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Supporting Online Material for

Video Cameras on Wild Birds

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Published 4 October 2007 on *Science* Express
DOI: 10.1126/science.1146788

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Materials and Methods

Marine biologists have pioneered the use of animal-borne video-cameras (*S1*–*S4*), benefiting from neutral buoyancy of tags when their study subjects dive, but until recently camera units were far too large for most land mammals, let alone flying birds. While video-cameras have recently been used on trained birds by special-effects wildlife cameramen (*S5*) and experimental biologists (*S6*), the challenge remained to design a system that could be used reliably and safely with wild, free-ranging individuals. After pilot-testing with captive crows in Oxford, we deployed four different prototype cameras between November 2005 and January 2006, followed by 18 units of our final design between October 2006 and February 2007.

Our camera units contained two independent transmitters: (i) a conventional VHF radio-tag that transmits permanently for about three weeks, enabling positional tracking of the animal and possible recovery of a shed camera tag; and (ii) a 2.4 GHz transmitter that broadcasts a color video-signal with sound for *c*. 70 min, once it has been activated by a timer chip that delays transmission for a specified habituation period (up to 48 hours). In six cases, VHF radio-tags were fitted with an additional tilt-switch that alters pulse intervals according to the bird's body posture (fig. S2). Packaged camera units (n = 18) varied only slightly in specifications (batteries, activity sensor, packaging), measured approximately 4.5×2.0×1.3 cm (main body, L×W×H), and weighed 14.54 ± 0.21 g (mean ± SE).

Data were recorded in real-time with separate, ground-operated portable receivers. We used: a 'Sika' receiver (Biotrack Ltd., Dorset, UK) with a hand-held 3-element Yagi antenna for positional tracking; a 'TR-5' receiver (Telonics Inc., Arizona, USA) with a mast-mounted dipole antenna for logging pulse intervals and signal strength; and a custom-built receiver with a helix antenna mounted in a parabolic dish for recording video-footage. To maximize video-reception, two independent ground crews operated redundant video-receiver systems from different vantage points during six successful video-shoots (for example, see Fig. 1B).

Live footage was captured on mini-DV tapes with digital NTSC video camcorders (Canon ZR200) with an image resolution of 720×480 pixels at a frame rate of 29.97 fps. The camcorders' firmware automatically screened-out footage of poor quality, yielding blank tape where video-reception was insufficient. We used Editstudio v5.0.1 software (Pure Motion Ltd., Stockport, UK) to capture raw footage from tapes, and to merge video-tracks of redundant receivers (where available) to produce one complete record of unique material. All video-footage was: (i) viewed repeatedly in real time to identify main events; and (ii) scored with JWatcher v1.0 software (*S7*), using slow motion and replays where necessary, to conduct detailed behavioral analyses (see below). No image enhancement techniques were used for producing supplementary Movies S1 to S4.

Supporting Text

Supporting Results and Discussion

Our animal-borne video-cameras enabled efficient recording of foraging events in wild New Caledonian crows, and were vastly superior to conventional VHF radio-telemetry for this purpose (*S8*). Overall we documented, in 7.5 hours of analyzable video-footage from 12 subjects, the handling of: six snails (shell-width *c*. 1.5–3 cm; two consumed, four empty shells inspected); three small lizards (snout-vent-length *c*. 2.5–4.5 cm; all consumed); two small invertebrates (<1 cm, *c*. 3 cm; both consumed); three unidentified objects (<0.5 cm; all consumed); eight fruit (seven at least partly eaten); and one bout of foraging on small berries. On nine occasions crows appeared to pick up very small objects, and in several other cases movement patterns suggested that the subject was feeding, but the beak was out of camera view. A few known food-sources were not documented by our video-cameras: carrion is taken throughout the study area whenever available, and four crows with successful video-shoots had potential access to patches of candlenut trees (*Aleurites moluccana*), which provide nuts and wood-boring beetle larvae (Cerambycidae) (*S9*, *S10*).

