Using Robots to Understand Animal Cognition

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Abstract

In recent years, robotic animals and humans have been used to answer a variety of questions related to behavior. In the case of animal behavior, these efforts have largely been in the field of behavioral ecology. They have proved to be a useful tool for this enterprise as they allow the presentation of naturalistic social stimuli whilst providing the experimenter with full control of the stimulus. In interactive experiments, the behavior of robots can be controlled in a manner that is impossible with real animals, making them ideal instruments for the study of social stimuli in animals. This paper provides an overview of the current state of the field and considers the impact that the use of robots could have on fundamental questions related to comparative psychology: namely, perception, spatial cognition, social cognition, and early cognitive development. We make the case that the use of robots to investigate these key areas could have an important impact on the field of animal cognition.

Key words: Robot, Animal cognition, Perception, Spatial Cognition, Social Cognition, Developmental Cognition
Robots have the potential to transform the field of social cognition. In particular, key features of robots can be manipulated in systematic ways to explore perception, social learning, and cognitive development in repeatable and comparable ways across the animal kingdom. In this paper, we make the case for the importance of using robots to investigate fundamental questions in the field of animal social cognition.

Several reviews have been written concerning the study of social behavior using robots that consider the issues from a robotics perspective (Balch, Dellaert, & Feldman, 2006; Fong, Nourbakhsh, & Dautenhahn, 2003); biology and robotics have influenced each other to investigate and improve the intelligence and cognitive capabilities of robotic systems (Adams, Breazeal, Brooks, & Scassellati, 2000; Brooks, 1991). A separate body of work has also successfully used robots to investigate social interactions from a behavioral ecological perspective (for reviews, see Krause, Winfield, & Deneubourg, 2011; Miklósi & Gácsi, 2012; Mitri, Wischmann, Floreano, & Keller, 2013). However, these techniques also offer novel and exciting prospects for studying the cognitive mechanisms underlying a variety of complex behaviors, particularly relating to social cognition; they have yet to be exploited in the field of comparative cognition. This paper will provide an overview of the current state of the field and make the case for the use of robots to investigate a variety of questions fundamental to our understanding of animal cognition.

Throughout this paper, we will be using the term ‘robot’ for different types of mechanical devices – from the very simple to the very complex – most of which have been described by their creators as robots. We acknowledge that there are different ways to define what constitutes a robot, but we have decided to use the term loosely for reasons of readability and simplicity.

Perception of Social Stimuli

As humans, we primarily rely on vision to perceive and assess other members of our species; however, animals may use a variety of different senses when evaluating novel stimuli. Understanding the sensory systems of animals and how they perceive their environment and process the information they glean from it, is a fundamental question in the field of comparative cognition. It is one that can be examined effectively using robots, but also one that is essential to understand in order to create appropriate robotic counterparts to investigate other cognitive questions.

