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How technology can advance the study of animal cognition in the wild

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Research on animal cognition has historically focused on the cognitive capabilities of a limited number of species through controlled laboratory studies. Animal cognition research is now broadening to study diverse taxa in their natural environments, which is facilitating insights into the fitness consequences of cognitive traits and a greater understanding of how ecological and social environments impact the expression of cognitive abilities. Many challenges remain regarding studying cognition in the wild, but recent technological advances have enabled researchers to overcome many of these challenges. Here, we highlight the technological advances leveraged for learning, social cognition, and spatial cognition field research, identify the current limitations of technology and barriers to its widespread use, and discuss promising technologies for field studies of animal cognition.

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Introduction

Studying nonhuman animal cognition, the mechanisms by which animals acquire, process, store, and act on information from their environment [1], in the wild allows researchers to capture the plethora of environmental, social, and metabolic factors that affect animal cognition [2]. This natural, complex variation is difficult to recreate in laboratory settings, and many species are intolerant of the stress and spatial limitations of long-term captivity. As animal cognition studies have moved out of the lab and into the field, insights into the fitness consequences of cognitive traits have flourished [3–7], but some challenges remain. These challenges are compounded as research expands beyond classically studied taxa like nonhuman primates and corvids. Researchers must cope with, for example, the limited visibility of focal individuals (e.g. sensitization to humans, nocturnality, environmental complexity), noncognitive confounds (e.g. neophobia, food motivation, social interference by conspecifics and heterospecifics), and morphological variation across species.

Computer and electronic technologies provide promising avenues to surmount these obstacles and have been increasingly leveraged in recent years to conduct cognitive assessments in the wild. For example, radio frequency identification (RFID), automated operant chambers, global positioning systems (GPS), camera trapping, biologging, and community science have all been successfully utilized in field studies of animal cognition (Table 1) [8–10]. Some advancements in technologies, such as artificial intelligence, miniature sensors, animal-borne cameras, unmanned aerial vehicles, and methodologies like the Internet of Things (IoT), are yet to be used in animal cognition research but show great promise as future directions for researchers. Here, we discuss how technology has been successfully leveraged in cognitive ecology, identify technological methods that have promise for use in animal cognition research, and discuss the limitations and barriers to utilizing technology in field studies of animal cognition.

Learning

Studying how animals learn in the wild helps elucidate the evolution of cognition and its relationship to environmental variables, life-history traits, and fitness [5–7,11]. Learning paradigms frequently require repeated measures of individuals, so studying learning in free-ranging animals comes with several challenges. Pseudoreplication, inconsistent subject participation,

Table 1

A summary of the technologies outlined in this review and their use in learning, social, and spatial cognition research. Examples of studies that have used each type of technology, or where the authors have outlined considerations for the use of each technology, are also indicated. This table does not represent an exhaustive list nor all possible uses of each technology, but rather serves as a quick reference for readers interested in learning more. Additional references can be found in the text.