We estimated that crows consumed eight small dietary items per hour of ground-foraging (see main text). This rate seems low and may indicate challenging foraging conditions (*S11*), but to our knowledge there are currently no data for other tropical crow species that would permit a robust comparison of prey-encounter rates. An alternative approach to assessing the ecological significance of tool use is a within-species comparison of foraging modes with and without tools (*S13*). Our video-cameras revealed that prey items collected during long bouts of ground-foraging were considerably smaller than the woodboring beetle larvae (fig. S1) that crows often hunt with stick tools (n = 33 random larvae extracted by us; total length 53.9 ± 2.3 mm, head width 12.2 ± 0.6 mm, weight 5.2 ± 0.5 g) (*S9*). We propose that cerambycid larvae – a hidden and otherwise unexploited food-source – constitute an important, highly nutritious addition to crow diet and have contributed to the evolution of tool use in this species. Crows are also known to use tools for targeting smaller prey [this study; (*S9*, *S14*)], and more camera deployments will show how diet and foraging efficiency vary with habitat, access to beetle larvae, and different tool types and modes of tool use.

In the main text we highlight data from two camera-tagged subjects to illustrate a range of crow behaviors and certain aspects of our tracking technology. In the following sections we provide supporting information for these two 'case studies', and add a third one describing the use of cameras for calibrating other telemetry devices. In *Case Study 1*, we showed for crow CC1, an adult male, typical prey-searching behavior, switching between foraging techniques with and without tools, and its successive selection, handling and consumption of different food items (Fig. 1, B and C; Movie S2). Early in the morning this bird settled in a small crescent-shaped valley, where it remained for the rest of the day, including the video-shoot. Whilst the bird was moving in thick vegetation along the slopes of the valley we received several long bouts of video-signal (Fig. 1C), documenting the following main foraging events: tool manufacture and use; capture of three small lizards; handling of two empty snail shells; and plucking and eating of a fruit. These events were interspersed within sequences of presumed food-searching, where the crow either moved on the ground (51% of 49 min of scorable video-footage, excluding periods of inactivity at night roost), or hopped from branch-to-branch in shrubs (47%). The short durations of locomotion bouts on the ground (n = 146 completely-recorded bouts; mean bout length 1612 ± 135 ms) or in shrubs and trees (n = 76; 959 ± 62 ms) illustrate the fine scale at which this subject was sampling the environment. We saw the bird only once despite being within *c*. 100 m of its estimated location throughout the video-shoot (observing the species' flush distance), with clear view of all relevant habitat patches.

Crow EK1, another adult male (*Case Study 2*), was recorded using at least three different tools for probing loose substrate on the ground (leaf litter and grass) during 45 min of scorable video-footage (Fig. 1D; Movie S3). Ground-based tool use has not been reported for New Caledonian crows before (*S9*), and our observations underscore that studies on the foraging economics of this species cannot rely on observing behaviors exclusively at tool-use 'hot-spots', like beetle-infested candlenut trees or the crowns of 'screw pines' (*Pandanus* spp.).

Finally, *Case Study 3* illustrates that video-tracking may have considerable scope for rapidly exploiting other existing telemetry technologies, such as VHF radio-tags with activity sensors that encode changes in body posture into the radio-signal. To date, this technique's potential for cost-efficient, long-term applications has remained largely untapped, as accurate calibration was not feasible. We deployed six camera units with integrated activity switches, and found that video-recordings can indeed be used for identifying a range of behaviors from their distinct signatures in streams of VHF radio-telemetry data. About 40 min before the scheduled video-shoot, crow HK5, an immature male, crossed over a ridge into a rugged subvalley (fig. S2; Movie S4). We managed to regain radio-contact and establish the bird's approximate location, but struggled to maintain permanent video-reception. However, when the bird moved slowly along the steep forested slope of a 209-m hill, we captured sufficient footage to document resting, ground-foraging, the handling of a fruit, and arboreal movements – activities that all produced distinct signatures in the VHF radio-signal (fig. S2, B and C). Judging from the similarity in signal patterns, we suspect that the crow was again foraging on the ground from 10:40–11:00am, long after its video-camera had expired. Following initial calibration with video-cameras, posture-sensitive radio-tags could enable long-term, remote monitoring of tool use in crows [which involves repetitive head and body movements; (*S14*)], or of behaviors that are of particular research interest in other bird species.

