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1 Worker thelytoky allows requeening of orphaned colonies but increases susceptibility to  
2 reproductive cheating in an ant

3

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22

23 ABSTRACT:

24 In some social insects workers can produce females asexually through thelytokous  
25 parthenogenesis. This allows them to produce replacement queens (i.e. requeening) if the  
26 queen has died, but also to compete with the queen for producing females (i.e. reproductive  
27 cheating). For the first time, we experimentally tested the role of worker thelytoky under  
28 quasi-natural conditions in the ant *Cataglyphis cursor*, where the queen uses both sexual and  
29 thelytokous reproduction. We reared pairs of orphaned and queenright colonies in enclosures  
30 for almost three months, during which they competed for resources. Orphaned colonies lost  
31 more workers than queenright colonies over the course of the experiment, presumably  
32 because of the costs of reproductive conflicts between workers. Nevertheless, they produced  
33 new queens through worker thelytoky and new colonies through colony fission. This is the  
34 first unambiguous demonstration that worker thelytoky allows requeening under natural  
35 conditions in this species. We further show that worker thelytoky results in reproductive  
36 cheating in the form of a few workers reproducing in presence of the queen (in queenright  
37 colonies) and of a few worker lineages producing more new queens than other lineages (in  
38 orphaned colonies). In addition, it also results in rare instances of social parasitism i.e.  
39 workers entering and reproducing in foreign colonies. These benefits to workers seem too  
40 occasional and too low to drive the evolution of theytoky in this species. We argue that  
41 thelytoky likely evolved in the queen caste, where it allows producing young queens and  
42 confers frequent and massive benefits by increasing gene transmission, but is also expressed  
43 in workers because of genetic correlations between the two castes.

44

45 Keywords: *Cataglyphis cursor*, cheating, cost of reproduction, thelytoky, social insects,  
46 worker reproduction

47

48 INTRODUCTION

49

50 Cooperative systems are exposed to the apparition of selfish elements that benefit from the  
51 common goods without paying the costs arising from their production (Chapuisat, 2009;  
52 Dobata & Tsuji, 2013; Hughes & Boomsma, 2008). By doing so, cheaters increase their  
53 fitness and decrease that of the other individuals. Cheating has evolved in a range of  
54 cooperative organisms, from bacteria to mammals (Ghoul, Griffin, & West, 2014; Riehl &  
55 Frederickson, 2016). In social hymenoptera, workers typically rear the offspring of their  
56 mother queen instead of their own, yet a low level of worker reproduction in presence of the  
57 queen (i.e. cheating) has been observed in various species (Barron, Oldroyd, & Ratnieks,  
58 2001; Bourke, 2011; Ratnieks, Foster, & Wenseleers, 2006; Ratnieks & Wenseleers, 2008;  
59 Sundström & Boomsma, 2001).

60

61 Because of the haplo-diploid sex determination system of hymenoptera, workers can  
62 potentially produce haploid sons (arrhenotoky) in most species (e.g. Ratnieks et al. 2006;  
63 Bourke 2011). However, worker policing (through oophagy and/or aggression) and self-  
64 restraint usually lessen or even prevent intra-colonial cheating (Ratnieks, 1988; Ratnieks et  
65 al., 2006). In addition, colony recognition similarly limits or prevents intraspecific social  
66 parasitism, that is the reproduction of foreign workers (Beekman and Oldroyd 2008). Despite  
67 this, low levels of intra-colonial cheating have been observed in many species (Barron et al.,  
68 2001; Bourke, 2011; Ratnieks et al., 2006; Ratnieks & Wenseleers, 2008; Sundström &  
69 Boomsma, 2001), and reproduction by drifting workers has also been detected in several  
70 species (Chapman, Nanork, et al., 2009; Chapman, Beekman, & Oldroyd, 2010; Chapman,  
71 Makinson, Beekman, & Oldroyd, 2009; Dobata et al., 2011; Nanork et al., 2007)

