only after several hours could he observe natural foraging and feeding behavior by the owls. Today one can add a simple IR filter to a standard searchlight, thus helping to insure against light-induced alterations in behavior. Although it is difficult to be certain that an animal is insensitive to IR light, experimental results strongly indicate that several species of mammals, birds, and insects do not respond to it (Southern et al., 1946; Conner and Masters, 1978; Wells and Lehner, 1978; Howell and Granovsky, 1982).

Near-IR image converters focus near-IR light (0.8μ-1.2μ), reflected from a subject, onto an IR-sensitive photocathode. The photocathode in turn emits electrons that are accelerated by high voltage before striking a phosphor viewing screen where a visible image is formed. Several workers have employed portable IR converters called "sniperscopes" originally developed by the military for use during World War II. These devices are available new from manufacturers and in the military surplus market (Slusher, 1978; Fulton and Mason, 1981).

Sniperscopes were used by Southern et al. (1946) to observe Norway rats (*Rattus norvegicus*), and by Foster and Tate (1966) to study the nocturnal activity and social hierarchy of animals visiting trees frequented during the day by yellow-bellied sapsuckers (*Sphyrapicus varius*). IR-sensitive equipment also has been used by Townsend and Risebrow (1982) to observe the feeding behavior of planktivorous fish (*Abramis brama*). Kruuk (1978) conducted detailed observations of European badgers (*Meles meles*) with the aid of "infra-red night glasses" manufactured by Old Delft Optical Industries, Delft, Holland. These glasses combined an image intensifier, infrared converter, and binoculars. With them Kruuk was able to move about freely and observe badgers in detail at 150 m in almost total darkness. Animals could be identified as badgers from as far as 250 m.

A drawback of near-IR converters is the need to use them in conjunction with an external light source such as an IR lamp. This light, which must be mounted on or near the image converter, limits the converter's range and its viewing angle. In addition, a power source is required to operate the light, thus adding weight to the system.

In situations where portability is not required, for example in stationary field studies, infrared illumination coupled with IR-sensitive video equipment has proved useful. Conner and Masters (1978), and Howell and Granovsky (1982) have described systems that use a commercially available video camera fitted with an IR-sensitive tube. Events may be observed as they occur, and recorded on video tape, but still-frame photographic recording is not possible (Howell and Granovsky, 1982). For recording purposes, professional or industrial grade video tape recorders are recommended because their fast tape speeds produce a high quality playback image. The quality of image produced by this system is superior to photography or video through portable image converters or image intensifiers (discussed on following pages) because there is no phosphor viewing screen between the subject and the film. Infrared video systems have been used to study behavior in coyotes (*Canis latrans*), the Florida deermouse (Peromyscus floridanus), pharoah ants (*Monomorium pharaonis*), and arctiid moths (*Utetheisa ornatrix*) (Conner and Masters, 1978; Wells and Lehner, 1978; Howell and Granovsky, 1982).

IMAGE INTENSIFIERS

Like near-IR converters, image intensifiers detect near-IR light; unlike converters, they are not confined to IR viewing. Rather, image intensifiers operate by amplifying both visible and near-IR light up to 50,000 times. This enables an observer to see, even on an overcast night, using only ambient visible light. At present there are two categories of image intensifiers on the market: first generation intensifiers and second generation intensifiers.

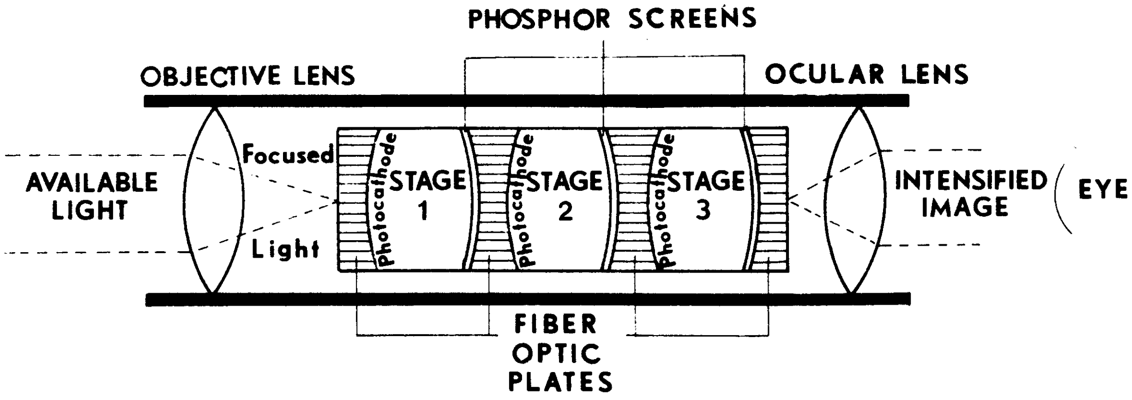

Figure 1

First generation image intensifiers employ three stages of light amplification (Fig. 1). Light entering the intensifier is focused by the objective lens onto a photocathode. The photocathode emits electrons proportional to the intensity of the incoming light. These electrons are accelerated into a phosphor screen that emits light proportional to the speed and number of electrons striking it, thus producing an amplified image of the original scene. This electron emission and acceleration process is repeated three times. Each of the three stages produces a light gain of approximately 40 to one, for a total gain after internal losses of approximately 50,000. Most first generation intensifiers incorporate an automatic brightness control that stabilizes the brightness of the image under varying light conditions. These controls will not protect the viewing screen from burns caused by high intensity lights (e.g., automobile headlights) that may etch permanent black spots into the viewing screen. The clarity of an image is high in the center portion of the screen, permitting acceptable photographs; however, the periphery of the image is often distorted. First generation image intensifiers are typically bulkier but less expensive than second generation intensifiers.