Apart from the applications mentioned in the main text, our camera technology may also be suitable for quantitative eco-physiological research. In most subjects and situations in our study, the cloaca and belly of the bird were in view of the tail-mounted camera (Movies S1 to S4), permitting the direct measurement of defecation and breathing rates. Together with data on movements and food consumption, these parameters could be used to estimate energy budgets (*S15*), and to study responses to natural or experimental stressors (*S16*).

Video-tracking permits unusually intimate insights into bird behavior and ecology, in locations and contexts where most conventional observation techniques fail. Its main advantage over many other telemetry applications is the direct and simultaneous mapping of the multitude of complex events that take place when an animal interacts with its environment (*S1*, *S2*). Habitat use, for example, is traditionally estimated from the spatial distribution of radio-fixes, but it remains unknown what a subject did in particular habitat types – where and how it searched for food, and whether it interacted with other animals. We have shown how the combination of animal-borne cameras with conventional VHF radio-telemetry can generate a rich record of an animal's behavior along a known movement trajectory, yielding data on search patterns, prey encounters and diet choice. In future, video-tracking could be used to investigate in great detail how behaviors vary with animal age and status, and across habitat types. This could ultimately enable the accurate parameterization of models of optimal-foraging behavior and individual-based population dynamics – a task that has proved difficult in the past. Animal-borne video-cameras provide new opportunities to study the biology of wild, free-ranging birds, and to tackle some long-standing questions in basic and applied ecology.

Ethical Notes

In long-term studies with birds, tags are typically recommended not to exceed 3% of the subjects' body mass (*S17*). Our camera units (<5%) were specifically designed for short-term deployment, as less than three days were required to complete a video-shoot. We took two measures to ensure that cameras were released quickly and reliably after data collection: (i) units were attached with only two thin, pre-weakened strips of adhesive tape to facilitate active removal by crows (design tested with captive crows); and (ii) we specifically targeted the (pre-) molting season for camera deployments to ensure that units were shed within a few weeks of tagging (42 molt-score readings for 40 wild-caught birds indicate that molt of rectrices peaks around January to February).

Of the four birds tagged in our pilot field season (see Materials and Methods), one was re-trapped 22 days after tagging and had its camera removed, two had molted their tags after 10 and 14 days, respectively, and three of them were re-sighted without cameras more than nine months after tagging, indicating good survivorship. One male bred successfully (one fledgling) when it was camera-tagged, and again a year later (two fledglings) without camera. In our second field season, two birds lost their tags before their cameras had triggered (both <2 days post-tagging), and one subject molted the unit after 21 days. We suspect that many other units were removed or molted after their VHF radio-tags had expired.

Our video-technology revealed that, at least in our study site, New Caledonian crows often forage on the ground for extended periods of time. We are confident that terrestriality of birds was not an artefact of tagging, because: (i) video-results are consistent with our independent radio-tracking observations (*S18*); (ii) crows showed normal flight behavior without any signs of impairment (for example, see Movie S1); (iii) subjects occasionally filmed other non-tagged crows on the ground (for example, see fig. S2A); (iv) general movement patterns, head turns, and the habitual use of the beak for probing into loose substrate indicated that tagged crows were actively scanning the forest floor for food; and (v) ground-foraging has been described for many other corvid species (*S12*).