72

73 Another, more subtle, form of cheating can occur when there are many patriline  
74 within a colony (i.e. the queen is mated with several males), given that patriline that are more  
75 successful at producing queens are advantaged by individual selection. A differential success  
76 at queen production could be achieved by various ways. Patriline may differ in their larval  
77 propensity to develop into queens, so that caste is partially determined by genetic variation  
78 among patriline (Anderson, Linksvayer, & Smith, 2008; Hughes & Boomsma, 2008;  
79 Schwander, Lo, Beekman, Oldroyd, & Keller, 2010). Workers may also preferentially rear  
80 larvae from their own patriline into queens. However, such nepotistic behaviours have rarely  
81 been detected, and have been subject to controversy when detected (Hannonen & Sundström,  
82 2003; Holzer, Kümmerli, Keller, & Chapuisat, 2006; Reeve & Keller, 1997; Tarpy, Gilley, &  
83 Seeley, 2004).

84

85 Finally, patriline may engage in direct reproductive competition when workers  
86 themselves are capable of producing new queens by thelytokous reproduction, as in some  
87 honey bees (Holmes, Tan, Wang, Oldroyd, & Beekman, 2015; Verma & Ruttner, 1983) and  
88 some thermophilic ants from the genus *Cataglyphis* (Aron, Mardulyn, & Leniaud, 2016).  
89 Some patriline may gain a disproportionately higher reproductive success than others either  
90 because a higher fraction of their workers are reproducing or because they are more fecund  
91 (Goudie et al., 2012). The selective pressure for the evolution of cheating is more pronounced  
92 when workers are able to produce females, because a worker that manages to produce the new  
93 queen in some way reincarnates herself into that queen (Greeff, 1996). Quite surprisingly, and  
94 although thelytokous reproduction has evolved independently in many social insect species  
95 (Wenseleers & Van Oystaeyen, 2011), worker thelytoky in queenright colonies has been  
96 observed in only two species, the Cape honey bee *A. m. capensis* (Goudie and Oldroyd 2014  
97 for a review and references therein) and the ant *C. cursor* (Doums, Ruel, et al., 2013). In the

98 Cape honey bee, reproductive workers can be considered cheaters in queenright colonies  
99 where they produce up to 60% of new queens (Allsopp, Beekman, Gloag, & Oldroyd, 2010;  
100 Jordan, Allsopp, Oldroyd, Wossler, & Beekman, 2008) whereas in *C. cursor*, the use of  
101 thelytoky by workers is less clear (Chéron, Monnin, Fédérici, & Doums, 2011; Doums, Ruel,  
102 et al., 2013). In addition, worker thelytoky may also confer benefits from intra-specific social  
103 parasitism, and indeed social parasitism has been observed in several species with thelytokous  
104 workers (Allsopp et al., 2010; Dobata et al., 2011; Moritz, Lattorff, Crous, & Hepburn, 2011).  
105 In the Cape honey bee, workers enter foreign colonies where they produce 6 to 62 % of  
106 queens (Härtel, Neumann, Raassen, Moritz, & Hepburn, 2006; Moritz et al., 2011). One  
107 clonal worker lineage has even been found to parasitize a closely related subspecies, *A. m.*  
108 *scutellata* where it behaves like pseudo-queens (reviewed in Goudie and Oldroyd 2014).

109

110 In social insects, the main force preventing the evolution of high levels of cheating is  
111 thought to be the costs of worker reproduction and of conflicts over reproduction, even  
112 though experimental evidences of such costs are scarce (Bourke, 2011; Ratnieks et al., 2006).  
113 Two studies in queenless ants showed a direct energetic cost (Gobin et al., 2013), and a cost  
114 on worker immune defence and on the time spent by workers to perform collective tasks  
115 (Bocher, Doums, Millot, & Tirard, 2008). Species with worker thelytoky are similar to  
116 queenless ants in that after the death (or experimental removal) of the reproductive  
117 individuals, all workers have the potential to produce diploid eggs. This can generate intense  
118 conflicts over reproduction, but it can also provide the major benefit of avoiding colony death  
119 following the loss of the reproductive individual. Indeed, in most monogynous species, the  
120 death of the queen induces the rearing of new queens from the young diploid brood already  
121 present in the colony and the production of male by workers through arrhenotoky (Bourke,  
122 2011). When no young diploid brood is available, the colony is hopelessly queenless and dies

