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► **To cite this version:**

Charlotte Canteloup, Joonho Lee, Samuel Zimmermann, Morgane Alvino, Markus Montenegro, et al..  
When monkeys meet an ANYmal robot in the wild. 2024. hal-04756363

**HAL Id: hal-04756363**

**<https://hal.science/hal-04756363v1>**

Preprint submitted on 28 Oct 2024

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1 **When monkeys meet an ANYmal robot in the wild**

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4

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14

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16

17 **Abstract**

18 Most of the animal-robot interaction studies have involved robots interacting with insects,  
19 birds, and frogs in labs. To date, only two studies used non-human primates and no study has  
20 tested the social integration of a robot in a group of wild primates. To fill this gap, we studied  
21 the interactions between the ANYmal robot and a group of 37 wild vervet monkeys in South  
22 Africa. ANYmal is a remote-controlled sheep-sized robot with an open box of food on its back.  
23 We gradually introduced it to the monkeys following five different steps over 6 days for a total  
24 exposition time of about 10h. The monkeys habituated to ANYmal very quickly with six

25 individuals eating the food in the robot's box from the second day. A few individuals emitted  
26 alarm calls towards the robot. In total, seven high rankers spent time near the robot and 21  
27 individuals approached it from a greater distance. High rankers displayed significantly more  
28 vigilant and self-centered behaviors and they, with females and juveniles, ate more food in  
29 the robot's box compared to low rankers, males, and adults conversely. This study offers  
30 exciting perspectives on the phenomena of social acceptance of machines in mammalian  
31 societies.

32 **Keywords:** animal-robot interaction; primate; ethorobotics; behavior; field experiment

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34

## 35 **Introduction**

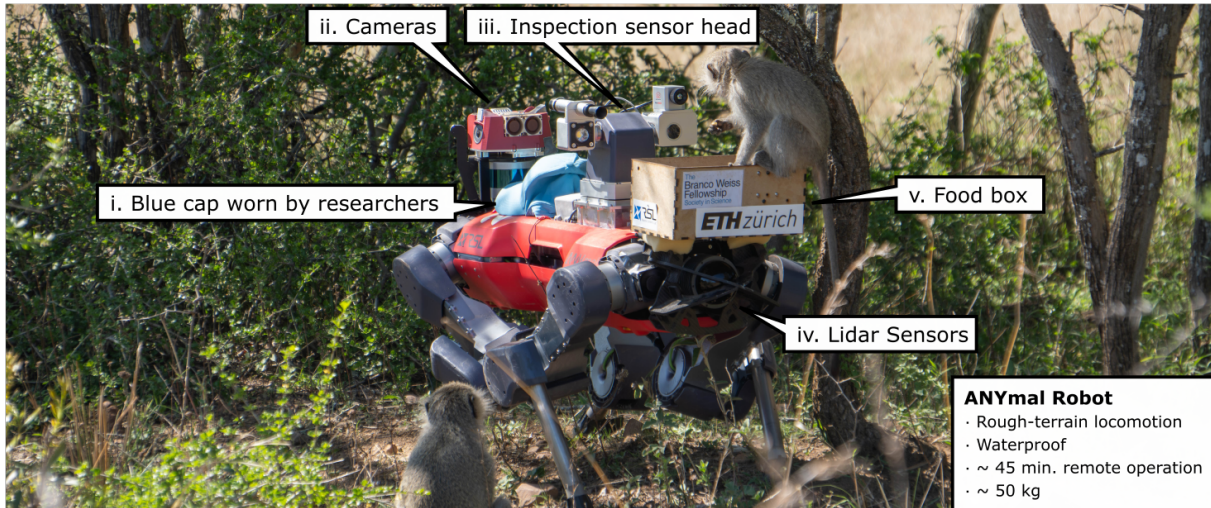
36 From food vending machines to domestic, military, and industrial robots, including  
37 artificial intelligence, robots have an exponentially growing important place in our society. In  
38 recent decades, robots have also been increasingly used in animal studies<sup>1,2</sup>. We define here  
39 a robot as “a machine that is able to interact physically with its environment and perform  
40 some sequence of behaviors, either autonomously or by remote control”<sup>1</sup>. The first studies  
41 date back to the fifties when some researchers such as Tinbergen<sup>3</sup> used manually manipulated  
42 dummies and decoys, to study the social behaviors of three-spined sticklebacks and gulls.  
43 Remote-controlled robots that perform a pre-programmed sequence of behaviors have  
44 subsequently been used in various animal-robot interaction studies. On the one hand,  
45 biomimetic robots mimicking the studied species have been designed to test whether  
46 communicative signals displayed by the robotic model could elicit a behavioral response in  
47 real animals<sup>4,5</sup>. For example, some researchers have investigated what kind of communicative  
48 signals are considered by squirrels to communicate an alarm<sup>6</sup>, by frogs to defend their