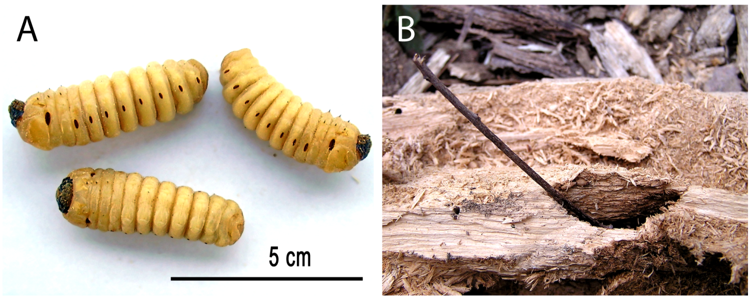

Fig. S1. New Caledonian crows forage with stick tools for large woodboring beetle larvae. **(A)** Long-horned beetles (Cerambycidae) deposit their eggs in candlenut trees. New Caledonian crows hunt the developing larvae by probing with stick tools into their burrows. Compare larvae to lizard and snail shown in the main text (Fig. 1B), which were the largest animal prey recorded with video-cameras during ground-foraging. **(B)** Sometimes the crows' tools can be found still inserted into holes. Note how thick this typical stick tool is compared to the video-recorded ground-foraging tools, especially the ones made from grass-like stems.

