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Using Robots to Understand Animal Cognition

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28 **Abstract**

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

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41 Key words: Robot, Animal cognition, Perception, Spatial Cognition, Social Cognition, Developmental
42 Cognition

43 Robots have the potential to transform the field of social cognition. In particular, key features of
44 robots can be manipulated in systematic ways to explore perception, social learning, and cognitive
45 development in repeatable and comparable ways across the animal kingdom. In this paper, we make
46 the case for the importance of using robots to investigate fundamental questions in the field of
47 animal social cognition.

48 Several reviews have been written concerning the study of social behavior using robots that consider
49 the issues from a robotics perspective (Balch, Dellaert, & Feldman, 2006; Fong, Nourbakhsh, &
50 Dautenhahn, 2003); biology and robotics have influenced each other to investigate and improve the
51 intelligence and cognitive capabilities of robotic systems (Adams, Breazeal, Brooks, & Scassellati,
52 2000; Brooks, 1991). A separate body of work has also successfully used robots to investigate social
53 interactions from a behavioral ecological perspective (for reviews, see Krause, Winfield, &
54 Deneubourg, 2011; Miklósi & Gácsi, 2012; Mitri, Wischmann, Floreano, & Keller, 2013). However,
55 these techniques also offer novel and exciting prospects for studying the cognitive mechanisms
56 underlying a variety of complex behaviors, particularly relating to social cognition; they have yet to
57 be exploited in the field of comparative cognition. This paper will provide an overview of the current
58 state of the field and make the case for the use of robots to investigate a variety of questions
59 fundamental to our understanding of animal cognition.

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

64

65 **Perception of Social Stimuli**

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

72 Traditional methods for investigating the cues used by animals to mediate their social interactions
73 generally involve exposing a test animal to a stimulus and observing its reactions, either to the
74 stimulus alone or to changes in some of the stimulus’ features. Under these circumstances, the use
75 of live animals has inherent constraints. Bidirectional interactions between the stimulus animal and

76 the test animal may make the data, at best, noisy, at worst, unusable. Furthermore, to investigate
77 key issues – such as the influence of visual and olfactory cues on conspecific recognition – one might
78 wish to experimentally manipulate a stimulus animal’s color or mask its natural odor. This is
79 problematic with live animals as, not only is it difficult to control the stimulus of interest (e.g., an
80 animal’s natural odor may begin to mask an artificial chemical stimulus over time), but the
81 manipulation may influence the stimulus animal’s behavior, thereby making it impossible to
82 determine what is responsible for any changes observed in the test animal’s behavior (D’Eath, 1998).

83 Consequently, it is common to use video stimuli to investigate perception in animals. Of course, this
84 limits experiments to the visual modality; however, it does provide consistent stimuli and allows
85 manipulation of color (e.g., Clark & Uetz, 1993; McKinnon, 1995), shape, size (e.g., McClintock &
86 Uetz, 1996), and speed of movement (e.g., Evans, Macedonia, & Marler, 1993). Further, stimuli can
87 readily be altered and/or additional information inserted into the video (e.g. Shashar, Rosenthal,
88 Caras, Manor, & Katzir, 2005).

89 To humans, video stimuli appear to be realistic representations of the real entity that they present
90 (e.g., Spetch, Cheng, & MacDonald, 1996). However, there may be issues with the visual stimulus as
91 it is presented. An animal’s perception of a video might differ greatly from that of a human (Baldauf,
92 Kullmann, & Bakker, 2008; Fleishman & Endler, 2000; Oliveira et al., 2000). Although some studies
93 have revealed no differences in behavioral responses toward real animals and video images of those
94 animals (e.g., Clark & Uetz, 1990; Ikebuchi & Okanoya, 1999; Macedonia & Stamps, 1994; Shimizu,
95 1998), others have shown the opposite to be true (D’Eath & Dawkins, 1996; Dawkins, Guilford,
96 Braithwaite, & Krebs, 1996; Dawkins, 1996). Computer monitors are designed to recreate color
97 images for human trichromatic vision and might therefore appear unrealistic to animals with a
98 different number of cone classes or cones with different spectral sensitivity (e.g., birds, Cuthill &
99 Bennett, 1993; reptiles, Fleishman, Loew, & Leal, 1993, and fish, McFarland & Loew, 1994; Rick,
100 Modarressie, & Bakker, 2006). The restriction of the monitor’s gamut to the human perceptual range
101 also makes it impossible to test ‘hidden’ visual attributes involving ultraviolet, infrared, or polarized
102 light (Baldauf et al., 2008; D’Eath, 1998).