Traditional methods for investigating the cues used by animals to mediate their social interactions generally involve exposing a test animal to a stimulus and observing its reactions, either to the stimulus alone or to changes in some of the stimulus’ features. Under these circumstances, the use of live animals has inherent constraints. Bidirectional interactions between the stimulus animal and
the test animal may make the data, at best, noisy, at worst, unusable. Furthermore, to investigate
key issues – such as the influence of visual and olfactory cues on conspecific recognition – one might
wish to experimentally manipulate a stimulus animal’s color or mask its natural odor. This is
problematic with live animals as, not only is it difficult to control the stimulus of interest (e.g., an
animal’s natural odor may begin to mask an artificial chemical stimulus over time), but the
manipulation may influence the stimulus animal’s behavior, thereby making it impossible to
determine what is responsible for any changes observed in the test animal’s behavior (D’Eath, 1998).
Consequently, it is common to use video stimuli to investigate perception in animals. Of course, this
limits experiments to the visual modality; however, it does provide consistent stimuli and allows
manipulation of color (e.g., Clark & Uetz, 1993; McKinnon, 1995), shape, size (e.g., McClintock &
Uetz, 1996), and speed of movement (e.g., Evans, Macedonia, & Marler, 1993). Further, stimuli can
readily be altered and/or additional information inserted into the video (e.g. Shashar, Rosenthal,
Caras, Manor, & Katzir, 2005).
To humans, video stimuli appear to be realistic representations of the real entity that they present
(e.g., Spetch, Cheng, & MacDonald, 1996). However, there may be issues with the visual stimulus as
it is presented. An animal’s perception of a video might differ greatly from that of a human (Baldauf,
Kullmann, & Bakker, 2008; Fleishman & Endler, 2000; Oliveira et al., 2000). Although some studies
have revealed no differences in behavioral responses toward real animals and video images of those
animals (e.g., Clark & Uetz, 1990; Ikebuchi & Okanoya, 1999; Macedonia & Stamps, 1994; Shimizu,
1998), others have shown the opposite to be true (D’Eath & Dawkins, 1996; Dawkins, Guilford,
Braithwaite, & Krebs, 1996; Dawkins, 1996). Computer monitors are designed to recreate color
images for human trichromatic vision and might therefore appear unrealistic to animals with a
different number of cone classes or cones with different spectral sensitivity (e.g., birds, Cuthill &
Bennett, 1993; reptiles, Fleishman, Loew, & Leal, 1993, and fish, McFarland & Loew, 1994; Rick,
Modarressie, & Bakker, 2006). The restriction of the monitor’s gamut to the human perceptual range
also makes it impossible to test ‘hidden’ visual attributes involving ultraviolet, infrared, or polarized
light (Baldauf et al., 2008; D’Eath, 1998).
Motion perception may also be limited by the use of video. Although for humans around 24 frames
per second are required to make motion in a video seem fluent, many animals have a higher flicker
fusion threshold (see Healy, McNally, Ruxton, Cooper, & Jackson, 2013); they might thus perceive a
video as a series of static, ‘strobed’ images. Further, videos also lack depth information (see D’Eath,
1998). Although with extensive training pigeons (*Columba livia*) are able to respond to changes in
depth cues of two-dimensional images, such as shading patterns or texture gradients (Cavoto &
other species might struggle to readily extract this information from two-dimensional stimuli. The use of robots allows us to circumvent these problems. It is possible, for example, to change as many perceptual features of a robot as required; further, different modalities of perceptual cues can be presented in different combinations. Exchangeable skins or body parts allows alteration of the visual stimulus (Kubinyi et al., 2004; Macedonia, Clark, Riley, & Kemp, 2013), whilst olfactory information can be manipulated by applying chemicals or odors from real animals (Asadpour, Tâche, Caprari, Karlen, & Siegwart, 2006; Carazo, Font, & Desfilis, 2008; López & Martín, 2002). Speed and movement can also be readily altered (although realistic movement may be difficult to replicate for some species) as can auditory information, for instance by being presented via embedded speakers. Further, these cues can be manipulated individually, all together, or in different combinations, in a highly repeatable way.

Perception of robots

The perceptual information that is important for a robot to be treated as a conspecific depends on the species of study. Motion, for example, seems to be a key factor in conspecific recognition, as studies comparing rats’ reactions to moving and immobilized conspecifics show (Alberts & Galef, 1973).

Animals’ skins have been used as a basis for a number of robots (Butler & Fernández-Juricic, 2014; Fernández-Juricic, Gilak, McDonald, Pithia, & Valcarcel, 2006; Partan et al., 2010; Partan et al., 2009; Patricelli et al., 2006; Patricelli & Krakauer, 2010; Rundus et al., 2007) (see Figure 1), effectively eliminating issues relating to color and body shape. Alternatively, synthetic ‘skins’ and body parts can be recreated artificially, for example, by 3D printing them or by making them from latex, and also color-matching robots to live conspecifics, taking into account the reflectance spectra of color patterns present on live animals and recreating them (Macedonia et al., 2013).

Replicas may be easier to create for some species than others. Care has to be taken in their design; for example, robots that are perceived to be very similar to a real conspecific, but not similar enough to be mistaken for one can evoke fearful behavior or disgust in humans. This is known as the uncanny valley effect (Mori, 1970) and has also been observed in macaques (Macaca fascicularis) presented with synthetic conspecific faces (Steckenfinger & Ghazanfar, 2009).

When interacting with a robot, visual information plays an important role (e.g., Faria et al., 2010). In particular, shape (e.g., Abaid, Bartolini, Macri, & Porfiri, 2012; Polverino and Porfiri 2013) and color
interactions with robots in many species. Movement patterns (Göth & Evans 2004), particularly
responsiveness toward another’s movement (Kopman, Laut, Polverino, & Porfiri, 2012; Polverino,
Phamduy, & Porfiri, 2013), also play a key role. However, robots do not necessarily have to be
visually similar to the test species: two-dimensional three-spined stickleback (Gasterosteus
aculeatus) replicas are sufficient to recruit conspecifics to follow them (Sumpter et al 2008), and
cockroaches (Periplaneta americana) will direct appropriate natural behaviors towards a box on
wheels when cockroach semiochemicals are applied to it (Asadpour, Tâche, Caprari, Karlen, &
Siegwart, 2006; Halloy et al., 2007). The salience of different cues does appear to depend on
individual experience (Partan, Fulmer, Gounard, & Redmond, 2010).