Common technologies used	Description	Learning	Social	Spatial	Considerations for use	References
GPS Collars/Tags	Animal-mounted collars, tags, or backpacks that record the location of the focal animal across space and time at a fixed rate		X	X	Power supply, size, and weight, terrain effects	[8,24–30,32,33,35,36,38–40,50,52, 63,65,67–69,72,77,78]
RFID	PIT tags that passively interact with scanners or proximity loggers to identify an individual with a unique ID	X	X		Radio and electrical interference, tag size, trigger range, animal size	[2–4,7,9,12–17,24,41,42,52,66]
Automated camera traps	Motion-triggered or scheduled cameras that can record activity at a location	X	X	X	Trigger range, power supply, animal size, camera position, lighting quality, data storage	[18,19,61,62]
Automated operant boxes	Chambers that operate by autonomously identifying individuals from images, collar ID, or RFID and presents animals with a task or training paradigm in the field; often built using Raspberry Pi or Arduino computers	X	X	X	Power supply, habituation, social interference, reward storage capacity	[9,12–17,54,66]
Artificial intelligence/ automatic identification	Algorithm-based identification of individual animals from video or photos of unique or identifiable morphology	X	X	X	Algorithmic training, image quality, identifiable morphology	[18–22,45,52,70]
Physiological biologgers	Sensors that record physiological data such as heart rate, temperature, spatial orientation, acceleration, etc.		X	X	Reliability, power supply, data storage and retrieval, size	[37,38,52,53,65,67]
Automated feeders	Stations that distribute food to individual animals based on an autonomous ID via RFID or other methods	X	X	X	Power supply, habituation, reward storage capacity	[3,4,7,12,15, 41,66]
UAVs	Drone vehicles that can observe and record visual data of remote groups		X	X	Limited data types, flight regulations, power supply, terrain, habituation	[41,42,52]
Community science applications	Internet or smartphone applications that invite members of the public to record animal sightings or behaviors		X	X	User error, habituation, individual or species misidentification, behavior misidentification, biased data collection	[10,46]
Animal-borne cameras	Video or photo cameras mounted to collars or backpacks worn by animals to observe and collect data from the animal's point of view	X	X	X	Power supply, trap–tag–release procedures, data storage and retrieval, video quality	[24,56–58]
Automated audio playback	Systems that autonomously play audio of interest to specific species, groups, or individuals and record animal reactions	X	X		Power supply, incidental triggers, appropriate controls (e.g. white noise), image quality	[61,62]
Untethered neural monitors	Monitors that gather and store data on brain or neuron activity from a free-ranging animal	X		X	Power supply, data storage and retrieval, size and weight, surgical procedures, animal welfare	[47–49]

and external or unknown influences like social interference, seasonal hormone effects, or behavioral variations can all confound learning studies in the field.

Technology can help mitigate these issues. For example, passive integrated transponder (PIT) tag and RFID technologies allow researchers to permanently and reliably identify individual animals and thereby collect critical repeated measures in the field [12,13]. Such techniques have extended field testing of associative and reversal learning to understudied, yet highly adaptive, species like raccoons (*Procyon lotor*) ([14], LA Stanton, PhD thesis, University of Wyoming, 2021). Field investigations of the learning and behavioral flexibility of raccoons and other urban species can inform our understanding of the role of cognition for animals in novel and disturbed environments, such as cities. RFID can be integrated with automation technologies like Arduino [12] and Raspberry Pi computer boards [14,15] to create automated operant chambers that react in real time to animal participants [14,16,17]. These open-source microcontrollers provide researchers with inexpensive, flexible ways to deploy automated cognitive tasks in the field. This is crucial for learning assessments where repeated or incrementing tasks are presented to the same individual over time.

Where PIT tagging or other forms of identification of individual animals are not feasible, machine learning may provide solutions. Using techniques only recently conceivable because of advances in deep learning [18,19], Shukla et al. [20] and Lahiri et al. [21] used machine learning algorithms and the unique nature of tiger (*Panthera tigris*) and zebra (*Equus quagga* and *Equus grevyi*) stripe patterns to identify individuals from camera trap photos. Clapham et al. [22] employed deep learning to individually identify brown bears (*Ursos arctos*) using facial recognition. If these methods can be improved to work reliably on imperfect, partial, or poorly lit images of animals with nuanced differences in morphology, future work can identify individuals without trapping and tagging programs. This would greatly broaden the capacity to study animal learning in a wider variety of taxa.

Spatial cognition

Studying spatial cognition in the wild can illuminate how animals learn and remember where to find resources, recover cached items, and how to migrate over long distances. Historically, spatial cognition research has been conducted in the lab using classic maze paradigms [23], but in the field, researchers must track animal movements across space and time. Researchers frequently employ GPS or very-high-frequency collars, backpacks, implants, or proximity sensors to gather spatial data [24]. These technologies have been used to infer spatial memory [25–27], collective decision-making [28], cognitive maps [29,30], and have potential for use in social–spatial cognition research [31]. For example, Jesmer et al. [8] took advantage of regional extinctions and reintroductions of GPS-collared, North American ungulate species to demonstrate social learning and cultural transmission of migratory routes.

For aquatic species, technologies such as pop-up satellite tags [32] enable study of fishes' movement in both horizontal and vertical space [33], and decreasing tag costs and size provide opportunities for spatiotemporal memory studies in fishes [34]. Other advances in the size and cost of GPS [35,36] and biologging technologies [37,38] provide opportunities for capitalizing on these data types in a broader range of contexts and species (but see [39,40]).