103 Motion perception may also be limited by the use of video. Although for humans around 24 frames
104 per second are required to make motion in a video seem fluent, many animals have a higher flicker
105 fusion threshold (see Healy, McNally, Ruxton, Cooper, & Jackson, 2013); they might thus perceive a
106 video as a series of static, ‘strobed’ images. Further, videos also lack depth information (see D’Eath,
107 1998). Although with extensive training pigeons (*Columba livia*) are able to respond to changes in
108 depth cues of two-dimensional images, such as shading patterns or texture gradients (Cavoto &

109 Cook, 2006; Cook & Katz, 1999; Cook, Qadri, Kieres, & Commons-Miller, 2012; Reid & Spetch, 1998),
110 other species might struggle to readily extract this information from two-dimensional stimuli.

111 The use of robots allows us to circumvent these problems. It is possible, for example, to change as
112 many perceptual features of a robot as required; further, different modalities of perceptual cues can
113 be presented in different combinations. Exchangeable skins or body parts allows alteration of the
114 visual stimulus (Kubinyi et al., 2004; Macedonia, Clark, Riley, & Kemp, 2013), whilst olfactory
115 information can be manipulated by applying chemicals or odors from real animals (Asadpour, Tâche,
116 Caprari, Karlen, & Siegwart, 2006; Carazo, Font, & Desfilis, 2008; López & Martín, 2002). Speed and
117 movement can also be readily altered (although realistic movement may be difficult to replicate for
118 some species) as can auditory information, for instance by being presented via embedded speakers.
119 Further, these cues can be manipulated individually, all together, or in different combinations, in a
120 highly repeatable way.

121

122 **Perception of robots**

123 The perceptual information that is important for a robot to be treated as a conspecific depends on
124 the species of study. Motion, for example, seems to be a key factor in conspecific recognition, as
125 studies comparing rats' reactions to moving and immobilized conspecifics show (Alberts & Galef,
126 1973).

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

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

139 When interacting with a robot, visual information plays an important role (e.g., Faria et al., 2010). In
140 particular, shape (e.g., Abaid, Bartolini, Macrì, & Porfiri, 2012; Polverino and Porfiri 2013) and color

141 (e.g., Göth & Evans 2004; Polverino, Phamduy, & Porfiri, 2013) appear to be crucial in mediating
142 interactions with robots in many species. Movement patterns (Göth & Evans 2004), particularly
143 responsiveness toward another's movement (Kopman, Laut, Polverino, & Porfiri, 2012; Polverino,
144 Phamduy, & Porfiri, 2013), also play a key role. However, robots do not necessarily have to be
145 visually similar to the test species: two-dimensional three-spined stickleback (*Gasterosteus*
146 *aculeatus*) replicas are sufficient to recruit conspecifics to follow them (Sumpter et al 2008), and
147 cockroaches (*Periplaneta americana*) will direct appropriate natural behaviors towards a box on
148 wheels when cockroach semiochemicals are applied to it (Asadpour, Tâche, Caprari, Karlen, &
149 Siegwart, 2006; Halloy et al., 2007). The salience of different cues does appear to depend on
150 individual experience (Partan, Fulmer, Gounard, & Redmond, 2010).