Second generation image intensifiers employ a single stage of light amplification (Fig. 2). A photocathode receives a focused light image from the objective lens. Elec-

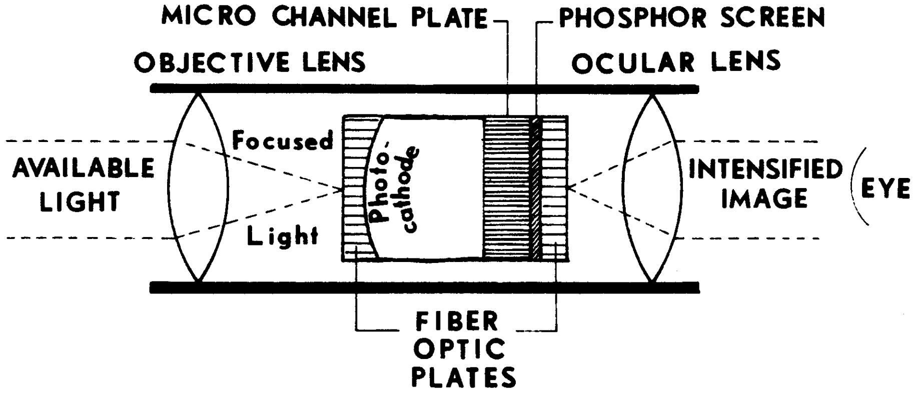

Figure 2

trons are emitted from the photocathode and accelerated toward a phosphor viewing screen. Before reaching the phosphor screen, however, the electrons pass through a micro channel plate (MCP). The MCP is a thin cross section of a bundle of small glass tubes, each of which emits several electrons when its surface is struck by a single electron. This process, called secondary emission, is capable of producing light gains of approximately 40,000 to one in one step. Unfortunately, the MCP introduces some scatter of electrons, reducing resolution and image clarity. For this reason, second generation intensifiers are not quite as clear at the center of the viewing screen as first generation intensifiers; however, second generation devices are less subject to edge distortion and to accidental burns from high intensity lights.

Both first and second generation image intensifiers are available in a variety of designs from a number of manufacturers (Javelin Electronics, Torrance, California; SECO, Milwaukee, Wisconsin; Varo, Garland, Texas; ITT Electro-Optical Products Division, Roanoke, Virginia; Litton Electron Tube Division, Tempe, Arizona). Many of these intensifiers are easily modified for 35-mm or video photography (see Spande, 1972; Boogher and Slusher, 1978; Fulton and Mason, 1981). Three designs that are particularly suitable for biological field work are general purpose and long distance viewing devices (= starlight scopes), night vision goggles, and miniature pocket scopes.

Many workers have used image intensifiers to watch animals at night. For example, Wolcott (1977) located, tracked, and observed the nocturnal behavior of ghost crabs (*Ocypode quadrata*), and Biderman and Dickerson (1978) watched boat-billed herons (*Cochlearius cochlearius*) at night to confirm food habits and feeding behavior. Entomologists have employed starlight scopes to observe movements, feeding, mating, oviposition, and predation of nocturnal insects (Lindgren et al., 1978). Starlight scopes continue to be used extensively to study bat behavior (J. W. Bradbury, M. B. Fenton, M. D. Tuttle, all pers. comm.). Ryan et al. (1982) recently used one to study responses of frog-eating bats (*Trachops cirrhosus*) to recorded frog calls in Panama. Night vision goggles, which are strapped onto one's head and thus free both hands for other tasks, have been used to watch the nocturnal behavior of white-tailed deer (*Odocoileus virginianus*) and maned wolves (*Chrysocyon brachyurus*) from distances of 100 m (C. M. Wemmer, pers. comm.). Other applications of image intensifiers have included such diverse tasks as observing mother-infant behavior in chimpanzees and gorillas, identifying and monitoring whales, conducting censuses of nocturnal seabirds, locating and tracking schools of fish from aircraft, observing nesting behavior of alligators and sea turtles, and studying patterns of sleep in humans. The list of applications for currently available image intensifiers is large and growing rapidly.

Under conditions where main-line power is available, total darkness television cameras provide an alternative to portable image intensifiers. Barclay (1982) employed one to observe communal night roosting behaviour of bats (*Myotis lucifugus*) inhabiting a barn. These video cameras incorporate an MCP amplification system and are sensitive to both visible and infrared light. Observations can be made directly on a video monitor, or via a video tape recording machine. Although the camera is not as light sensitive as a second generation portable intensifier, viewing a television monitor is easier on the eyes than squinting into the eyepiece of a scope (M. B. Fenton, pers. comm.).

Image intensifiers will not work in total darkness; some light is required to start the intensification process. A number of workers have supplemented very low ambient light with light from a dim red lamp (M. B. Fenton, pers. comm.; O. J. Reichman, pers. comm.). Image intensifiers are also sensitive in the near-IR region, and supplemental IR radiation has been used to illuminate bats in roosts (J. W. Bradbury, pers. comm.). Intensifiers cannot produce a discernable image without some target contrast, hence, cryptically-colored animals may be difficult to see. Contrasting markers may alleviate this problem, but the monochromatic image of the viewing screen prohibits the use of color as an identifier.

The particular image intensifier and accessories required will depend upon the requirements and field conditions of an individual's research. Interchangeable objective and ocular lenses are available for most models of image intensifiers, making them adaptable to a wide variety of viewing distances and light intensities. It is important to match the lenses to the viewing conditions; for example, too long a lens prevents focusing on near objects. The amount of light entering an intensifier depends on the aperture or f-number of its objective lens: the smaller the f-number, the more light passing through the lens. The magnification of an image intensifier is determined by the focal lengths of its lenses. A 300-mm objective lens will produce an image three times the size of that produced by a 100-mm lens. However, ocular (=eyepiece) lenses used in night vision devices produce the reverse phenomenon, and the overall magnification of the intensifier is determined by dividing the focal length of the objective lens by the focal length of the eyepiece. Eyepiece focal length also influences viewing fatigue; a 25-mm eyepiece must be viewed up close with one eye whereas a 50-mm eyepiece may be viewed from a normal reading distance of about 30 cm, greatly reducing eye fatigue.