Often, researchers seek to test the limits of spatial cognition in their focal species. In these cases, RFID-enabled automated feeders can be placed in spatial arrays to mimic mazes commonly used in laboratory research [4,41]. Automated feeders can be programmed to allow certain individuals access to predetermined feeders or locations via their unique PIT tags [42], thereby controlling for confounding variables such as side biases and social interference, while simultaneously collecting data on which individual(s) visit and when [12].

Additionally, unmanned aerial vehicles (UAVs) equipped with cameras provide enhanced observations of species that are difficult to detect or observe [43,44] and can be used in conjunction with machine learning to provide high-resolution data on animal movement, perception, and decision-making [45]. Mobile phone applications, such as '*Wingtags*', '*iNaturalist*,' and '*Animal Tracker*', harness community-scientist reports of species locations and behavior [46]. These applications give scientists the opportunity to supplement animal movement with behavioral data via crowdsourcing across animal habitats.

Research on the neural mechanisms underlying spatial cognition is typically conducted in the lab, but recent advances may allow for directly measuring neural mechanisms in free-ranging animals [47]. For example, Vyssotski et al. [48] used GPS and electroencephalogram units to record movement and brain activity concurrently in free-flying pigeons to assess the relationship between brain activity and landmark use. Similarly, Takahashi et al. [49] demonstrated a wireless log for recording extracellular neuron activity of head direction in free-swimming salmonids. In combination with the other technologies discussed in this review, neuron monitors would allow researchers to observe the animal brain under true social and spatial complexities *in situ*; however, researchers must thoroughly consider the potential risks and ethical implications of such invasive procedures before applying them in field studies.

Social cognition

By studying social cognition in the wild, researchers can more accurately capture complex social dynamics and environmental pressures that influence the evolution of animal sociality. Studies of sociality require tracking groups or individuals, observing the often cryptic interactions among individuals, testing the nature of socially transmitted information, and identifying individuals without disrupting group dynamics. While technologies like GPS collars and proximity loggers are used for the study of social cognition (e.g. [8,50–53]), these methods may not be appropriate for all species (Table 1). Other technologies may provide solutions.

Klump et al. [10], for instance, conducted large-scale public surveys to compile community-scientist observations of a novel foraging behavior in free-ranging, urban parrots, and identified cultural transmission of this innovative behavior. Wild et al. [16] used automated puzzle boxes to study network-based diffusion of innovation and problem solving in wild great tits (*Parus major*). Morinay et al. [54] also used an automated problem-solving task to determine the relationship between problem solving and heterospecific social learning in wild bird populations.

Open-access databases offering big-data records or digitized historical data, often too costly to store at the researcher scale, can also advance the study of animal cognition [25]. For example, Whitehead et al. [55] used digitized historical datasets and found that sperm whales (*Physeter macrocephalus*) likely socially learned to change defensive behaviors to avoid whalers' harpoons. Moreover, animal-borne cameras provide researchers an opportunity to observe social, feeding, and movement behaviors [56–58]. These information-rich data provide insight into the causal relationships between social encounters and subsequent movement behaviors, which lays the groundwork for studies of group decision-making, cooperation, and social learning [59]. Lastly, playback experiments, a staple of social cognition research [60], can be conducted using camera traps that automatically play audio clips when triggered and record subjects' behavioral responses [61].