49 territory<sup>7</sup> and during courtship<sup>8</sup> , or whether starlings responded to the orienting behavior of  
50 a robotic conspecific<sup>9</sup>. Biomimetic robots have also been used to test whether locusts can use  
51 social information provided by a robotic demonstrator to avoid predators<sup>10</sup> or whether a  
52 robotic fish can recruit real fishes from a refuge and initiate new swimming direction<sup>11</sup>. These  
53 studies suggest that biomimetic robots can be perceived by animals as conspecifics. On the  
54 other hand, other types of non-biomimetic robots that do not perfectly match the species  
55 under study, have been used to test whether animals can recognize them as social partners.  
56 Authors found that dogs responded more to a furry dog-like AIBO robot compared to a  
57 remote-controlled car<sup>12</sup>, but less to a pointing humanoid robot than to a human<sup>13</sup>; both dogs  
58 and cats discriminated between animate and inanimate unidentified moving objects<sup>14</sup>, but  
59 without any evidence that they developed individual recognition of them<sup>15</sup>. One study  
60 reported that chicks raised with a robot improved their spatial abilities<sup>16</sup>. Interestingly, rats  
61 learnt from a rat-sized robot a lever-pushing task to obtain food<sup>17</sup> and they even behaved pro-  
62 socially towards a robotic rat, by releasing it from restraints, especially if the robot had  
63 previously been helpful to them compared to an unhelpful robot<sup>18</sup>. In primates, marmosets  
64 have been reported to attribute goals to a small four-legged robot but not to a moving box<sup>19</sup>  
65 and chimpanzees were particularly sensitive to a doll-like robot that reproduced their  
66 behavior, from which they even requested social responses<sup>20</sup>. These studies suggest that  
67 animals can perceive unfamiliar robots as animate to some extent based on some lifelike cues,  
68 such as a body with a head and legs, biological motion, and self-propulsion. With the  
69 development of technology, some robots have been designed with an autonomous mode, so  
70 that they can interact with their environment, learn, and even adapt, leading some scientists  
71 to claim for 'mixed societies of animals and robots'<sup>21,2</sup>. Mobile robots capable of detecting  
72 obstacles, adjusting their trajectories, and controlling certain group behaviors, have been

73 introduced in the lab to precocial chicks. The chicks followed the robots, aggregated with  
74 them, and developed an attachment to them through the learning process of filial imprinting,  
75 showing distress after separation<sup>21,22</sup>. Autonomous robots have been notably used to  
76 investigate animal collective behaviors. Such robots have been socially integrated into  
77 cockroaches' groups, leading groups' decisions to move to shelters<sup>23</sup>. In the same vein,  
78 autonomous robots have been successfully developed to manoeuvre flock of ducks<sup>24</sup>, to  
79 investigate self-organisation in ant colonies<sup>25</sup> and to create biohybrid systems by coordinating  
80 the collective behaviors of honeybees and zebrafishes using socially integrated robots<sup>26</sup>.

81 Most of the animal-robot interaction studies took place in laboratories with  
82 insects<sup>10,23,25,26</sup>, fishes<sup>2,11</sup>, frogs<sup>8</sup>, birds<sup>5,9,16,21,22,27</sup> and, within mammals, with rats<sup>17,18</sup> and  
83 dogs<sup>13-15,28</sup>. Only two studies have been conducted so far with primates, both in captivity, one  
84 with marmosets<sup>19</sup> and one with chimpanzees<sup>20</sup>. Comparatively, far fewer studies have been  
85 conducted in the wild, with some species of insects<sup>29</sup>, frogs<sup>7</sup>, crocodiles and lizards<sup>30</sup>, birds<sup>4,31</sup>  
86 and squirrels<sup>6</sup>. To our knowledge, no animal-robot interaction studies have been done with  
87 wild primates. To fill this gap, we introduced an ANYmal robot<sup>32-34</sup> (Fig. 1) to a group of 37  
88 vervet monkeys living in their natural habitat in South Africa. The ANYmal robot is a highly  
89 mobile and sophisticated four-legged robot designed for autonomous operation in harsh  
90 environment. The use of artificial agents with unfamiliar embodiment allows for high flexibility  
91 of motion without the influence of the familiar physical appearance, thus providing high  
92 control and repeatability. We report here a first study that aimed at investigating the reaction  
93 of the monkeys to the robot and their interaction in the field.