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

156

157 **Social Interactions**

158 Robots have been used extensively to investigate social interactions, with a focus on group behavior
159 and social dynamics. They appear to be extremely effective for this sort of task and have been used
160 to manipulate group behavior in terms of shelter choice (cockroaches *Periplaneta americana*,
161 Asadpour et al., 2006; Halloy et al., 2007), inter-individual distances, shoal orientation (sticklebacks
162 *Gasterosteus aculeatus*, Faria et al., 2010), and foraging behavior (house finches *Haemorhous*
163 *mexicanus*, Fernández-Juricic et al 2006; and bees *Apis mellifera carnica*, Landgraf et al 2011; 2012).
164 Observation of interactions with conspecifics or humans also modulates an animal's responses
165 toward a robot (dogs *Canis lupus familiaris*, Lakatos et al 2014).

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

174 appear to be more relevant than the use of a realistic model. This information is a crucial prerequisite
175 to examining the costs and benefits of mate choice (e.g. Booksmythe, Detto, & Backwell, 2008).

176 Another good example is the study of headbobbing displays in lizards. These function as both
177 aggressive and mating displays and can readily be elicited by a headbobbing robot (brown anolis
178 *Anolis sangrei*, Partan et al. 2011; sagebrush lizards *Sceloporus graciosus*, Smith & Martins 2006). Use
179 of robots can assess male competition (e.g. sagebrush lizards *Sceloporus graciosus*, Martins et al
180 2005), female choice (Martins et al 2005), factors that influence communication (*Anolis gundlachi*,
181 Ord & Stamps, 2008), and even species discrimination (*Microlophus grayii* and *Microlophus*
182 *indefatigabilis*, Clark et al 2015; *Anolis grahami*, Macedonia, Clark, Riley, & Kemp, 2013; Macedonia &
183 Stamps, 1994; *Anolis gundlachi*, Ord & Stamps, 2009) (Figure 1d).

184

185 **Spatial cognition**

186 We have a fairly good understanding of the mechanisms underlying spatial navigation in a number of
187 species. Roboticists use this information to construct robots with similar 'skills' (e.g. Möller,
188 Lambrinos, Pfeifer, & Wehner 2001) with the aim of making robots more efficient navigators.

189 Although this work provides clear benefits for robotics research and engineering, it also offers
190 insights into animal cognition. Robots are useful for investigating the perceptual and neurological
191 bases for navigation and spatial cognition by replicating the mechanisms behind them or reverse
192 engineering typical behaviors of animals (Milford, Wyeth, & Prasser, 2004).

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

199

200 **Social learning and use of social cues**

201 The transfer of complex behavioral information (as opposed to specific stimuli, such as isolated
202 vocalizations) between individuals has typically been studied using live animals. For example, in
203 studies on social learning, demonstrators are often trained to perform particular behaviors and then
204 the ability of naive observers to acquire the behavior through observation is tested. This approach
205 has shown that a surprisingly wide variety of species can, through observation alone, acquire

206 sophisticated behavioral information from conspecifics with sufficient accuracy for them to repeat
207 the behavior themselves (e.g., birds, Fritz & Kotrschal, 1999; Todt, 1975; reptiles, Kis, Huber, &
208 Wilkinson, 2014; Wilkinson, Kuenstner, Mueller, & Huber, 2010; fish, Brown & Laland, 2003;
209 mammals, Call, Carpenter, & Tomasello, 2005). However, the experimental paradigm of using live
210 demonstrators imposes limitations on the ability to extract information on the mechanisms of
211 information transmission. In particular, there is a need for demonstrators to perform behaviors with
212 sufficient accuracy and repeatability to allow others to learn from them, and so that all observers
213 have the potential to receive the same information.

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

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

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

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

238 technology and in our understanding of animal perception and, with the choice of suitable model
239 species, many of these issues can be overcome.