Image intensifiers produce a quiet whistling sound when operating. Under most conditions this should not be a problem, but if absolute silence is required, soundproofing may be necessary. Intensifiers vary in size, weight, and portability. A typical intensifier tube and eyepiece weighs approximately 1.2 kg; objective lenses vary in focal length from 75 mm to 1200 mm and from about 0.5 kg to 6.5 kg in weight. Long-range image intensifiers may require a heavy-duty tripod. All of the portable instruments are powered by replaceable mercury batteries. The typical life of a set of batteries is approximately 40 hours. The image intensifier tube has a life of about 8000 hours, corresponding to 4 or 5 years of heavy use. The tube is replaceable but is about 75% of the cost of an entire unit. Prices vary based on the particular model and accessories desired. Our advice is to contact the various manufacturers listed earlier and describe your desired application.

THERMAL VIEWERS

Thermal viewers, or far-IR image converters, have been available to the public for a relatively short time. These devices, far more complex in construction than any previously described, operate by converting far-IR radiation (3.0μ-14.0μ) into a visible-light image. Far-IR radiation is emitted by all objects at temperatures above absolute zero; the intensity of radiation varies with the temperature of the source. Thermal viewers focus thermal radiation onto an array of electronically supercooled detectors. Each detector emits an electronic signal proportional to the temperature that it perceives. The collected signals are then amplified and transmitted to an array of light emitting diodes that create a visible image. Because the detectors in a thermal viewer are cooled to roughly −90°, even objects with relatively low temperatures are "hot" enough to be seen in complete darkness, severe weather, dust, and smoke. ". . . the Handheld Thermal Viewer can identify a man at up to 200 meters, detect him at over 500 meters in the open . . . and at 60 to 80 meters in the woods" (Fulton and Mason, 1981). These instruments should prove useful for watching animals at night, but we are unaware of their use in current field studies. Further information is available from SECO, Milwaukee, Wisconsin, USA.

VIEWING INSTRUMENTS DISCUSSION

The visibility of a study animal may be greatly increased by using a viewing instrument. Under conditions of relatively high amibient light, or when coupled with light-emitting markers (see following pages), binoculars may be sufficient. However, many field situations are characterized by low ambient light (e.g., heavily wooded areas) or study animals that are easily disturbed by artificial illumination. By allowing researchers to "see in the dark," image converters and image intensifiers make possible the observation and description of many activities not otherwise perceivable. We anticipate that the list of potential uses for these devices can only lengthen in the future. At present, the U.S. Army is working to develop synergistic night vision devices that are designed to operate over a wide band of radiation, from visible wavelengths through far-IR wavelengths. If and when these become available to the public, they will undoubtedly find a receptive audience among field biologists.

In this review we have concentrated on techniques suitable for the direct observation of nocturnal animals. If conditions demand the surveillance of an area in the absence of an investigator, a remote-sensing system may be useful (e.g., Lancia and Dodge, 1977; Schemnitz and Giles, 1980; Cooper and Afton, 1981; Goetz, 1981). In some cases workers may wish to record nocturnal observations on film for later analysis. Information on photographic and video techniques particularly suitable for field biologists is available in Blaker (1976) and Lehner (1979). An invaluable review of still and motion-picture photography through image intensifiers and image converters is provided by Fulton and Mason (1981).

MARKERS

All marking techniques, whether for diurnal or nocturnal studies, must be evaluated in terms of the goals of a particular project. The following six factors are among those to be considered before deciding which technique to use: 1) the number of individuals to be identified; 2) the distance over which identification is necessary; 3) the length of time identification is necessary; 4) the ease of capture of the study animal; 5) the effect of capture on the animal; and 6) the effect of a marker on the behavior of the animal (Lehner 1979).

The number of individuals in a population that can be individually marked is a function of the number of potential marking positions and whether a single or more than one color is used. Walker and Wineriter (1981) presented a simple formula for determining the number of unique marks (N) for a marking system using a fixed number of potential marking positions (n), a fixed number (k) of which are used on each individual:

$$N_{(n),k} = \frac{n!}{k!(n-k)!}.$$

For example, with six potential positions, any two of which are used on one animal, $N_{(6),2} = 15$. Walker and Wineriter (1981) gave additional formulae that incorporate more than one color and a variable number of marking positions per animal.

The variety of techniques available for marking animals is considerable. Each type of marker has a specific weight, visibility, longevity, ease of application, and potential effect on its recipient. All markers have one feature in common: they enhance the contrast of the marked animal. Contrast is a prerequisite for viewing animals at night, with or without viewing instruments. We review here only those techniques used in nocturnal studies. Extensive treatments of diurnal markers, many of which could be modified for nocturnal use, are available in Day et al., (1980) and especially Stonehouse (1978). Good reviews of techniques for specific groups of animals are as follows: Twigg (1975) for mammals; Marion & Shamis (1977) for birds; Stott (1971) and Arnold (1966) for fish; Ferner (1979), Swingland (1978), and Spellerberg and Prestt (1978) for reptiles and amphibians; and Peterson (1959) and Southwood (1978) for insects.

Markers may be divided into two categories: passive and active (Buchler, 1976). Examples of passive markers include paints, dry pigments, and reflective tapes, all of which must be used in conjunction with a light source of some kind to be detected at night. Active markers include radio-isotope tags, radio transmitters, and a variety of miniature light-emitting tags. Some active markers are useful primarily for locating and tracking animals; others permit more detailed nocturnal observations of behavior.