**A. Robot**



**ANYmal Robot**

- Rough-terrain locomotion
- Waterproof
- ~ 45 min. remote operation
- ~ 50 kg

**B. Operation modes**

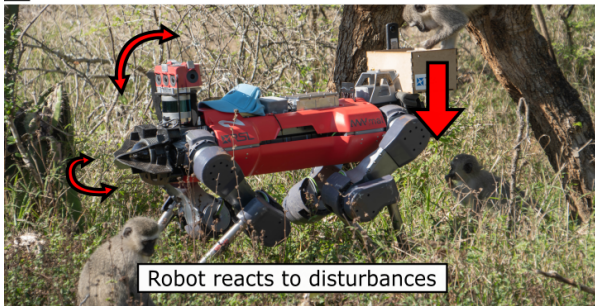
**1** Lying down



**2** Inactive standing



**3** Active standing



Robot reacts to disturbances



**4** Stepping & head turning



94

95 Figure 1. A) The ANYmal robot used in the experiment. B) Operation modes of the robot. We started from a static

96 (1) lying down mode and gradually added more motions (3, 4). Picture credit: Joonho Lee

97

98 **Presentation steps of the ANYmal robot to the monkeys**

99

100 The field experiment consisted of introducing an ANYmal robot (Fig. 1) to the group of  
101 wild vervet monkeys for one week. Because the robot was big, compared to the monkeys, we  
102 gradually introduced it to the group of monkeys following four different steps to avoid  
103 frightening them (Table 1; Table SI\_1; Fig. 1B-4).

104 We experimented with four different operation modes of the robot: lying down mode,  
105 inactive standing mode, active standing mode, and stepping/head-turning mode. In the lying  
106 down mode, the robot was inactive. In the inactive standing mode, the robot stood on its four  
107 legs with the leg joints fixed. In the active standing mode, the robot stood still but reacted to  
108 external disturbances and moved its body depending on the surroundings. In the  
109 stepping/head-turning mode, the robot stepped or turned its inspection head (Fig.1B-4)  
110 following the operator's commands.

111 During the first step, the robot was lying down, with food inside the box and spread on  
112 the ground around the robot (Fig.1B-1). In the second step, the robot was in inactive standing  
113 mode. In this mode, the robot did not react to the monkeys. Food was placed inside the box  
114 and spread on the ground (Fig.1B-2). Although still cautious, the monkeys began to approach  
115 and touch the robot.

116 In the third step, the robot was in active standing mode (Fig.1B-3), moving its body  
117 slightly in response to the approaching monkeys and the additional weight. This movement  
118 made the monkeys more vigilant than in the previous step. There was food only inside the  
119 box. In the final step, the robot was in stepping/turning mode, moving its body slightly and  
120 occasionally turning its inspection head 360°. There was only food inside the box (Fig. 1B-4).

121

Step	Robot position	Food location	Date	Time	Session number	Experiment duration	Agonistic behaviours	Alarm calls	Eat food ground	Eat food box	contact-arm length distance	> arm-length-10m distance
1	lying down	ground + box	07/10/2021	11:40	1	24	0	0	0	0	0	0
1	lying down	ground + box	07/10/2021	16:31	2	19	0	3	6	0	3	10
1	lying down	ground + box	07/10/2021	17:08	3	12	1	0	3	0	3	5
1	lying down	ground + box	07/10/2021	17:27	4	37	0	2	3	0	0	4
1	lying down	ground + box	08/10/2021	05:32	5	53	6	2	11	6	6	12
1	lying down	ground + box	08/10/2021	06:30	6	26	0	0	6	0	0	7
2	inactive standing	ground + box	08/10/2021	07:17	7	40	4	0	3	0	0	5
2	inactive standing	ground + box	09/10/2021	05:39	8	57	9	0	2	6	6	11
2	inactive standing	box	09/10/2021	06:55	9	19	0	0	0	0	0	0
2	inactive standing	box	09/10/2021	07:45	10	38	0	0	0	6	6	8
3	active standing	box	09/10/2021	16:51	11	26	3	0	1	5	4	6
3	active standing	box	10/10/2021	16:59	12	47	37	1	-	5	4	9
4	moving & head turning	box	11/10/2021	08:41	13	66	0	0	[3]	6	5	14
4	moving & head turning	box	11/10/2021	16:25	14	60	6	0	[4]	5	5	8
4	moving & head turning	box	12/10/2021	05:40	15	81	14	4	[3]	6	7	12

122

123

124 Table 1. Summary table of the experiment by step; robot position; food position; date; time (start time of the  
 125 experiment); session number; experiment duration (in minutes: seconds); number of agonistic behaviors  
 126 displayed by monkeys towards the robot; number of alarm calls emitted by monkeys in response to the robot;  
 127 number of individuals eating food on the ground; [Numbers in brackets represent the individuals that ate food  
 128 leftovers on the ground]; number of individuals eating food inside the box on the robot's back; number of  
 129 individuals present in contact and within arm length distance to the robot during scans; number of individuals  
 130 present within more than arm length distance and up to 10m to the robot during scans.

131

132 On the first day, we brought the robot to the field in the late morning when the group  
 133 of monkeys was more than 100m away across the river, but no individual got closer to the  
 134 robot. The second session consisted of the first encounter between the robot and the  
 135 monkeys that occurred later in the same day in another part of the monkeys' territory. Two  
 136 minutes into the session, one adult female (Guat) approached the robot that was lying down  
 137 on the ground within one meter, stood-up bipedally for few seconds while looking inside the  
 138 box on the robot's back, and immediately left. In total, six individuals from the dominant 'G'  
 139 matriline (Table\_SI\_1) approached and started to eat the food on the ground in front of the  
 140 robot during this session. On the second day, six individuals started to eat food inside the  
 141 robot's box (Table 1; Table SI\_1). Overall and across the experiments, eight individuals emitted  
 142 12 alarm calls towards the robot (Table 1; Table SI\_1). A total of four individuals emitted 80



143 agonistic behaviors, mostly head bobbing towards the robot. An individual (Gri) jumped on  
144 the robot for the first time on the third day (session 10; step 3).