123 gradually after a bunch of male production. By allowing requeening of orphaned colonies,  
124 worker thelytoky can avoid colony death even when no brood is present (Holmes et al., 2010).

125

126 In this study, we investigated the level of intra- and inter-colonial worker reproduction  
127 in the ant *C. cursor* and tested the capacity of queenless colonies to requeen in spite of a  
128 potential cost of reproductive conflicts between workers. To do so, we orphaned colonies at  
129 the end of the hibernation period and let them compete with queenright colonies in quasi-  
130 natural conditions until the time of sexual production. In *C. cursor*, the queen combines or  
131 alternates thelytokous and sexual reproduction to produce new queens (called “gynes” before  
132 they mate and start their own colony), but she only uses sexual reproduction to produce  
133 workers (Doums, Cronin, et al., 2013; Percy, Aron, Doums, & Keller, 2004). Workers from  
134 orphaned colonies kept under laboratory conditions use thelytokous reproduction to produce  
135 gynes at the end of the hibernation period, and to produce workers later in the season  
136 (Cagniant, 1980; Chéron, Monnin, et al., 2011; Clémencet, Rome, Fédérici, & Doums, 2008).  
137 Worker-produced gynes mate and monogyny is then restored by the killing of all but one  
138 gyne. Theoretically, a colony could hence be immortal since workers allow both colony  
139 growth and colony requeening. However, the extent of worker reproduction in the field is  
140 unknown.

141

142 First, we measured queen production in orphaned colonies, as evidence of their  
143 capacity to requeen, and compared the rate of worker survival of orphaned and queenright  
144 colonies under competition. Queenless colonies may suffer dramatic reduction of colony  
145 efficiency because of the costs associated with the massive worker reproduction, such as  
146 agonistic interactions, oophagy and lowered investment in foraging and colony maintenance  
147 tasks (Bocher et al., 2008; Clémencet et al., 2008; Malka, Shnieor, Katzav-Gozansky, &

148 Hefetz, 2008; Miller & Ratnieks, 2001). We therefore expected a lower worker survival rate  
149 in orphaned than in queenright colonies.

150

151         Second, we tested for the occurrence of cheating lineages in both orphaned and  
152 queenright colonies. In orphaned colonies, we compared the paternity frequencies in workers  
153 and gynes. Differential reproductive successes of patrilineages would result in a discrepancy  
154 between these two frequencies. Under laboratory conditions, a previous study show that some  
155 patrilineages produced significantly higher fractions of gynes than as expected according to their  
156 frequencies among workers, suggesting that they had a higher reproductive success than the  
157 other patrilineages and that the frequency of cheating lineages was low (Chéron, Monnin, et al.,  
158 2011). However, new queens were collected at the pupal stage and it thus remains possible  
159 that cheating behaviours could take place at a later developmental stage, such as by selective  
160 killing of new queens from other patrilineages, and thus possibly result in more pronounced  
161 differential success of competing patrilineages and higher levels of cheating. On the other hand,  
162 contrary to laboratory settings, selective killing of brood could be avoided in natural nests by  
163 physically separating brood of different patrilineages. In our experiment, we determined in  
164 queenright colonies whether some gynes had been produced by workers instead of by the  
165 queen. In previous studies, no worker-produced gynes had been detected among more than  
166 200 gynes produced by queenright colonies in the field (Doums, Cronin, et al., 2013).  
167 However, some diploid males had been produced by worker thelytoky in queenright colonies,  
168 showing that some workers attempted to reproduce in presence of the queen (Doums, Ruel, et  
169 al., 2013).