Radio-isotope tags, or "radiotracers," are used largely in mark-recapture studies and for tracking purposes. They do little to facilitate observations once a subject is located. Thus, we will not discuss radiotracers further, but refer the reader to excellent reviews by Peterle (1980) and Schultz and Whicker (1982). We have also omitted coverage of the increasingly sophisticated field of radio-telemetry. The best radio-telemetry system can locate an animal to within approximately 5 m of its actual location from a distance of 100 m; the human eye can do considerably better! In addition, establishing radio fixes from mobile animals is difficult, whereas visual tracking is often facilitated by movement of the subject. For information on radio-telemetry equipment and applications, see Macdonald (1978), Cochran (1980), Cheeseman and Mitson (1982), and Patric et al. (1982). For descriptions of radio-telemetry used in conjunction with viewing instrumetns and markers of the type reviewed herein, see Kruuk (1978), Parish and Kruuk (1982), and Reeve (1982).

PASSIVE MARKERS

Sometimes animals under study will habituate to visible lights at night. When this is the case, the investigator may wish to employ natural anatomical marks or diurnal tags to identify individual animals. For example, Hodgdon and Larson (1973) marked beavers (*Castor canadensis*) with 2-cm colored plastic ear tags. These were visible at night with a six-volt flashlight from platforms placed 4 and 8 m above water level. The lights did not appear to alter the behavior of the marked animals. Under similar conditions, Emlen (1968) observed the nocturnal behavior of 79 individually marked bullfrogs (*Rana catesbeiana*) inhabiting a 5-acre pond. Frogs were fitted with pre-shrunk nylon elasticized banding around their waists. Each band had a unique pattern or number painted on it. Emlen could recognize individual frogs from distances of 8 to 12 m using a headlamp and 7 × 50 binoculars. He wrote: "The behavior of marked males did not differ from that noted in unmarked individuals and no differences in mortality, emigration rates, or weight loss were observed between the two groups. Males with waistbands continued to maintain normal calling stations and to repel other males intruding from adjacent areas. In addition, several marked males were observed in amplexus with females" (Emlen, 1968).

Other investigators have used reflective paint and self-adhesive reflective sheeting (Scotchlite®, 3-M Co., St. Paul, Minnesota) to mark animals. The reflective surface, composed of countless microscopic glass beads, increases the distance over which a tag can be seen, even in daylight. At night, scanning an area with a spotlight is often sufficient to see reflective tags. The viewing distance of a reflective tag is determined by its size, color, and the strength of the active light source shining on it. Rennison et al. (1958) added reflective glass beads to a gum acacia and detergent solution which they painted in 2-mm diameter spots on the thoraces of tsetse flies (*Glossina pallidipes*). These dots were visible for a distance of 10 m with a 12-volt flashlight. Richter (1955) tested various colors and disc sizes of Scotchlite reflective sheeting as nocturnal tags in cottontail rabbits (*Sylvilagus*). Patterns of full discs, half-discs, crosses, triangles, and parallel bars were distinguishable with the unaided eye at distances of "practical value in the field." Binoculars were required to make positive identification of less brilliant patterns at greater distances. Silver was the most reflective color; yellow and gold were difficult to distinguish. The pressure-sensitive tape adhered well to plastic tags, lasting more than 4 months in the field. These were used in conjunction with other, active, tags for nocturnal observation.

Ealey and Dunnet (1956) used Scotchlite reflective tape to mark nocturnal marsupials. They fitted 80 euros (*Macropus robustus*) and 64 quokkas (*Setonix brachyurus*) with collars made from polyvinyl chloride bearing unique patterns of reflective tape. Animals were identified for up to 100 m with the aid of a rifle spotlight clamped to 15 × 50 binoculars. Identification at over 200 m was made possible with a more powerful spotlight and a 25× telescope. The authors noted that (1) white, silver, and yellow tape were difficult to differentiate; (2) red tape on a yellow collar was a highly conspicuous combination, day or night; (3) reflective patterns set against a non-reflective background were preferable to those on a reflective background; and (4) narrow reflective strips were preferable to wide strips.

Most reported applications of reflective tape have been for relatively large animals; however, Williams et al. (1966) glued color-coded patterns of tape directly to the fur of neotropical bats (*Phyllostomus hastatus*). This procedure permitted the censusing of individuals in a roosting colony from distances of up to 30 m using a six-volt spotlight and binoculars. Bradbury and Vehrencamp (1976) attached celluloid bird rings to the forearms of several species of emballonurid bats. The rings were modified by gluing on six colors of Scotchlite reflective tape, allowing the identification of marked bats in the roost and during foraging bouts. The authors noted bats did not chew the bands and there was no irritation to their wing membranes.

Fluorescent substances that emit a visible glow in the presence of UV radiation have also been used as passive markers. Such markers eliminate the need for a visible light source and may be preferable to other passive tags when dealing with animals easily disturbed by visible light. For example, fluorescent paints and dry pigments have been used extensively to mark insects, which are subsequently located and tracked at night with the aid of a battery-powered UV lamp (McDonald, 1960; Southwood, 1978). More recently fluorescent powders have been dusted onto the fur of rodents, rendering them visible under UV light. Although real-time observations could be made only over short distances, animals left trails of powder behind as they travelled through their habitat and the tracks could be followed several hours later (Duplantier et al., 1984; Lemen and Freeman, 1985). Eisner et al. (1969) and Aneshansley and Eisner (1975) described a more sophisticated UV viewer for use in the field. This device is a television camera equipped with a UV-transmitting lens and filter. It may be used in conjunction with a video recording unit if one wishes to make a video tape.

