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8
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 &

Cook, 2006; Cook & Katz, 1999; Cook, Qadri, Kieres, & Commons-Miller, 2012; Reid & Spetch, 1998), 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, 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, Macrì, & Porfiri, 2015; Spinello, Macrì, & Porfiri, 2013), making this secies ideal for

155   investigating the effects of drugs on social interactions and cognition.

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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

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

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**

9

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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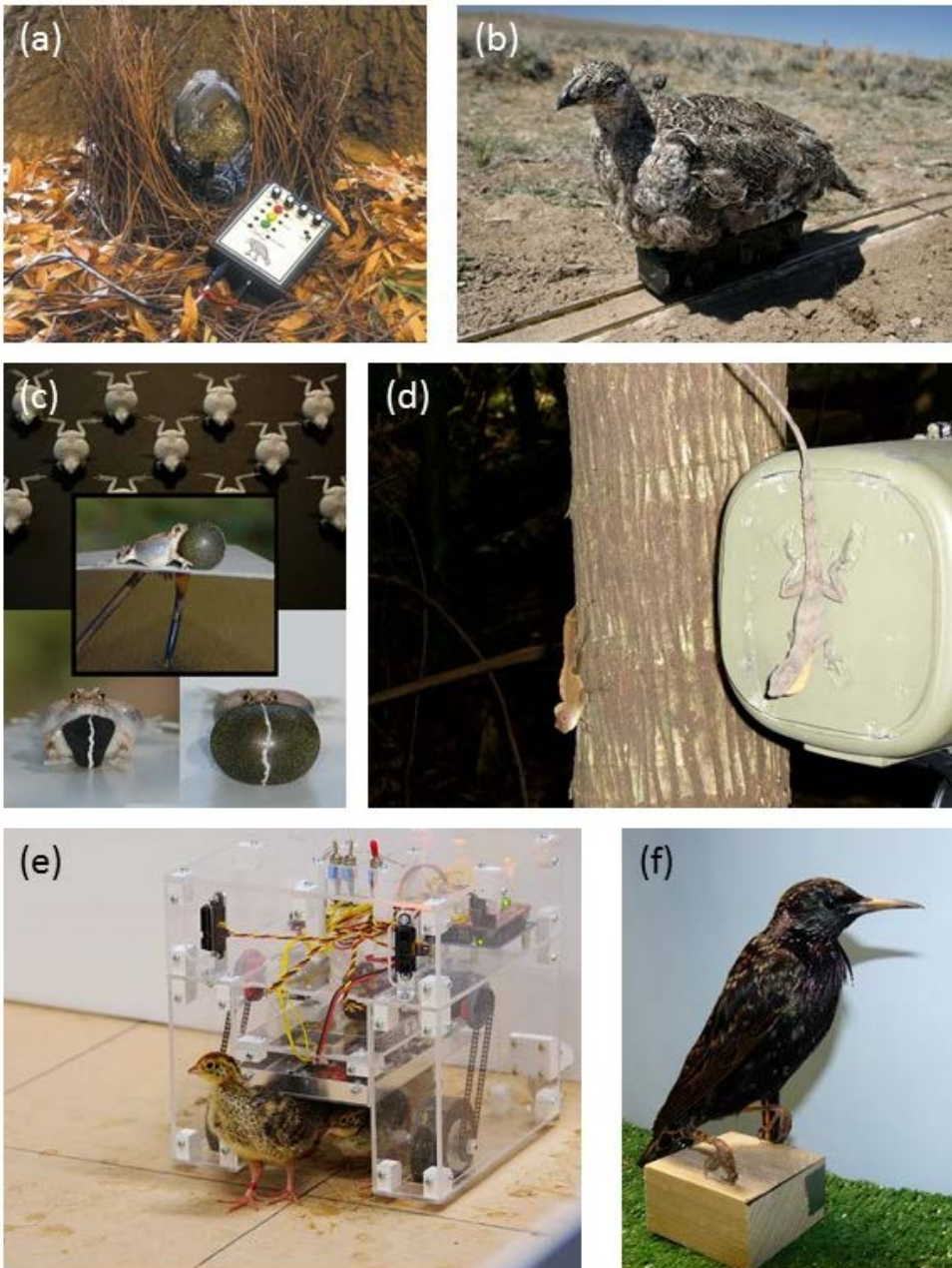
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501   Fig.1: Examples of robots that have been used in studies interacting with animals. (a) robotic female
502   bower bird (*Ptilonorhynchus violaceus*) with controls (Patricelli et al., 2006); (b) robotic female
503   greater sage grouse (*Centrocercus 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)