170



171 Third, because orphanage may be a time of fragility with weakened colony integrity,  
172 we checked whether drifting occurred and whether drifting workers reproduced, as suggested  
173 in a previous study (Chéron, Monnin, et al., 2011).

174

175

## 176 MATERIAL AND METHODS

177

### 178 *Colony collection and experiment*

179

180 At the end of the hibernation period (8<sup>th</sup> to 10<sup>th</sup> March 2011), 18 colonies were completely  
181 excavated in the population of Argelès-sur-Mer near Perpignan (42.5722°N, 3.0437°E). They  
182 contained an average of 961.8 workers (range: 427-2101) and no brood (Table A1). Two of  
183 these colonies were collected with no queen. Whether the queen died during hibernation or  
184 was lost during excavation is unclear. Colonies were then paired by colony size, with each  
185 pair comprising one queenright and one queenless colony (either collected with no queen or  
186 experimentally orphaned). Workers from colonies collected queenless should not behave  
187 differently than workers from experimentally orphaned colonies because eggs laying had not  
188 started at the time of collection. Removed queens were stored in 90% Ethanol (10% TE). The  
189 queen of queenright colonies was marked with a dot of paint (UniPaint marker, Mitsubishi  
190 pencil Co Ltd) and returned to its colony.

191

192 Colonies were transplanted into experimental enclosures located at the Mediterranean  
193 Garden of Mas de la Serre (42.4740°N, 3.1161°E) in Banyuls-sur-mer, i.e. 12.5 Km from  
194 their population of origin. Paired colonies were installed in the same enclosure (i.e. one pair  
195 of colonies per enclosure) as described in Cronin et al. (2012). Enclosures were 10.8 m<sup>2</sup> in

196 area. They consisted of a circular, vertical, metal chamber 1 m high filled to a height of  
197 approximately 0.5 m with a 1:1 sand:earth mix (see details in Cronin et al. 2012). Enclosures  
198 have the same number than in Cronin et al. (2012), and enclosure #7 was not used.

199

200 Colonies were recovered from the enclosure at the time of sexual production (23<sup>rd</sup> to  
201 29<sup>th</sup> of May 2011). In *C. cursor*, colony fission (i.e. the founding of new colonies by queens  
202 with the help of workers) takes place soon after sexual production (Chéron, Cronin, et al.,  
203 2011; Lenoir, Quérard, Pondicq, & Berton, 1988). We timed the collect of colonies to  
204 maximize the probability that most sexuals would have emerged or be sufficiently advanced  
205 in their development to be sexed by dissection of large cocoons. At the same time, we paid  
206 attention to collect colonies before monogyny was restored (i.e. before all but one gynes were  
207 killed) to avoid losing gynes necessary for genetic analyses. Although we were largely  
208 successful and indeed collected a large number of sexuals, colony fission had started in five of  
209 nine enclosures (Figure 1). All nests except one (the queenright nest in enclosure 2) were fully  
210 excavated, and we censused the number of workers, gynes, males and large cocoons (i.e.  
211 cocoons of sexual). Large cocoons were opened and all were at the pupal stage and could be  
212 sexed by morphology. In enclosure 2, the nest with the marked queen not found in May was  
213 discovered in September, when we checked the enclosure for another purpose. The nine  
214 marked queens were therefore eventually all recovered. Colonies are identified by the number  
215 of the enclosure followed by QR or QL for queenright and queenless (orphaned) colonies,  
216 respectively, and a letter identifying colonies that were initially transplanted in the enclosure  
217 (a) and new colonies that they produced by fission (b to d). For instance, 1-QR-a and 1-QL-b  
218 design the queenright colony initially transplanted in enclosure 1 and a new colony produced  
219 by fission of the orphaned colony of enclosure 1, respectively.