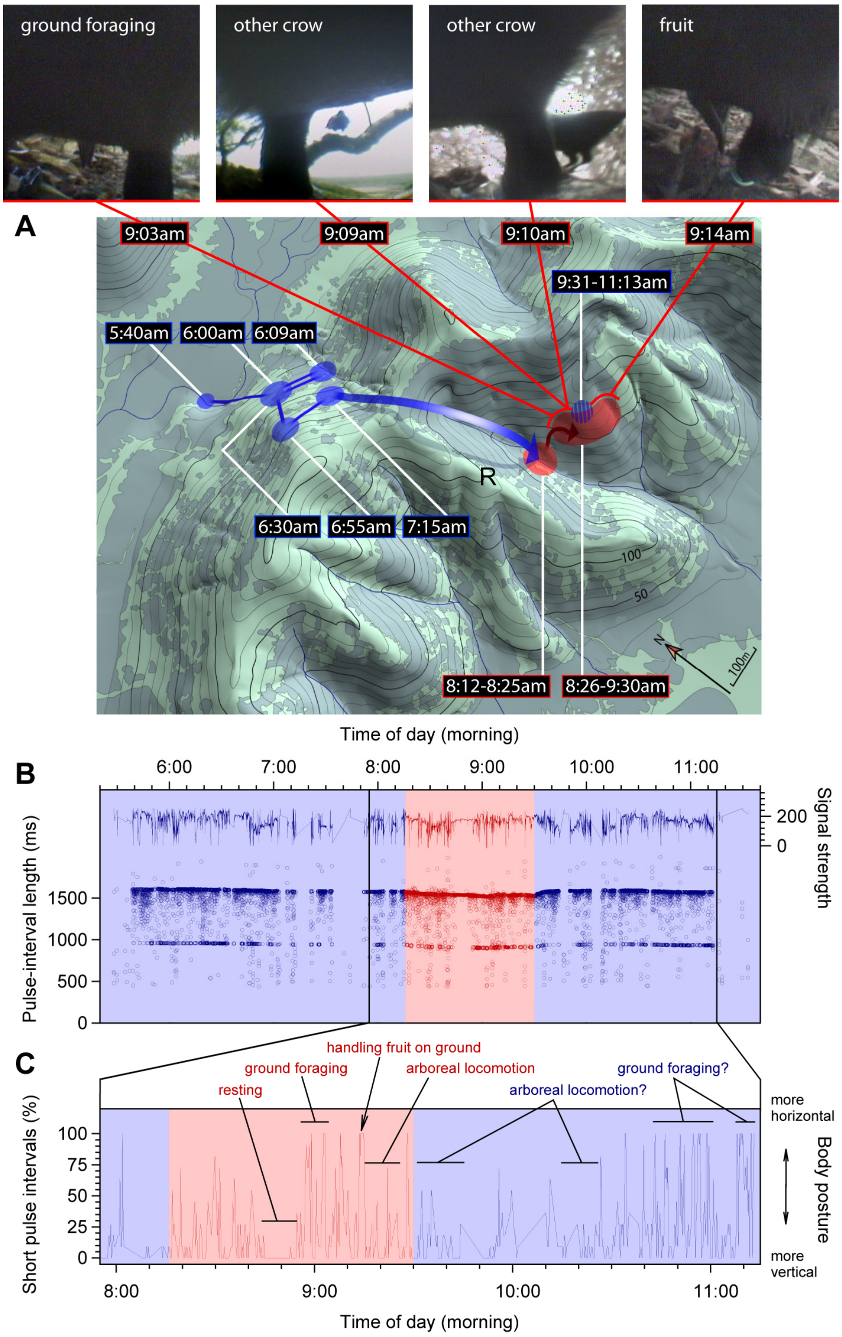

Fig. S2. Calibrating posture-sensitive VHF radio-tags with animal-borne video-cameras (crow: HK5; 23 Feb 2007; video-shoot: 8:16–9:30am; Movie S4). **(A)** Selected activities and three-dimensional foraging trajectory of the bird. For a general description of the tracking set-up, and colors and symbols used in the map, see Fig. 1. The hatched blue circle shows the location of the bird after the video-shoot. **(B)** The VHF radio-tag of this unit was fitted with an additional 'tilt-switch' that toggled the pulse interval between 'long' (1593 ms; tail vertical) and 'short' (953 ms; tail horizontal). Pulse-interval length and a measure of signal strength were logged continuously before (blue), during (red), and after (blue) the video-shoot (n = 10889 qualified radio-pulses). The gap in the data from 7:34–7:52am is due to temporary loss of signal contact when the bird moved over the mountain ridge. **(C)** Relating direct video-observations to pulse-rate patterns. The percentage of short pulse intervals in uninterrupted sequences of 11 radio-pulses as a function of the median time-value of bouts is shown for the time period 7:55–11:15am (n = 569 bouts). Ground-foraging and arboreal locomotion produced distinct signatures in the radio-signal, and comparison of patterns suggests that the bird performed these behaviors again after the video-camera had expired.

Supplementary Movies

Movies S1 to S4 provided on *Science* Online are of considerably lower quality (image resolution 360×240 pixels; frame rate 15 fps; average bit rate 0.3 Mbps) than raw footage (720×480 pixels; 29.97 fps; 25.2 Mbps). High-quality versions of files are available from the authors upon request.

Movies consist of separate ‘scenes’, which are preceded by relevant background information. Most scenes are edits from longer video-sequences. Movie S1 is a compilation of material from different birds, illustrating various behaviors that are referred to in the main and/or the supporting text. Movies S2 to S4 are detailed case studies and provide scenes for one subject each; these movies should be considered as data appendices. The following table lists individual scenes for the four movies.

	Movie S1	**Movie S2**	**Movie S3**	**Movie S4**
	Compilation various subjects	*Case Study 1* crow 'CC1' scenes in temporal order	*Case Study 2* crow 'EK1' scenes in temporal order	*Case Study 3* crow 'HK5' scenes in temporal order
		see Fig. 1, B and C	see Fig. 1D	see fig. S2
Scene				
1	extracting and eating snail	capturing lizard; ground foraging	overlooking study area	flight
2	handling snail	tool manufacture; tool use	manufacturing tool 'A'	ground foraging
3	flight; picking fruit; consumption on ground	capturing lizard	using tool 'A'	ground foraging
4	capturing lizard	ground foraging	flight	branch-to-branch hopping; flight
5	tool use in loose substrate	capturing lizard; long-distance flight	using tool 'B'	other crow in view; flight
6	long-distance transport of tool	eating fruit	walking with tool 'C'	landing on ground next to other crow
7	tool use in dead wood	handling snail	using tool 'C'; prey extraction	handling fruit on ground
8	ground hopping	handling snail	long-distance transport of tool 'C'	branch-to-branch hopping
9	branch-to-branch hopping	flight; picking fruit; consumption on ground	walking with tool 'C'	
10	inter-perch flights	flight; investigating fruit; flight	using tool 'C'	
11		settling at night roost	walking with tool 'C'	
12			walking with tool 'C'	