Responses toward robots can be altered through administration of drugs. Caffeine, for instance,
makes zebrafish (Danio rerio) more sensitive to a robotic conspecific’s movements; ethanol causes a
decrease in the fish’s attraction toward a robot that was modelled after a fertile female (Ladu,
Mwaffo, Li, Macrì, & Porfiri, 2015; Spinello, Macrì, & Porfiri, 2013), making this species ideal for
investigating the effects of drugs on social interactions and cognition.

Social Interactions

Robots have been used extensively to investigate social interactions, with a focus on group behavior
and social dynamics. They appear to be extremely effective for this sort of task and have been used
to manipulate group behavior in terms of shelter choice (cockroaches Periplaneta americana,
Asadpour et al., 2006; Halloy et al., 2007), inter-individual distances, shoal orientation (sticklebacks
Gasterosteus aculeatus, Faria et al., 2010), and foraging behavior (house finches Haemorhous
Observation of interactions with conspecifics or humans also modulates an animal’s responses
toward a robot (dogs Canis lupus familiaris, Lakatos et al 2014).

A particular focus has been the study of mating behavior; the use of robots allows investigation into
the relative importance of different cues for mating success in a manner that would be impossible to
study using other methods. Robots can be used to investigate the features relevant for mate choice
(e.g., Patricelli et al., 2006; Patricelli & Krakauer, 2010) (Figures 1a and 1b), which then allows the
manipulation of mate value. For example, visual input is important, but specific salient features—
such as the size and movement of the fiddler crab (Uca mjoebergi) arm (Reaney, Sims, Sims,
Jennions, & Backwell, 2008; Reaney, 2009) or the inflation of the Túngara frog (Physalaemus
pustulosus) throat pouch (Klein, Stein, & Taylor, 2012; Taylor, Klein, Stein, & Ryan, 2008) (Figure 1c)—
appear to be more relevant than the use of a realistic model. This information is a crucial prerequisite to examining the costs and benefits of mate choice (e.g. Booksmythe, Detto, & Backwell, 2008).

Another good example is the study of headbobbing displays in lizards. These function as both aggressive and mating displays and can readily be elicited by a headbobbing robot (brown anolis *Anolis sangrei*, Partan et al. 2011; sagebrush lizards *Sceloporus graciosus*, Smith & Martins 2006). Use of robots can assess male competition (e.g. sagebrush lizards *Sceloporus graciosus*, Martins et al 2005), female choice (Martins et al 2005), factors that influence communication (*Anolis gundlachi*, Ord & Stamps, 2008), and even species discrimination (*Microlophus grayii* and *Microlophus indefatigabilis*, Clark et al 2015; *Anolis grahami*, Macedonia, Clark, Riley, & Kemp, 2013; Macedonia & Stamps, 1994; *Anolis gundlachi*, Ord & Stamps, 2009) (Figure 1d).

### Spatial cognition

We have a fairly good understanding of the mechanisms underlying spatial navigation in a number of species. Roboticsists use this information to construct robots with similar ‘skills’ (e.g. Möller, Lambrinos, Pfeifer, & Wehner 2001) with the aim of making robots more efficient navigators. Although this work provides clear benefits for robotics research and engineering, it also offers insights into animal cognition. Robots are useful for investigating the perceptual and neurological bases for navigation and spatial cognition by replicating the mechanisms behind them or reverse engineering typical behaviors of animals (Milford, Wyeth, & Prasser, 2004).

Robots may also be useful to investigate spatial tasks in groups of animals. When searching for a food source, rats (*Rattus norvegicus*) not only remember the locations that they have previously visited, but they are also able to remember the locations that another rat has visited and avoid repeated visits to these sites (Brown, 2011; Keller & Brown, 2011). The use of robotic animals in these types of experiments would make it possible to control for many factors such as scent traces, patterns and orders of visiting the locations, as well as the behavioral interactions between animals.

### Social learning and use of social cues

The transfer of complex behavioral information (as opposed to specific stimuli, such as isolated vocalizations) between individuals has typically been studied using live animals. For example, in studies on social learning, demonstrators are often trained to perform particular behaviors and then the ability of naive observers to acquire the behavior through observation is tested. This approach has shown that a surprisingly wide variety of species can, through observation alone, acquire
sophisticated behavioral information from conspecifics with sufficient accuracy for them to repeat the behavior themselves (e.g., birds, Fritz & Kotrschal, 1999; Todt, 1975; reptiles, Kis, Huber, & Wilkinson, 2014; Wilkinson, Kuenstner, Mueller, & Huber, 2010; fish, Brown & Laland, 2003; mammals, Call, Carpenter, & Tomasello, 2005). However, the experimental paradigm of using live demonstrators imposes limitations on the ability to extract information on the mechanisms of information transmission. In particular, there is a need for demonstrators to perform behaviors with sufficient accuracy and repeatability to allow others to learn from them, and so that all observers have the potential to receive the same information.