220

221 *Success of queenright and queenless colonies*

222

223 The queenright colony could be identified by the presence of the marked queen in all  
224 enclosures, but when more than one queenless nest was recovered their origin was uncertain.  
225 Queenless nests from the five enclosures where fission had started were assigned to either the  
226 queenright or the orphaned colony using the genotypes of two workers per nest (see below  
227 genetic analysis).

228

229         The ratio of workers lost during the course of the experiment was compared between  
230 orphaned and queenright colonies using a non parametric Wilcoxon paired test. Colonies were  
231 paired by enclosure to control for potential differential success among enclosures (Cronin et  
232 al. 2012). Given that there is no hibernating brood and that worker emergence only starts at  
233 the time or just after sexual production, colonies can only lose workers between March (time  
234 of transplantation) and May (time of collection). We calculated the ratio of workers lost as the  
235 difference in worker number between March and May divided by the number of worker in  
236 March. When a colony had fissioned into several nests, we pooled the nests belonging to the  
237 same colony (identified through the genetic analysis above) to obtain colony size in May and  
238 reproductive success.

239

240         We compared sexuals production by orphaned and queenright colonies after parentage  
241 identification of sexuals (see genetic analysis below) using a Wilcoxon paired test. As for the  
242 ratio of workers lost, we pooled the sexuals from newly founded nests with those from the  
243 corresponding mother colony. To determine the number of males produced, we removed the  
244 foreign males identified by the genetic analysis (see below) from the number of males  
245 collected.

246 Note that for enclosure 2, the queenright nest was not found in May but was collected  
247 a few months later as explained above, hence enclosure 2 was removed to perform the  
248 Wilcoxon paired tests.

249

#### 250 *Genetic analysis*

251

252 To identify the mode of reproduction and the colony of origin of sexuals, we genotyped the  
253 queens of experimentally orphaned (n=7) and queenright (n=9) colonies and all sexuals  
254 collected (males: 128 adults and 29 pupae dissected out of large cocoons; gynes: 349 adults  
255 and 56 pupae) at 8 microsatellites (Doums, Cronin, et al., 2013; Pearcy, Clémencet,  
256 Chameron, Aron, & Doums, 2004) (multiplex 6: cc51, cc58, cc65, cc100 and multiplex 7:  
257 cc61, cc11, cc46, cc99). In each enclosure, we genotyped around 20 workers from the  
258 queenless nest that produced the more gynes, which was likely to be the transplanted  
259 orphaned colony, to compare patriline distribution in workers and gynes. For enclosure 4, we  
260 also genotyped 20 workers from the queenright nest because the results showed that three of  
261 its ten gynes were produced by workers from the paired orphaned colony (see Results). We  
262 also genotyped two workers from each smaller queenless nests, which were likely to be newly  
263 founded nests, to assign them to either the initial orphaned or queenright colony as their  
264 mother colony (see below). A total of 806 individuals were thus genotyped (16 queens, 227  
265 workers, 157 males and 405 female sexuals, Table A1).

266

267 DNA was extracted from the head (half of the head for gynes) of each individual in  
268 500  $\mu$ L of Chelex 10% with 20  $\mu$ L of protein K. The samples were incubated for 4h at 55°C  
269 followed by 15 min at 100°C. After centrifugation, 20  $\mu$ L of supernatant was taken for  
270 subsequent PCR. PCRs were carried out in a 10  $\mu$ L volume containing 1  $\mu$ L DNA solution

271 (10–40 ng of DNA), 150  $\mu$ M of each dNTP, 100 nM of each primer (except for Ccur65: 250  
272 nM; Ccur99: 150 nM; Ccur100: 200 nM), 1X Taq buffer (with MgCl<sub>2</sub> 1.5 mM final) and 0.75  
273 unit of Taq DNA polymerase (Q Biogen). Thermocycle conditions were as follows: 10 min at  
274 94°C followed by 10 amplification cycles at 94°C for 15 s, 52°C for 15 s, 72°C for 30 s, 20  
275 amplification cycles at 89°C for 15 s, 52°C for 15 s, 72°C for 30 s and a final elongation step  
276 of 10 min at 72°C. Amplification products were loaded together on a 3500 Genetic Analyzer  
277 (Applied Biosystems) and allele sizes were estimated using GenMapper 4.0 software. A  
278 previous study detected no linkage disequilibrium or departure from Hardy-Weinberg  
279 equilibrium in the population studied (Doums, Cronin, et al., 2013).