ACTIVE MARKERS

Battery-powered lights

A variety of easily constructed light-emitting tags incorporate battery-powered light bulbs. These include penlights, pinlights, LEDs (light-emitting diodes), and other miniature incandescent lamps in direct contact with mercury batteries. All of the devices reviewed below are simple to construct with (usually) less than $10.00 worth of easily-obtainable electronic components. The chief factor to consider in choosing a light-emitting tag, or any kind of marker for that matter, is weight. The often-cited maximum weight for a marker is 6% of the subject's weight (Brander and Cochran, 1971), but less is probably better.

Bellrose (1958) apparently was the first worker to use a battery-powered light marker. He attached penlights (small flashlights) to the legs of mallards (*Anas platyrhynchos*) to determine the direction in which the birds would fly when released at night. He was able to follow the ducks for over 1.6 km under all nocturnal sky conditions. Trapp (1972) constructed a device consisting of a ''grain of wheat'' lamp (Miniature Lamp Engineering Co., Hastings-on-Hudson, New York) and four mercury batteries (RM 625). When observed through 7 × 50 binoculars, ringtails (*Bassariscus astutus*) marked with the lamps were visible for one-half km. A modification of this technique was used by Fisher and Cross (1979) who soldered a subminiature lamp (WL1516; JKL Components Corp., Los Angeles, California) to a size 675 mercury battery, and then glued the device to the study animal. This provided light for 16 hours and was visible at 260 m with the unaided eye. The marker, which weighed less than 2.5 g, was tested on five species of nocturnal rodents (*Dipodomys heermanni, D. ordii, Neotoma fuscipes, Peromyscus crinitus*, and *P. truei*), two bats (*Pipistrellus hesperus* and *Antrozous pallidus*), and, after waterproofing in silicone rubber, on the Pacific pond turtle (*Clemmys marmorata*). Barbour and Davis (1969) equipped bats with minute ''pinlights'' (Kay Electric Co., Pine Brook, New Jersey) attached to small mercury cells. They were able to determine feeding ranges of individual bats but occasionally lost contact with them because of distant background lights.

In a fascinating study, Carr et al. (1974) visually tracked the movements of marine green turtles (*Chelonia mydas*) after marking them with styrofoam floats towed at the end of 24 m lines. The lens-shaped floats were 30 cm in diameter, 20 cm deep, and coated in fiberglass. Each float supported a fiberglass mast bearing an orange flag and a three-volt flashlight bulb powered by batteries imbedded in the body of the float, for tracking day or night. ''Numerous previous trials with floats of this and other designs have shown no discernable effect on the locomotion, orientation or goal-drive of the experimental animals. Turtles thus rigged, after being interrupted in their nesting and being displaced for long distances, promptly returned to emerge and nest, dragging their floats behind them'' (Carr et al., 1974). Towed floating bobbers and styrofoam cubes employed by Hasler and Wisby (1958) and Jahn (1966) for diurnal tracking of green sunfish (*Lepomis cyanellus*) and cutthroat trout (*Salmo clarki*), respectively, might be easily modified in the fashion of Carr et al.'s device for the nocturnal tracking of fish.

Penlights, pinlights and other small incandescent lamps are low cost and relatively easy to incorporate into tags. However, they have brief lifespans and, in the case of penlights, are often impractically bulky. One way to increase the battery life of a light-emitting tag is to use low-drain LEDs that switch off periodically. For example, Wolcott (1977) designed a small flashing marker, weighing less than 1 g, that consisted of a simple resistor-capacitor circuit linked to a single LED. By varying the resistors, the flash duration and flash rate could be altered. With 4 g of batteries, the device had a useful life of one month and was visible for 5 m with the unaided eye. Of greater significance was that these flashing tags increased subject contrast enough to allow observation for up to 300 m with the aid of a first generation night vision scope. Wolcott could successfully locate and track individual ghost crabs (*Ocypode quadrata*) which are difficult to detect in daylight, let alone at night, for periods of several weeks. By encapsulating each tag in epoxy resin, it was made waterproof and rugged enough to withstand sand-tunneling and surf-bathing by the crabs.

A modification of Wolcott's circuit was used by Clayton et al. (1978) to track black skimmers (*Rynchops niger*) at night. The authors built tags incorporating three focused-source LEDs linked in parallel. After being glued to a bird's spinal feather tract with quick setting epoxy, each tag was visible with the unaided eye for 30 m and for up to 125 m with 7 × 35 binoculars. The weight of each tag, including 2.2 g of batteries, was 9 g and each had a useful life of 2 weeks. Clayton was able to monitor the activity of marked birds in a nesting colony on dark nights, thus determining the constancy of incubation by sexes, the number of feeding forays, and responses to predators.

A much simpler flashing tag can be constructed using oscillating integrated circuits such as LM 3909 (National Semiconductor Corp.) or IC 7555 (Radio Shack, Tandy Corp.). These tags weigh little and are not susceptible to alterations in flash rate or duration due to changes in ambient temperature. Brooks and Dodge (1978) marked beavers (*Castor canadensis*) with flashing tags, each of which incorporated three color-coded LEDs in circuitry with an LM 3909 oscillator and two 1.35-volt batteries. A single pulse resistor controlled the flash frequency to provide identifying permutations and to conserve current. Components of each flasher were mounted on circuit boards to provide structural integrity, and the entire unit was waterproofed and attached to reinforced neoprene webbing made into neck collars for the beavers. The three LEDs were positioned on collars opposite to the circuitry and batteries, which thus acted as a counterweight to keep the lights at the nape of the beaver's neck. With LEDs of two different colors, up to six beavers could be marked. Tags were visible for 50 m with the unaided eye and 150 m with 7 × 50 binoculars. Observers using binoculars could correctly identify a tag's color combination from a distance of 100 m. Each marker required 80 g of batteries and had a projected life-span of 21 weeks, although the longest any collar remained on a beaver was 13 weeks. The total weight of the marker was 158 g, less than 1% of a beaver's weight.