145

146

#### 147 **Monkeys' vigilance reactions towards the robot**

148

149 Too few alarm calls have been emitted by the monkeys (Table 1) to perform statistical  
150 analyses but i) most of the callers were juveniles and ii) they produced snake and eagle alarm  
151 calls, instead of a 'leopard alarm call', which is usually used for a few species of carnivores<sup>35</sup>  
152 as a predator deterrent<sup>36</sup>, suggesting that they did not consider the robot as a terrestrial  
153 predator. In fact, young vervet monkeys are more likely to produce alarm calls to a wider range  
154 of animals than adults who are more specific in producing alarm calls only to known  
155 predators<sup>37</sup>. Because the robot wore the same blue cap as the observers, provided food to the  
156 monkeys and that the observers walked close to the robot in the field, it is possible that the  
157 monkeys perceived the robot as a safety indicator, and even as a feeding opportunity.  
158 Moreover, this group of monkeys is very well habituated to humans with field experiments  
159 regularly conducted since 2011, which may have facilitated their curiosity towards novelty<sup>38</sup>.

160 Although very few alarm calls were emitted, the monkeys displayed some vigilant  
161 behaviors such as 'standing up bipedal' and some self-centered behaviors such as 'yawning'  
162 and 'self-scratching'. On the one hand, we found a significant effect of rank on the number of  
163 times individuals stood up bipedally (Zero-Inflated Poisson model: ZIP\_1; Table SI\_2) and on  
164 the number of self-centered behaviors (Zero-inflated negative binomial model: ZINB\_1; Table  
165 SI\_2). Higher-ranked individuals were 94 % more likely per unit of rank to stand-up bipedal  
166 than lower-ranked individuals (ZIP\_1;  $p < 0.001$ ; Table SI\_2) and they were 95 % more likely

167 per unit of rank to display self-centered behaviors than lower-ranked individuals (ZINB\_1;  $p =$   
168 0.004; Table SI\_2). Self-centered behaviors occur more frequently in stressful situations but  
169 the relation between rank and yawning and self-scratching appears unclear<sup>39</sup>. Here, it is  
170 possible that high rankers were torn between their motivation for food and their  
171 apprehension of the robot. Another potential explanation would be that observers missed  
172 these behaviors in low rankers because they were further away during the experiment,  
173 making these behaviors more difficult to detect in the bush. We also found a significant effect  
174 of sex on the number of times individuals stood up bipedally (ZIP\_1; Table SI\_2). Surprisingly,  
175 males were 52% less likely to stand up than females ( $p = 0.001$ ; Table SI\_2), while it has been  
176 reported that males are usually more vigilant than females who are more wary<sup>40</sup>.

177 On the other hand, we found no significant effect of age on the number of times the  
178 monkeys stood up bipedally (ZIP\_1;  $p > 0.05$ ; Table SI\_2) and no significant effect of age and  
179 sex on the number of self-centered behaviors (ZINB\_1;  $p > 0.05$ ; Table SI\_2).