280

281 We used the software Colony (Jones & Wang, 2010) to assign workers to their mother  
282 queen (and subsequently assigned the queenless nests in the enclosure in which fission had  
283 started), determine worker patriline and, for the two colonies that had been collected  
284 queenless, infer queen genotype. Colony was run assuming multiple mating by females, a  
285 medium prior with a paternal sibship of four and a maternal sibship of 20. We provided the 16  
286 available mother queens and assumed a probability of the mother being in these 16 queens of  
287 0.9 (since two queens were missing). We were able to deduce the genotype of the mother  
288 queen for only one of the two colonies that had been collected queenless (nest 3-QL-a).  
289 Colony proposed up to eight mothers for the other queenless colony (nest 6-QL-a, see results)  
290 hence we did not use it for comparing patriline distribution in workers and gynes.

291

292 *Origin and mode of production of gynes*

293

294 All gynes could unambiguously be identified as offspring of either the queen or workers of  
295 the queenright or orphaned colony, because these queens had at least four diagnostic loci

296 (with no common alleles). The assignment was done manually because recombination during  
297 thelytoky can lead to the transition from the heterozygous to the homozygous state (Pearcy et  
298 al. 2011 for queens, Chéron, Monnin, et al. 2011 for workers). Hence at some loci, a worker-  
299 produced gyne could be homozygous at a paternal allele and have no common allele with the  
300 mother queen. We therefore only used heterozygote loci to assign the gynes to one of the two  
301 possible colonies.

302

303           In queenright colonies, we assessed whether gynes were produced by sexual or  
304 thelytokous reproduction of the mother queen, or by thelytokous reproduction of workers. We  
305 compared the genotype of gynes with those of the mother queen. If all alleles of a gyne were  
306 present in the queen, we concluded that the gyne had been produced parthenogenetically by  
307 the queen. When at least one locus of a gyne was heterozygous with one allele present in the  
308 mother queen and one allele not present in the mother queen, we concluded to sexual  
309 reproduction of the queen. For a few gynes, we observed a maternal or non-maternal allele at  
310 the homozygous state for one or two loci (see results) and concluded that the gyne had been  
311 produced by thelytoky of a worker (see Doums, Cronin, et al. 2013 for additional  
312 informations on the identification of worker produced gynes). In this last case, the PCR  
313 amplification was performed a second time to confirm the genotype.

314

### 315 *Origin of males*

316

317 In *C. cursor*, workers do not produce males in presence of the queen (Doums, Ruel, et al.,  
318 2013; Pearcy, Timmermans, Allard, & Aron, 2009). We therefore considered that males  
319 carrying one or more alleles absent in the queen were foreigners. To investigate further the  
320 origin of foreign males, we tested whether they could be the offspring of one of the other

321 queens from our enclosures using the software Colony. None of the 42 haploid foreign males  
322 could be the offspring of a queen of our enclosures. Moreover, for six of the eight loci, the  
323 allelic distribution was significantly different between the queens and the pool of foreign  
324 males (fisher exact tests:  $P = 0.02$  (L46);  $P = 0.07$  (L51);  $P < 0.001$  (L11);  $P < 0.001$  (L58);  $P$   
325  $= 0.01$  (L61);  $P < 0.001$  (L99);  $P < 0.001$  (L100);  $P = 0.27$  (L65)). Given that genetic  
326 differentiation can be very high even at the scale of few kilometres in this species (Clémencet  
327 et al., 2005), it is very likely that the foreign males originated from colonies naturally  
328 occurring in the vicinity of the enclosures.