More generally, ‘noise’ in the information (caused, for example, by variation in the proficiency with which a demonstrator performs a task or variation in the information accessible to the naive animal, perhaps because of visual occlusion) is a factor largely outside the experimenter’s control, and often extremely difficult to quantify. Therefore, although animals can undoubtedly extract relevant information in order to learn demonstrated behaviors, it is often unclear (a) whether variation in learning ability stems from the demonstrator or the learner and (b) to which specific aspects of a complex behavioral repertoire the learner is responding.

Robots represent an ideal solution to these problems. They can perform realistic and repeatable behaviors under tight experimental control, thereby engendering consistency in the information available to observers (or imposing experimentally-manipulated noise on the information) and allowing specific aspects of behavior to be controlled independently.

Despite the clear advances that the use of robots could bring this field, very few studies have used robots in this context. A single study has examined gaze following using a robotic counterpart and found it to be effective. European starlings (Sturnus vulgaris) focused their attention to a specific location in response to changes in the orientation behavior of a robotic bird (Butler & Fernández-Juricic, 2014) (Figure 1f). In contrast, dogs had difficulty following the pointing gestures given by a humanoid robot (Lakatos et al 2014) and performed at a significantly lower level with the pointing robot than with a pointing human, while chimpanzees interacted socially with humanoid robots, especially when the robot was imitating them (Davila-Ross et al., 2013).

One possible reason for the scarcity of these sorts of studies is the fact that, although the use of robots eliminate the unreliability that comes with using a live demonstrator, other issues might arise. Replicating accurate visual information and movement is inherently difficult, and, in some cases, may lead to similar perceptual issues to those highlighted above. Further, mechanical properties such as noisy motors may also be disturbing for the animal. Nevertheless, we believe that, with advances in
technology and in our understanding of animal perception and, with the choice of suitable model species, many of these issues can be overcome.

Clearly, much further work is necessary in this area. However, robots provide the control with which to answer mechanistic questions about information transfer; they also allow us to manipulate the quality and reliability of that information and investigate the impact of, for example, familiarity of the demonstrator, unreliable demonstrators, or partial demonstrations.

**Early experience and cognitive development**

Robots can also be used to study the ontogeny of cognitive and behavioral traits in animals. It is theoretically possible to fully control an animal’s experiences by exposing it to one or several robotic animals from birth. It has been shown, for example, that chicks (*Gallus gallus domesticus*) will readily imprint on a robot (Gribovskiy, Halloy, Deneubourg, Bleuler, & Mondada, 2010); this can allow manipulations which may have powerful effects on cognition. Japanese quail chicks (*Coturnix japonica*) that were raised with a heated robot (simulating the hen) that was mobile for 1 h per day showed better spatial abilities and more exploration in an arena than did control birds that were exposed to an immobile heater (De Margerie, Lumineau, Houdelier, & Richard Yris, 2011) (Figure 1e). Thus, small differences in the rearing conditions can have profound effects on the development of crucial cognitive skills.

The use of robots allows investigation into the role of early experience on cognitive development in a systematic and controlled manner. Robots allow the possibility of investigating some key developmental questions and make it possible to distinguish genetic predispositions from learned behaviors. For example, the parent robot could perform behaviors that are not naturally within the animal’s repertoire, behave in ways that are contradictory to how adult animals usually behave, or manipulate foraging choices.

As well as investigating the development of aspects of cognition already considered in this article, key questions relating to development of an animal’s physical understanding can be investigated using robots in which these properties are manipulated. Doing so will allow the controlled examination of fundamental questions related to folk physics, including the cognitive development of concepts such as gravity, solidity, occlusion, and containment.

**Conclusions**
Robots present an exciting prospect for future studies in the field of animal cognition. If designed correctly, they would allow a fine level of control over both the information provided in experimental manipulations and, potentially, the general environment that an animal experiences. Using robots in behavioral experiments will allow us to gain insight into questions in comparative psychology, which, until now, have not been possible to ask. This interdisciplinary work should permit novel and exciting avenues of investigation and expand the boundaries of animal cognition research.

References


Fig.1: Examples of robots that have been used in studies interacting with animals. (a) robotic female bower bird (*Ptilonorhynchus violaceus*) with controls (Patricelli et al., 2006); (b) robotic female greater sage grouse (*Centrocercus urophasianus*) (Patricelli & Krakauer, 2010); (c) robotic túngara frog (*Physalaemus pustulosus*) (Klein et al., 2012); (d) *Anolis gundlachi* interacting with a robotic anolis (Ord & Stamps, 2008, 2009); (e) Japanese quail chicks (*Coturnix coturnix japonica*) interacting with a robotic hen (de Margerie et al., 2011); (f) robotic European starling (*Sturnus vulgaris*) (Butler & Fernández-Juricic, 2014).