180

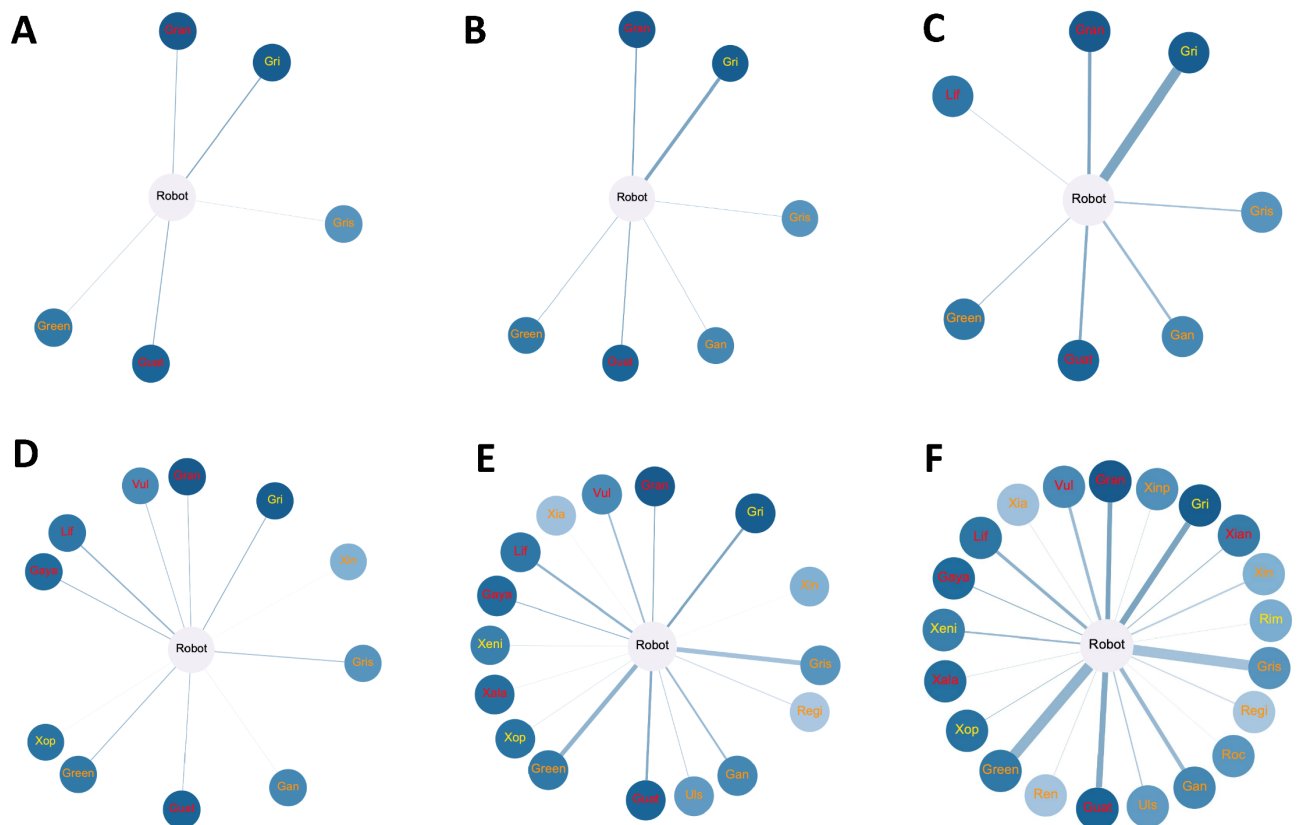
181

## 182 **High rankers, females and juveniles monopolize the robot**

183 We found a significant effect of rank on the number of scan points spent in close spatial  
184 proximity to the robot. Higher-ranked individuals were 88 % more likely per unit of rank to  
185 spend time close to the robot than lower-ranked individuals (ZINB\_4; coefficient= -0.13; odds  
186 ratio = 0.88;  $p = 0.02$ ; Figure 2). This effect can be linked to the significant effect of rank on  
187 the number of seconds spent eating food on the ground (ZINB\_2; Table SI\_2) and on the  
188 number of seconds spent eating food inside the box (ZINB\_3; Table SI\_2). Higher-ranked  
189 individuals were 92 % more likely per unit of rank to spend time eating food on the ground  
190 than lower-ranked individuals ( $p = 0.003$ ; Table SI\_2). Higher-ranked individuals were 84 %

191 more likely per unit of rank to spend time eating food inside the box than lower-ranked  
 192 individuals ( $p < 0.001$ ; Table SI\_2). These results are coherent with the fact that dominants  
 193 commonly monopolize a food source, especially when it is a known and desirable food<sup>41</sup>.  
 194 Individuals from the 'G' family were already among the first ones who foraged the most in a  
 195 previous puzzle box experiment and a novel food test<sup>42,43</sup>, likely due to their high social status.  
 196 It is also possible that high-ranking individuals recognized the box's affordance as they  
 197 experienced multiple box experiments in the past (reviewed in <sup>44</sup>). A future study involving  
 198 the ANYmal robot without a box is planned to investigate this effect.

199  
 200



201  
 202 Figure 2. Spatial proximity networks around the robot across time. Cumulative close proximity networks (contact-  
 203 arm length distances) A) on day 1; B) up to day 2 and C) up to day 6. Cumulative distant proximity networks (more  
 204 than arm length distance and up to 10m) D) on day 1; E) up to day 2 and F) up to day 6. Each node represents an

205 individual labelled by its name (three letters code for males, four letters code for females). Colours of the label  
206 name code for the age: adults are written in red; juveniles are written in orange and infants are written in yellow.  
207 The colour gradation of the nodes represents the hierarchical ranks: dark blue represents the higher-ranked  
208 individuals, while light blue represents lower-ranked individuals. Edges between the robot and the individuals  
209 represent the strength of association. The thicker the edge, the more the individual spent time in spatial  
210 proximity to the robot. Social networks were created with Gephi 0.10.1 software<sup>45</sup>.

211

212 We also found significant effects of sex and age on the number of seconds spent eating  
213 food on the ground (ZINB\_2; Table SI\_2) and on the number of seconds spent eating food  
214 inside the box (ZINB\_3; Table SI\_2). Females were 30 % more likely to eat food on the ground  
215 than males (ZINB\_2;  $p = 0.01$ ; Table SI\_2). Females were 50% more likely to eat food inside  
216 the box than males (ZINB\_3;  $p = 0.01$ ; Table SI\_2). This observed sex effect is driven by the fact  
217 that only one of the adult males and mostly females from the dominant 'G' matriline ate food  
218 around the robot and on the robot's box.