In 1981 we constructed flashing tags similar in design to those of Brooks and Dodge (1978). These were attached to giant kangaroo rats (*Dipodomys ingens*) in a study of nocturnal activity patterns and home range size (Braun, 1985) (Fig. 3a). To minimize weight, only one LED was incorporated into a circuit consisting of an IC 7555 oscillator and two RW48 silver oxide batteries (Fig. 3b). Four different colored LEDs (red, amber, green, and yellow) were distinguishable for more than 25 m with the unaided eye and at more than 75 m with 7 × 50 binoculars. Tags were still visible with the binoculars at 100 m, but colors could not be differentiated. Each marker was attached to a plastic strip collar and the whole unit was made waterproof and dustproof with epoxy resin. The total weight of a tag was approximately 5.5 g, and its useful life was approximately 21 days. Permutations of flash duration and frequency were created by varying R_1 and C_1 (Fig. 3b); however, if flash duration was made too short, some colors could no longer be differentiated (e.g., yellow and green). Tagged kangaroo rats maintained their body weights and did not perceptibly alter their behavior in response to the markers.

The most sophisticated flashing tag reported to date is one designed for wallabies

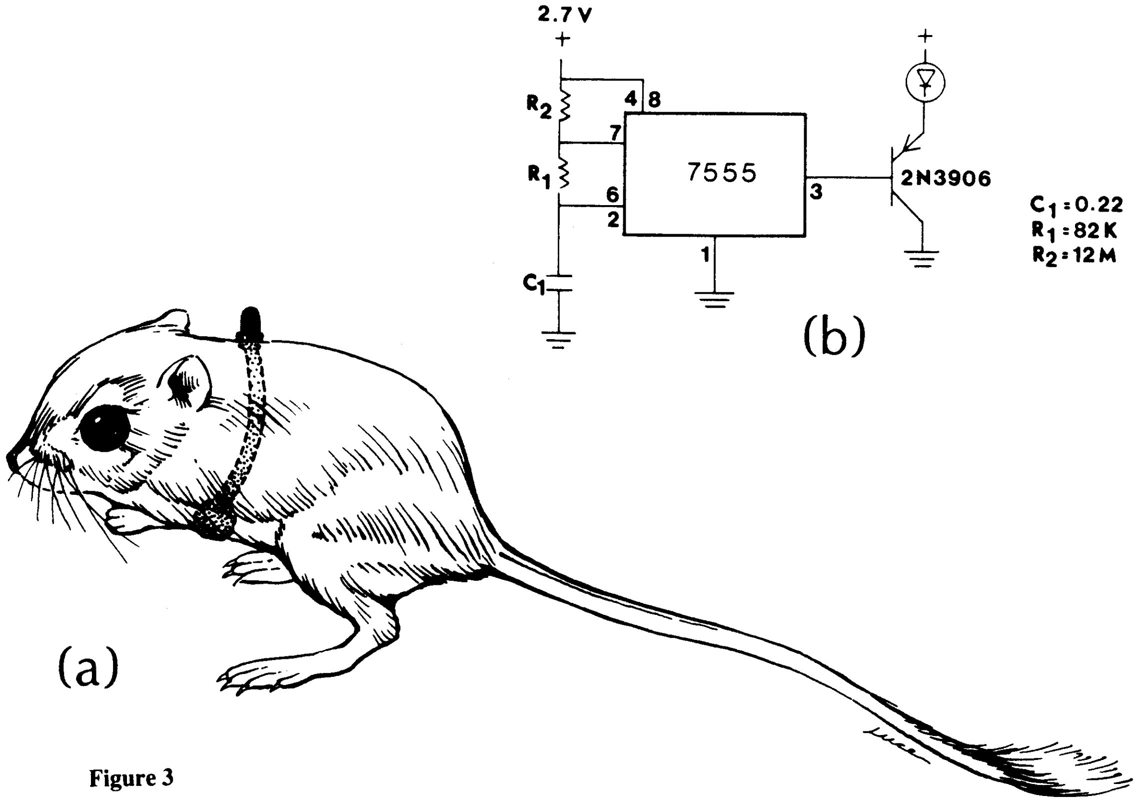

Figure 3

(*Petrogale penicillata*) by Batchelor and McMillan (1980). This device permitted the identification of a large number of animals by marking them with tags having individually-programmed flash sequences. Each tag's flash sequence was programmed by connecting LEDs to a decade counter with one of ten outputs. The number of LEDs attached to the outputs determined the number of flashes in a sequence. The circuitry of each tag also included a light dependent resistor (LDR), which permitted the LEDs to flash only under conditions of low ambient light intensity or darkness. The resultant decrease in battery drain nearly doubled the useful life of a tag. Tags weighing 30 g had an estimated life of 16 weeks and could be correctly identified with 10 × 50 binoculars at 100 m; with an image intensifier this range was extended to 800 m. Batchelor and McMillan estimated that substituting mercury RM-12 batteries for the EP-675 cells would increase tag life to 5 years. This modification would raise tag weight by only 120 g, an increase theoretically tolerated by subjects weighing as little as 3 kg. Batchelor and McMillan also pointed out that solar rechargeable batteries could be used to power tags, if not precluded by their relatively high cost or the small size of a subject animal. Finally, they noted that a radiotransmitter can be attached to the same circuitry used in the flashing tag, an option presenting obvious advantages.