Barriers and solutions to widespread technology use in animal cognition

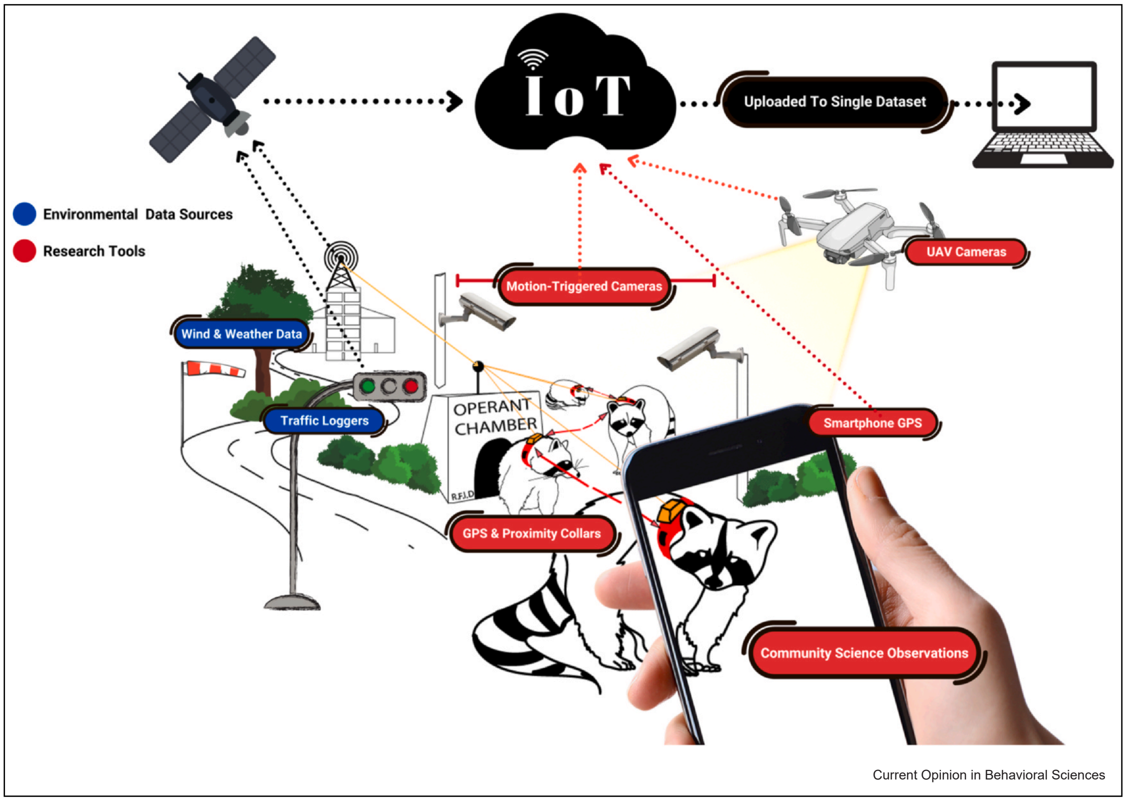
Any field that uses technology contends with inherent limitations. Researchers must consider issues with the reliability, cost, and deployment of cameras, GPS, and RFID systems. Motion-sensor camera traps may trigger at undesirable rates [62]; GPS collars have variable fix rates based on terrain, are limited by battery life, and require minimum body weights [63–65]; and RFID systems have issues with radio interference and inconsistent trigger rates [66]. These limitations can restrict experimental designs.

In some cases, the continued development of technology will increase the usability of these methods in the field. For example, battery-powered GPS collars are too heavy for some species (i.e. the 5% rule), and alternative options like solar-powered GPS collars are infeasible for species that are often occluded from the sun. However, advances in battery size and life will result in lighter collars that will satisfy the 5% rule (but see [65]), thereby expanding spatial cognition research to a broader range of taxa. For example, the International Cooperation for Animal Research Using Space (ICARUS) Initiative [67] has created a global animal-movement tracking system using miniature transmitters to expand movement ecology to new and understudied species. Additionally, Bluetooth low-energy technologies, where small, power-efficient units utilize Bluetooth connections to transmit data between animal-mounted units and stationary loggers over short distances, could create compact, energy-efficient tags for smaller species [68].

Moreover, the increasing ubiquity of technology means that more community scientists will be able to contribute to animal cognition research, which may provide solutions to large-scale data collection in some circumstances. Further, the increase in technology in the commercial hunting, fishing, and pet-care markets has made camera traps, GPS pet-tracking collars, pet cameras, and accelerometer collars much more accessible to the average user. Studies like Massa et al. [69], which used a commercially available pet-tracking collar to record the movements of a wild barn owl (*Tyto alba*), demonstrate the efficacy of these relatively inexpensive technologies in wildlife research.