329

### 330 *Comparison of worker and gyne patriline distribution in queenless nests*

331

332 The genotypes of 201 workers were used for determining patriline distribution in orphaned  
333 colonies and in the queenright colony of enclosure 4 using the software Colony.  
334 Unfortunately, we could not consider nest 6-QL-a because it was collected queenless before  
335 the onset of the experiment and it was not possible to deduce the genotype of the queen from  
336 workers' genotypes (see above). We considered the diploid males as gynes since they are  
337 produced by thelytokous reproduction of workers (Doums, Ruel, et al., 2013). We determined  
338 the patriline of the diploid males visually (see above). The distribution of paternity frequency  
339 was compared between workers and gynes using a Fisher exact test with the null hypothesis  
340 that there was no difference in patriline distribution.

341

342 All statistical analyses were conducted using the R program (R Core Team, 2016) with  
343 RStudio (RStudio Team, 2016), and graphics were drawn with ggplot2 package (Wickham,  
344 2009).

345

346

## 347 RESULTS

348

### 349 *Success of queenright and queenless colonies*

350

351 At least two nests were found in each enclosure, and they matched the two colonies initially  
352 transplanted in the enclosures. The process of colony fission had started at the time of colony  
353 collection in five enclosures where more than two nests were recovered (Figure 1). Newly  
354 founded nests contained fewer workers (median 56 workers, quartiles 40-103) and no or few  
355 gynes and hence could not be confounded with the two colonies initially transplanted, which  
356 were more populous (median 314 workers, quartiles 280-479) except for nest 8-QL-a (Figure  
357 1). The genetic analysis of two workers from each of the 12 newly founded nests allowed to  
358 unambiguously assign them to their mother nest. Nine (75%) originated from orphaned  
359 colonies and three from queenright colonies (Figure 1). This demonstrates that orphaned  
360 colonies can found new colonies by fission.

361

362 The ratio of workers lost during the 11 weeks spent in the enclosures varied from 0.32  
363 to 0.68 (Figure 2a). Orphaned colonies lost a higher ratio of workers than paired queenright  
364 colonies in all but one enclosure, and overall worker loss was significantly higher for  
365 orphaned colonies (median of 0.58 vs. 0.41, respectively, Wilcoxon paired test :  $V = 2$ ,  $ddl =$   
366  $7$ ,  $p = 0.023$ ; Figure 2a).

367 All orphaned colonies produced gynes, and these gynes were all thelytokous offspring  
368 of natal workers (i.e. workers that were themselves daughters of the mother queen that we  
369 experimentally removed or inferred). In *C. cursor*, worker thelytoky allows requeening in the  
370 laboratory (Cagniant, 1980; Chéron, Monnin, et al., 2011). This is the first unambiguous



371 demonstration that it also allows requeening under semi-natural conditions and despite the  
372 presence of a queenright competitor colony.

373

374 We compared sexuals production by orphaned and queenright colonies after parentage  
375 identification of sexuals (see below). As for the ratio of workers lost, we pooled the sexuals  
376 from newly founded nests with those from the corresponding mother colony. A total of 405  
377 gynes were produced, with 79% produced by orphaned colonies. All orphaned colonies  
378 produced gynes whereas less than half queenright colonies did (Figure 1). Six out of eight  
379 orphaned colonies produced more gynes than the paired queenright colony, even though this  
380 was marginally not significant (Wilcoxon paired test:  $V = 4$ ,  $ddl = 7$ ,  $p = 0.055$ ; Figure 2b).  
381 On the opposite, orphaned colonies produced only eight males and they were all diploid (see  
382 below), while two queenright colonies produced a total of 98 haploid males (57 and 41)  
383 (Figure 1).