219 Concerning age, Juveniles were 137,4 % more likely to eat food on the ground than  
220 adults (ZINB\_2;  $p < 0.001$ ; Table SI\_2). Juveniles were 110,2 % more likely to eat food inside  
221 the box than adults (ZINB\_3;  $p < 0.001$ ; Table SI\_2). These results are in accordance with  
222 previous studies reporting that juveniles were more likely to eat a novel food<sup>46</sup>, and they were  
223 more exploratory towards novel objects<sup>47</sup>, suggesting that they overcome neophobia faster  
224 and take more risks than adults<sup>48</sup>.

225 Finally, we found neither a significant effect of age and sex on the number of scans  
226 spent in close proximity to the robot (ZINB\_4;  $p > 0.05$ ; Figure 2) nor a significant effect of  
227 rank, age, and sex on the number of scans spent in more distant spatial proximity to the robot  
228 (ZINB\_5;  $p > 0.05$ ; Figure 2).

229

230

## 231 **Conclusion**

232           Despite the technical challenges, we successfully introduced an ANYmal robot to a  
233 group of wild vervet monkeys. This study offers exciting opportunities for future animal-robot  
234 interaction studies in natural settings and for research questions such as: can monkeys learn  
235 from the robot and follow the robot's food choice? Does a simple service make the robot  
236 accepted? Can knowledge from the robot be trusted? Can robots become group leaders? By  
237 implementing an artificial intelligence algorithm to visually identify individuals in the videos  
238 recorded by the robot through facial and body recognition, we could in future studies collect  
239 automatized social data to assess social networks.

240

241

## 242 **Methods**

### 243 *Experimental model and subject details*

244           One group of wild vervet monkeys (*Chlorocebus pygerythrus*), called 'Noha', took part  
245 in the study. NH was composed of 37 individuals (7 adult males; 10 adult females; 7 juveniles  
246 males; 7 juveniles females; 3 infants males; 3 infants females). Males were considered as  
247 adults once they dispersed, and females were considered as adults after they gave birth for  
248 the first time. Individuals that did not fulfil these criteria were considered as juveniles, with  
249 the exception of infants that were aged less than one year old. 'Noha' had been habituated to  
250 the presence of human observers since 2010. All individuals were identifiable thanks to  
251 portrait photographs and specific individual body and face features (scars, colours, shape  
252 etc.).

253 Ethics guidelines: Our study adhered to the “Guidelines for the use of animals in  
254 research” of Association for Study of Animal Behaviour and was approved by the relevant local  
255 authority, Ezemvelo KZN Wildlife, South Africa.

256

#### 257 *Study site*

258 The study was conducted within the INKAWU Vervet Project (IVP) in a 12000-hectares  
259 private game reserve: Mawana (28°00.327S, 031°12.348E) in the KwaZulu-Natal province,  
260 South Africa. The vegetation of the study site consisted in a savannah characterized by a  
261 mosaic of grasslands and clusters of trees of the typical savannah thornveld, bushveld and  
262 thicket patches. Mawana game reserve hosts various species of animals including elephants,  
263 giraffes, zebras, warthogs, and numerous species of antelopes. The common predators of  
264 vervet monkeys consist of hyenas, jackals, caracals, servals and several species of snakes and  
265 raptors.

266

#### 267 *Hierarchy establishment*

268 Agonistic interactions (e.g. stare, displacement, chase, hit, bite) were collected from  
269 January 2021 to October 2021 on all individuals of the group via *ad libitum* sampling  
270 method<sup>49,50</sup> and food competition tests (i.e. corn provided to the whole groups from a plastic  
271 box). Data were collected by C.C and different observers from the IVP team. Before beginning  
272 data collection, observers had to pass an inter-observer reliability test with 80% of reliability  
273 for each data category between two observers. Data were collected on tablets (Vodacom  
274 Smart Tab 2) equipped with the Pendragon software version 8. Details about *ad libitum* data  
275 collection and hierarchy assessment have already been published in a previous paper<sup>51</sup>.

276 Individual hierarchical ranks were determined by the outcome of dyadic agonistic  
277 interactions recorded *ad libitum* and through food competition tests using the 'EloRating'  
278 package<sup>52</sup> in R studio software version 2022.07.1<sup>53</sup>. Hierarchy of the group was significantly  
279 linear ( $h' = 0.14$ ;  $p = 0.013$ ) and ranks were assessed by I&SI method<sup>54</sup>.

280

### 281 *Robot preparation*

282 The ANYmal robot, a quadrupedal, sheep-sized robot originally developed by the  
283 Robotic Systems Lab at ETH Zürich, Switzerland, was adapted for this study in a game reserve.  
284 This adaptation involved adding a wide-angle camera module (Fig. 1A-ii), a long-range zoom  
285 camera (Fig. 1A-iii), and the food box (Fig. 1A-v). These modifications brought the robot's  
286 weight to approximately 50 kg and allowed it to operate for about 50 minutes on a single  
287 battery charge.