Many of the markers and devices covered in this review rely on small batteries for their sources of power. When available, silver oxide batteries will provide slightly higher voltage and longer life than mercury batteries of equal size and weight. Lithium batteries have a much longer shelf life, higher voltage, and better performance at low temperatures than either mercury or silver oxide cells, but they are not available for use on very small animals (the smallest lithium cell currently available weighs about 4 g). Batteries can be inspected for internal defects and age with a simple x-ray technique (Harding et al., 1976). Soldering electrical leads to batteries often damages the cells. This damage can be avoided by using either conductive epoxy instead of solder, or a plastic battery holder to which the leads are attached (Kuck, 1966). Kuck's technique allows quick battery replacement in the field.

CYALUME®

High intensity active tags are easily made using CYALUME chemical light, a chemiluminescent liquid available from American Cyanamid Co., Bound Brook, New Jersey. CYALUME is normally packaged in the form of inexpensive "lightsticks" sold in stores supplying hardware or outdoor sporting goods. A typical lightstick consists of a 15 cm × 1.5 cm flexible plastic cylinder containing (a) 7.5 ml of yellow-green fluorescer liquid, and (b) a glass ampule containing 2.5 ml of clear activator liquid. Both components are internally and externally non-toxic. By sharply bending the plastic cylinder, the internal glass ampule shatters, thus combining the fluorescer and activator liquids. The resultant solution emits a bright green-white light that drops in intensity with time. The standard CYALUME lightstick glows perceptibly for 8-12 hours. The duration and intensity of light is dependent on the proportion of activator to fluorescer in the solution; more activator produces a brighter, but faster-decaying, light. Buchler (1976) provided detailed instructions for the easy removal, storage, and subsequent mixing of a lightstick's liquid components. This simple procedure permits one to create a chemical light tag of known duration and intensity by combining predetermined amounts of fluorescer and activator immediately prior to use. Once mixed, the chemiluminescent solution cannot be turned off.

A chief advantage of CYALUME is that it can be injected into a container of virtually any shape or size, which can then be attached to the subject of study. For example, Buchler (1976) injected small glass spheres with CYALUME and glued these to the fur of over 100 little brown bats (*Myotis lucifugus*). He also tested the technique on green frogs (*Rana clamitans*), snapping turtles (*Chelydra serpentina*), and flying squirrels (*Glaucomys volans*). Clayton et al. (1978) marked black skimmers (*Rynchops niger*) with CYALUME-filled plastic bulbs and we marked two species of kangaroo rats (*Dipodomys ingens* and *D. nitratoides*) with CYALUME tags made from small gelatin capsules. Unfortunately, kangaroo rats easily succeeded in removing glued-on tags by grooming themselves, in some cases within just a few minutes of tagging. Likewise, Buchler (1976) retrapped bats and flying squirrels that had removed glued-on tags. A second method we tried was more successful; kangaroo rats equipped with CYALUME-filled collars made from transparent plastic tubing were unable to remove them. The collars were light in weight, and produced a constant bright glow that was visible for over 75 m with the unaided eye. After a few hours of tracking, the animals were retrapped and divested of their lightless collars. We also routinely injected CYALUME into small glass or gelatin vials glued to numerous wooden grid stakes in the kangaroo rat colony under study. This produced a 1.0 ha illuminated grid, which greatly facilitated the mapping of nocturnal movements by marked animals (Braun, 1985).

Another parameter governing the duration and intensity of CYALUME is dispersion of the solution. CYALUME contained in a spherical capsule produces a much brighter, longer-lasting light than an equal amount of solution painted on an animal. A CYALUME-filled sphere with an outer diameter of 5 mm is visible to the unaided eye at 225 m. The visibility of a sphere twice this size is 475 m (Buchler, 1976), and spheres of approximately 2 cm in diameter may be seen for 600 m, unaided, and for over 1.5 km with 7 × 35 binoculars (Clayton et al., 1978). The chief disadvantage of CYALUME is its extremely short lifespan. This can work to one's advantage, however, particularly if one wishes to observe an animal for a brief period without having to recapture it to remove a persistent light. Spent tags epoxied to animals fall off after a week or two if not removed by grooming before then. It is not clear whether a light tag as bright as CYALUME significantly affects the behavior of the animal wearing it. However, Buchler (1976) observed what he considered to be normal flying and foraging behavior by CYALUME-tagged bats. Clayton et al. (1978) observed no overt changes in the behavior of tagged skimmers; for example, within 20 minutes of tagging, one bird left the nesting colony and returned with a fish to feed its young.

Betalights

Betalights (Saunders-Roe Developments, Ltd., Middlesex, England) are self-contained, sealed glass capsules filled with tritium gas and internally coated with phosphor. The tritium, which is radioactive, emits low-energy beta particles that strike the phosphor coating, causing it to emit a continuous, visible-light glow. Beta particles not absorbed by the phosphor are absorbed by the glass capsule, eliminating the possibility of external radiation. Betalights have received wide attention for several years by workers who require small, highly visible, active tags with long lives. "Long lives" in this case requires emphasis: the lights have useful lives of 10-20 years and will, therefore, outlive most potential subjects! In short, betalights possess characteristics of the ideal light-emitting marker, unfortunately, they are not as easy to acquire as other devices reviewed in this paper (see below).

Betalights are available in a wide range of sizes, varying from the smallest in production, a 0.51 mm × 6.5 mm tube, to discs 22.5 mm in diameter and tubes 150 mm long. Hence, they can be employed as active tags on a wide variety of subjects. For example, betalights are easily affixed to eartags with glue (O. J. Reichman, pers. comm.; Davey et al., 1980) or incorporated into collars containing other tracking equipment (Kruuk, 1978; Macdonald, 1978; Parish and Kruuk, 1982; Reeve, 1982). They have even been glued to the heads of rodents where they remained attached for several weeks (Thompson, 1982). Projects using betalights include behavioral studies of foxes (Macdonald, 1978), European badgers (Kruuk, 1978; Parish and Kruuk, 1982), rabbits (Davey et al., 1980), hedgehogs (Reeve, 1982), white-footed mice (M. R. Stromberg, pers. comm.), and heteromyid rodents (Thompson, 1982; O. J. Reichman, pers. comm.). Another useful application for betalights is to set them out as nocturnal reference points in study areas or grid systems. This eliminates the need for periodical replacement of exhausted batteries or chemicals (see discussion of CYALUME).