The pervasiveness of technology also provides the potential to harness existing technological infrastructure for cognition research using an IoT approach [70–72]. IoT is a method of data collection using a network of independent sensors that can communicate to a central hub to consolidate information efficiently across different software, hardware, and management entities. By using existing technological infrastructure, researchers can supplement their study-specific sensors to gain a holistic view of the biotic and abiotic stimuli affecting the cognition and behavior of wild animals (Figure 1). For example, Figure 1 shows collared, PIT-tagged raccoons interacting with an RFID-enabled automated operant chamber. The data gathered by the GPS and proximity collars can provide insights into spatial memory and social learning, weather and traffic sensors can provide measures of environmental variables that may impact an individual's learning performance, and the GPS location of a mobile phone user could supply

Figure 1



An IoT approach to animal cognition in the field. Here, we illustrate how a researcher can integrate an RFID-enabled operant chamber, GPS and proximity collars, motion-triggered, night-vision cameras, UAV cameras, community-scientist observations, smartphone GPS, traffic loggers, and environmental data from wind and weather sensors. All data are automatically uploaded to a single dataset for future analysis. This allows the researcher to access the plethora of environmental and social variables that impact animals' cognitive performance.

data on whether raccoon behavior is influenced by human presence. By harnessing an IoT approach in this way, scientists could greatly reduce their financial and management burdens.

The methodological and commercial availability of these technologies is not the only barrier to their widespread use in animal cognition. Major barriers across the animal cognition community exist with regard to technological and digital literacy, equity of inclusion, and access to often expensive technologies. Without providing access and targeted programs for historically excluded communities, technological methods and resources that can advance the study of animal cognition will continue to be held by those traditionally granted power and privilege.

Targeted efforts in institutions teaching animal cognition and behavior can advance student digital and technological literacy. While contemporary students are often assumed to be technologically or digitally literate, this may not be true for all [73]. Thus, technology courses should be woven into curriculums whenever possible. Without proper exposure to or training with current and novel technologies, adoption of technology in the study of animal cognition will remain limited.

As field research expands globally, greater effort should be made to recruit and support local faculty, student, and community member involvement in field cognition studies [74–76]. This inclusion will diversify questions and approaches in the study of animal cognition and should be a targeted goal of all research institutions, especially those pursuing research outside of their local community.

Lastly, the costs related to utilizing novel technologies can be a large barrier to access. Currently, the time, effort, and expenses associated with many technologies, such as GPS collars or do-it-yourself (DIY) units, remain high [39,77,78]. Further, disparities in cellular and satellite coverage can limit the application of some methodologies discussed here as they often rely on existing technological infrastructure. This means that the technology needed to monitor wildlife for cognition studies, especially to achieve large sample sizes, can be resource prohibitive. Cognitive ecologists should prioritize utilizing open-access technologies, such as Arduino and Raspberry Pi, publish the code and plans for constructing cognitive testing devices used in the wild [79], and translate these materials into local languages if studies are done abroad. Making schematics, program code, and other detailed methods openly available to all researchers will greatly decrease the time and effort required to create a DIY or specialized sensor. Though by no means an exhaustive list of the issues stemming from inequality within our scientific community, these are starting points for animal cognition scientists to improve the accessibility of their research and technology.

Conclusions

Advanced technologies offer tools that animal cognition researchers can adapt for use in the field. RFID-enabled operant chambers, GPS, and platforms for community science have been recently used in cognitive assessments of wild animals. Technologies like active neuron sensors, affordable and miniature GPS tags, animal-borne cameras, artificial intelligence, UAVs, and methodologies like IoT may soon be adapted for use in field cognition studies. Despite the exciting advancements provided by technology, researchers require open, equitable access to these technologies to apply them in a multitude of environments. In some cases, technological developments may resolve inequalities, while in other cases, the burden of action lies on advantaged scientists and communities. Insights into nonhuman animal cognition in the field will allow researchers to fully understand how animals respond when exposed to ecologically relevant conditions and stimuli. Although cognition has been notoriously difficult to study in the wild, current and future technology provide an exciting path forward.

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Author contributions

Hannah J. Griebling: Writing – original draft, Investigation, Conceptualization, Project administration. **Christina M. Sluka**: Writing – original draft, Investigation, Conceptualization. **Lauren A. Stanton**: Writing — review & editing, Conceptualization. **Lisa P. Barrett**: Writing — review & editing, Conceptualization. **Jaylen B. Bastos**: Writing — review & editing, Visualization, Conceptualization. **Sarah Benson-Amram**: Writing – review & editing, Conceptualization, Supervision.

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Nothing declared.

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