288 To navigate the rough terrain of the game reserve, we employed a reinforcement  
289 learning (RL)-based locomotion controller<sup>34,55</sup>. The robot's locomotion and balance were  
290 managed by a neural network controller, which processed proprioceptive measurements such  
291 as joint angles, velocity, and robot pose, alongside exteroceptive measurements from lidar  
292 sensors (Fig. 1A-iv). By integrating this multi-modal information, the neural network-based  
293 controller could generate real-time control commands for all 12 joints at a frequency of 50 Hz.  
294 We trained the controller with additional simulated disturbances for this experiment,  
295 enhancing the robot's stability and safety even when monkeys jumped on or pushed it. The  
296 robot could traverse various rough terrains and cross a river within the reserve.

297

298 For continuous data collection and operation, we utilized the autonomy system  
299 developed by Team CERBERUS for the DARPA Subterranean Challenge<sup>56</sup>. This software was  
300 designed for the autonomous deployment of robots in cave-like environments, supporting  
301 both the remote control of the robot and its inspection head. Although we prepared a fully  
302 autonomous mode, it was not used during this study and we remote-controlled the robot  
303 around the monkeys for safety.

304

### 305 *Experiment*

306 The field experiment consisted in introducing an ANYmal robot (Fig. 1) to the group of  
307 wild vervet monkeys. For this experiment, we added on the robot a blue cap (Fig. 1A-i) that is  
308 worn by researchers, and an open wooden box (filled with corn and apple slices) fixed on its  
309 back (Fig. 1). On the first day, the box was an opaque plastic box with an open lid, and it was  
310 fixed on the robot's back. Due to unforeseen noise and vibration of the box when the robot  
311 was moving, on the second day, we changed the plastic box to a lighter wooden box of the  
312 same dimensions (20x20x15cm), without any lid, and kept it for the rest of the experiment.  
313 Although the robot can move autonomously, it was remotely controlled, at least 5m away, by  
314 J.L and S.Z for the purpose of the study. Note that we fixed the mobile head on the robot only  
315 for the last step of the experiment due to its fragility.

316 The experiment lasted one week from October 7<sup>th</sup>, 2021, to October 12<sup>th</sup>, 2021.  
317 Experiments took place once or several times a day, either at sunrise at the monkeys' sleeping  
318 site or in the afternoon, depending on where the group was located and if it was easily  
319 accessible for the robot. C.C led the experiment with the help of M.A and one or two field  
320 assistants to directly identify the monkeys, along with J.L and S.Z who controlled the robot.



321 Before the actual start of the experimental session, the robot approached the group of  
322 monkeys by walking in their direction and stopped a few meters away from them close to a  
323 potential refuge for the monkeys such as a tree. An experimental session started when the  
324 food was placed on the ground and/or inside the wooden box. From time to time during the  
325 trials, the researchers made some food calls, a lip-smacking call, to attract the monkeys. When  
326 the box was empty, E.v.d.W approached the box and baited it again. An experimental session  
327 ended when food was no longer available and/or when the group started moving away from  
328 the robot. During the experiment, all monkeys were free to approach the robot within the  
329 constraints of the social group dynamics. A total of 15 experimental sessions were run in  
330 'Noha' for a total of 10h05min (Table 1; Table SI\_1). The average duration of an experimental  
331 session was 40.33 minutes. Experiments were video recorded using a JVC camera (EverioR  
332 Quad Proof GZ-R430BE) to which C.C said aloud the identities of the individuals approaching  
333 the robot, eating the food on the ground and inside the box, being within 10m spatial  
334 proximity of the robot along with their behavioral reactions.

335

### 336 *Video analysis*

337 All the video recordings were later analysed by C.C with VLC software version 3.0.16.  
338 Twenty percent of the video were also analysed by M.A and the inter-observer reliability was  
339 substantial ( $\kappa=0.70$ ). During video analysis in slow motion or frame by frame, the following  
340 variables were encoded: the date, the exact time of each behavioral event and the identity of  
341 the actor and the recipient when relevant. Behavioral events were either considered as state  
342 events such as 'eating food on the ground' and 'eating food inside the box' for which we  
343 recorded the duration; or as point events to get the frequency of self-centered behaviors  
344 (yawn; self-scratch), agonistic behaviors (stare attack; head bob) and alarm calls towards the

345 robot, vigilance behaviors (stand-up bipedal). Every minute, we used scan sampling<sup>49</sup> to record  
346 the identity of individuals being in close spatial proximity to the robot (between in contact and  
347 arm-length distance) and in more distant spatial proximity to the robot (between more than  
348 arm length distance and 10m distance). We ended up with a total of 417 scans of spatial  
349 proximity over the whole experiment.