References and Notes

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S2. R. W. Davis *et al*., *Science* **283**, 993–996 (1999).
S3. T. M. Williams *et al*., *Science* **288**, 133–136 (2000).
S4. A. Takahashi *et al*., *Proc. R. Soc. B (Suppl.)* **271**, S281–S282 (2004).
S5. The wildlife documentary 'Animal Camera' was first screened in 2004 on BBC One (UK). Captive eagles, hawks, falcons and pigeons were trained to wear body harnesses to which camera units could be attached for the brief duration of a shoot.
S6. G. K. Taylor *et al*., paper presented at the 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 8–11 January 2007.
S7. D. T. Blumstein, J. C. Daniel, C. S. Evans, *JWatcher 1.0: An Introductory User's Guide* (2006; www.jwatcher.ucla.edu).
S8. During 471 man-hours of VHF radio-tracking 13 crows in 2006–2007, we observed only 25 instances of food-handling (excluding feeding on carrion and nut-cracking), and 29 cases of tool-handling.
S9. G. R. Hunt, R. D. Gray, *Acta Zool. Sinica (Suppl.)* **52**, 622–625 (2006).
S10. G. R. Hunt, F. Sakuma, Y. Shibata, *Emu* **102**, 283–290 (2002).
S11. During 2006–2007, we used several different survey techniques (e.g., pitfall traps and sweep nets) to assess the abundance of invertebrates in our study area. The results confirm that ground-dwelling and arboreal invertebrate prey are scarce, even during the crows' breeding season. Little is known about the diet composition of other (sub-)tropical corvids, but it seems that most species have access to considerably larger prey (e.g., large lizards, snakes) than New Caledonian crows (*S12*).
S12. D. Goodwin, *Crows of the World* (University of Washington Press, Seattle, ed. 2, 1986).
S13. S. Tebbich, M. Taborsky, B. Fessel, M. Dvorak, *Ecol. Lett.* **5**, 656–664 (2002).
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S17. J. C. Withey, T. D. Bloxton, J. M. Marzluff, in *Radio Tracking and Animal Populations*, J. J. Millspaugh, J. M. Marzluff, Eds. (Academic Press, London, 2001), chap. 3.
S18. During conventional VHF radio-tracking [see (*S8*)], we often located crows on the ground but were generally unable to approach close enough to confirm foraging; in 2006–2007, we observed just seven cases of food-handling on the ground (excluding carrion and nuts).

S19. We thank: J. Watts (British Technical Films, UK) and R. Joyce for help with technology development; S. Blancher (Domaine Provincial de Gouaro-Déva, Province Sud, New Caledonia), and N. Barré and J. Spaggiari (both Société Calédonienne d'Ornithologie, New Caledonia) for invaluable logistical support in New Caledonia; J. Troscianko for field assistance in 2006 and help with artwork; K. Jones for molecular sexing; and P. Rota (Direction des Infrastructures de la Topographie et des Transports Terrestres, New Caledonia) for providing topographic data for 3D-models. Fieldwork was carried out with permissions from the Centre de Recherches sur la Biologie des Populations d'Oiseaux (France) and the Direction des Resources Naturelles (Province Sud, New Caledonia), and was in accordance with the University of Oxford's procedures for local ethical review. We also thank I. Couzin, B. Cresswell (Biotrack Ltd., Dorset, UK), T. Guilford, P. Harvey, B. Sheldon, A. Sugden, A. Thomas and two referees for discussion and/or comments on the manuscript. This study was financially supported by the Biotechnology and Biological Sciences Research Council (UK) (grant BB/C517392/1 to A.K.), the Province Sud, two Rhodes Scholarships (C.R. and L.B.), two Oxford University Vice Chancellors' Fund Awards (C.R. and A.W.), and two Junior Research Fellowships (Linacre College to C.R.; Brasenose College to A.W.).