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

244

245 **Early experience and cognitive development**

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

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

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

267

268 **Conclusions**

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

275

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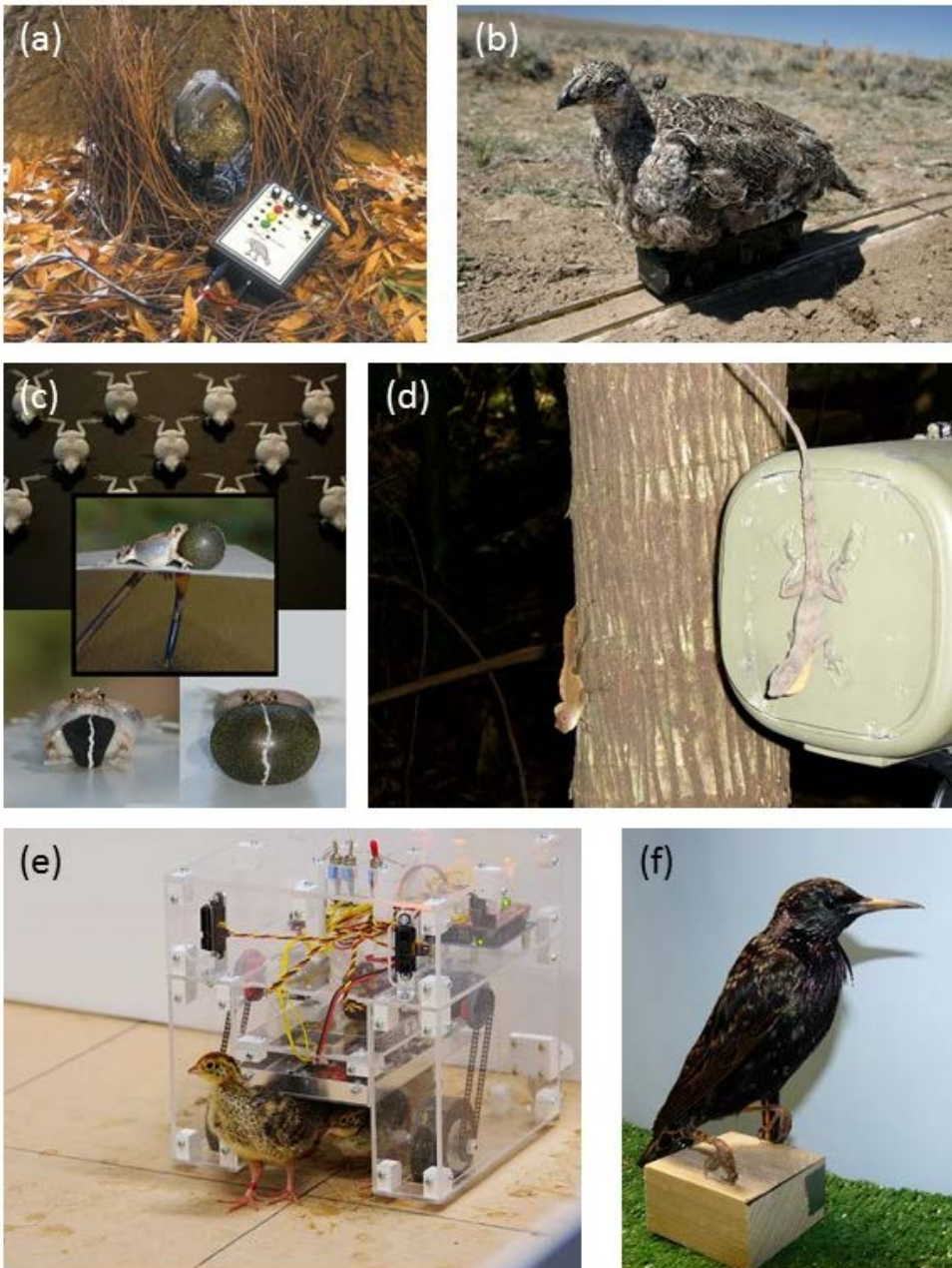
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501 Fig.1: Examples of robots that have been used in studies interacting with animals. (a) robotic female
502 bower bird (*Ptilonorhynchus violaceus*) with controls (Patricelli et al., 2006); (b) robotic female
503 greater sage grouse (*Centrocercus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