350

### 351 *Statistical analysis*

352 Because our data sets comprised more than 50% of 0, we fitted Zero-Inflated  
353 regression models to our data (using the 'glmmTMB' package on R). We used the DHARMA  
354 package on R to assess all model diagnostics (dispersion test and zero inflation test on a  
355 GlmmTMB) and we visually checked the shape of Q-Q plots and residual deviation plots. Based  
356 on the models' diagnostics and the comparison of the models AIC, we selected either Zero-  
357 Inflated Poisson regression models (ZIP) or Zero-Inflated Negative Binomial regression models  
358 (ZINB). For all the models, effect sizes are reported as odds ratio.

359 Models were run using the following R packages: 'lme4', 'nlme', 'MASS', 'pscl' and  
360 'glmmTMB' in R studio (version 2023.03.0+386).

361

### 362 Effects of sociodemographic factors on monkeys' behaviors

363 We fitted a ZIP model (ZIP\_1) to test for the effect of age, sex and rank on the number  
364 of vigilant behaviors (i.e. stand-up bipedal).

365 We fitted ZINB models to test for the effects of age, sex and rank on the number of  
366 self-centered behaviors displayed by monkeys (ZINB\_1), and on the number of seconds they  
367 spent eating the food on the ground (ZINB\_2) and inside the box (ZINB\_3).

368

## 369 Effects of sociodemographic factors on spatial proximity to the robot

370           We fitted two ZINB models on observed spatial proximity data: 'ZINB\_4' to test for the  
371 effect of sex, age and rank on the number of scan points spent in contact or within arm's  
372 length distance to the robot and 'ZINB\_5' to test for the effect of sex, age and rank on the  
373 number of scan points spent within more than arm length distance and up to 10m of distance  
374 to the robot. To deal with the non-independence of our spatial proximity data, we generated  
375 2000 random data sets by permuting the sex, age and rank columns so values of number of  
376 scans spent in proximity to the robot are randomly allocated to individuals 2000 times. The  
377 ZINB models have been fitted for each of the 2000 permutations, generating a distribution of  
378  $\beta$  estimates that we compared with the observed  $\beta$ . The null hypothesis was that the observed  
379  $\beta$  coefficient is not different from the random set of  $\beta$  values. We rejected this hypothesis if  
380 the observed  $\beta$  value was lower/greater than 95% of the random values, meaning that the  
381 model estimate was significantly different from a random distribution.

382

383

## 384 **Acknowledgments**

385           We thank the IVP onsite manager, Mike Henshall, and the whole IVP team for their  
386 help and support in the field, especially Aaron Mencia for his assistance in data collection. We  
387 are grateful to the van der Walt family for their permission to conduct the study on their land.  
388 We thank Frédéric Schütz and Loïc Brun for their advice and statistical help. This study has  
389 been funded by a collaborative grant from the Branco Weiss Fellowship—Society in Science  
390 granted to M.H and E.v.d.W. The INKAWU Vervet Project was funded during the time of this  
391 study by the Swiss National Science Foundation (PP00P3\_198913) granted to E.v.d.W. At the  
392 time of writing, C.C was supported by the CNRS and by NeuroStra. This work of the

393 Interdisciplinary Thematic Institute NeuroStra, as part of the ITI 2021-2028 program of the  
394 University of Strasbourg, CNRS, and Inserm, was supported by IdEx Unistra (ANR-10-IDEX-  
395 0002) under the framework of the French Program “Investments for the Future”. At the time  
396 of writing, E.v.d.W was supported by the European Research Council under the European  
397 Union’s Horizon 2020 research and innovation program for the ERC ‘KNOWLEDGE MOVES’  
398 starting grant (grant agreement No. 949379).

399

#### 400 **Authors contributions**

401 The ANYmal robot has been prepared by M.H., J.L., and S.Z. and it has been controlled  
402 in the field by J.L, and S.Z. The initial conception of the project has been designed by M.H. and  
403 E.v.d.W. The experiment has been originally designed by C.C., J.L., S.Z., M.H, and E.v.d.W.  
404 M.M. made the food box and additional parts for robot. The experiment has been performed  
405 in the field by C.C., J.L., S.Z., M.A, and E.v.d.W. The video records of the experiment have been  
406 analyzed by C.C and M.A. The data have been analyzed by C.C. The figures have been prepared  
407 by C.C and J.L. The paper has been written by C.C and J.L. The funding has been acquired by  
408 M.H. and E.v.d.W. All authors reviewed and edited the draft.

409

#### 410 **Competing interests**

411 The authors declare no competing interests.

412

#### 413 **Research Ethics**

414 The study was approved by the relevant local wildlife authority, Ezemvelo KZN Wildlife,  
415 South Africa (no reference number was provided). The study adhered to the “Guidelines for  
416 the use of animals in research” of the Association for the Study of Animal behaviour.

417

418 **Data availability**

419 The datasets are made available at: <https://doi.org/10.5281/zenodo.13309750>

420

421 **Code availability**

422 The R scripts for statistical analyses are available at:

423 <https://doi.org/10.5281/zenodo.13309750>

424

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