The intensity and color of a betalight depends on the amount of tritium it contains, its size, its shape, and the color of its phosphor coating. Lights currently available range in brightness from 60 microlamberts to 2000 microlamberts (for comparison, one lambert = 296 footcandles; the cocktail lounge mentioned previously would be illuminated at a level of approximately 340 microlamberts). Spheres and discs tend to be brighter than straight or curved tubes. The color of the light also affects its brightness. Davey et al. (1980) provided the following relative brightness scale: red—15, blue—30, deep orange—60, orange—65, white—75, green—100, and yellow—110. Saunders-Roe stated that it is possible to produce betalights of any color in the visible spectrum. As a specific example of visibility, a 10-mm diameter yellow light with an intensity of 250 microlamberts is visible for up to 300 m when viewed through 10 × 40 binoculars (Davey et al., 1980). The manufacturers claim normal viewing distances of up to 400 m. With suitable nocturnal viewing devices, this distance should increase to well over a kilometer.

Given the variety of colors, shapes, and sizes of betalights available, one can mark a large number of animals with unique tags for individual identification. Lights of several different colors are easily distinguished, as are lights of different intensities (Davey et al., 1980). Lights of different shapes are recognizable and some shapes, such as tubes, may be differentiated by painting them with bands of opaque paint (M.R. Stromberg, pers. comm.).

Betalights are designed to be safe light sources; they are nonflammable and unaffected by water, oil, and a majority of corrosive chemicals. Lights containing less than 2 curies of tritium are exempt from registration under the Radioactove Substances Act of 1960 (U.K.); lights containing more than 2 curies of tritium are not normally available. Some researchers have had difficulty in obtaining Betalights, and there may be local regulations prohibiting their importation. We suggest that interested readers check with the radiation control officer at their university or institution for any licensing or registration requirements.

Because betalights contain small amounts of radioactive gas, it is important to avoid breaking large numbers of them, particularly in poorly ventilated rooms or where oxidation of the tritium gas may result (e.g., around open flames). Littering a field site with lost or detached lights is also to be discouraged; the half-lives of these devices are too long, we feel, for them to be left lying around, regardless of the tiny amount of tritium they contain. We recommend their use only under conditions where the recovery of a majority of lights is possible. Further information on betalights, including guidelines for their storage and disposal, is available from the manufacturer.

Marker Discussion

Under conditions of high ambient light, or with animals that easily habituate to artificial lighting, passive energy-reflecting tags may be sufficient. Dyes, bleaches, colored tags, and reflective tapes and paints have all been used successfully. However, observations of active animals with passive markers are often intermittent and brief. Furthermore, the use of a visible light source, such as a flashlight, to detect passive markers may frighten animals or otherwise alter their behavior, perhaps in ways not obvious to the investigator. When an investigator wishes to avoid the potential adverse effects that illuminating the scene may have on the animals, active energy-emitting tags are recommended. Active tags such as battery-powered lights, CYALUME, and betalights provide sufficient contrast to locate and track animals at great distances. Each type of tag has specific characteristics of weight, longevity, and brightness. The latter is an especially important consideration because the light from a bright marker may be visible to the marked animal itself. Of greater concern is the possible effect of a bright tag on the behavior of a marked animal's conspecifics, not to mention its predators and prey! For example, combination radio/battery-powered light tags are throught to disturb bats in their roosts (J.W. Bradbury, pers. comm.). The best general advice we can offer is to pick the most unobtrusive marker possible and attempt to ascertain its side effects.

A better way to eliminate problems due to bright visible tags is to mark animals with "invisible" lights. Battery-powered tags can be made extremely dim by increasing the resistance between the battery and the bulb. Thus, one can make an LED flasher that is invisible to the unaided eye, yet easily discernable through an image intensifier. Another way to achieve the same effect is by building markers that incorporate infrared LEDs, which are as easily purchased as visible-light LEDs. IR markers can be located and tracked with image intensifiers because most intensifiers are sensitive to light in the near-IR range.

SUMMARY

During the last half-century descriptive natural history has given way, in part, to a more critical and quantitative approach to the study of animals in the field. Many aspects of such study, from primary field surveys to measuring the results of experimental manipulation, require the ability to observe and often recognize individual animals. On average, half of an animal's life is spent in darkness, but only recently have investigators been able to observe easily a wide variety of animals at night.

We have presented a number of techniques suitable for observing and marking animals for nocturnal studies. Visibility of a subject may be greatly enhanced through the use of viewing instruments. These may range from a pair of standard binoculars to a specially equipped image intensifier. The choice of viewing instrument will depend on the particular conditions under which observations will be made. The most important requirement for seeing animals at night, however, is subject contrast, a property that will be constantly changing for active animals moving through a mosaic of shadows and vegetation. Even the most expensive image intensifier has difficulty discriminating between a cryptically colored animal and its background (Wolcott, 1977).

One way to increase the subject contrast of animals is to mark them with passive or active tags. These provide intense, reliable sources of contrast that are easily located and tracked. We encourage investigators to use markers in addition to viewing instruments in their research. The advantages of coupling these systems are reciprocal; a marker greatly extends the range of a viewing instrument and vice versa.

In conclusion, wildlife biologists and ethologists now have at their disposal an array of recently developed techniques for observing behavior of noctural animals. We hope that this review will assist researchers wishing to collect data at night and those attempting to design their own techniques for the observation of nocturnal animals.

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