384

385 Orphaned colonies that produced many sexuals experienced more worker reproduction  
386 and associated conflicts than colonies that produced few sexuals. If reproduction and conflicts  
387 are costly the former suffered a higher cost which may have resulted in a higher loss of  
388 workers. Supporting this idea, we found a positive significant correlation between the rate of  
389 worker loss and the number of sexuals produced in orphaned (Wilcoxon paired test,  $P =$   
390  $0.004$ ) but not in queenright colonies (Wilcoxon paired test,  $P = 0.11$ ).

391

392 *Origin and mode of production of gynes*

393

394 Orphaned colonies produced numerous gynes (320) and all were thelytokously-produced by  
395 workers. In contrast, in the four queenright colonies that produced gynes most gynes were

396 thelytokously-produced by the mother queen (72 out of the 85 gynes i.e. 85%, including all  
397 gynes from nests 1-QR-a, 3-QR-a and 5-QR-a, Figure 1). The remaining 12 gynes were non-  
398 clonal and found in two nests. Two from the newly founded nest 3-QR-b were produced by  
399 worker thelytoky. However, it is unclear if these gynes were produced in presence of the  
400 queen. Indeed, nest 3-QR-b is a small new nest and it is possible that it had been founded by  
401 workers (by accidental colony fission) following the implantation of colonies in the enclosure.  
402 Ten non-clonal gynes were found in nest 4-QR-a. Five were likely worker-produced, two  
403 were either worker-produced or sexually-produced by the queen, and the remaining three  
404 were offspring of foreign workers (they had at least four heterozygote loci with no alleles in  
405 common with the mother queen, Table A2). It is telling that these three foreign gynes  
406 belonged to two patriline (P1 and P3) found in the orphaned colony from the same enclosure  
407 (4-QL-a). This strongly suggests that worker drifting and intra-specific social parasitism had  
408 occurred, and this is corroborated by the finding that one of the 19 workers screened in  
409 queenright colony 4-QR-a also belonged to the same patriline (P1) from the orphaned colony.  
410 There is therefore little doubt that drifting occurred from the orphaned to the queenright  
411 colony and was followed by reproduction, i.e. that social parasitism occurred.

412

413

414 *Origin of males*

415

416 Out of the 121 males found in queenright colonies, 15 could be considered as foreigners as  
417 they had six to seven alleles different from those of the queen. Out of the remaining 106  
418 males, one was diploid (nest 1-QR-a) and had a genotype similar to gynes, suggesting that it  
419 resulted from inbreeding linked to thelytokous reproduction by the queen. The remaining 105

420 males were found in nests 1-QR-a, 2-QR-b and 8-QR-a and resulted from queen arrhenotoky  
421 (Figure 1).

422

423 Far fewer males (36) were found in orphaned colonies. All haploid males (27) were  
424 likely foreigners as they harboured one to eight alleles absent from workers. All these foreign  
425 males were adults and collected in nests producing gynes. Nine males were diploid, of which  
426 eight belonged to the same patriline as gynes and could have been produced by worker  
427 thelytoky while the remaining one was probably a foreigner.

428

429 *Comparison of worker and gyne patriline distribution in queenless nests*

430

431 A total of 201 workers were used to determine patriline distribution (nest 6-QL-a was  
432 excluded as the genotype of the mother queen could not be determined, see M&M). All but  
433 two were offspring of the mother queen. One of these two foreign workers (in nest 8-QL-a)  
434 could not be the offspring of any of our sampled queens. The second foreign worker (in nest  
435 4-QR-a) came from the orphaned colony of the same enclosure (nest 4-QL-a). The  
436 distribution of patrilines significantly differed between gynes and workers in three out of the  
437 eight colonies tested (Figure 3). In one of these three nests, most gynes belonged to patrilines  
438 not sampled in workers (Figure 3, nest 2-QL-a).

439

440 DISCUSSION

441

442 In many species of social insects, orphanage results in colony death. In others, the lost queen  
443 is replaced and the colony carries on, yet orphanage is a crisis situation during which colony  
444 functioning is disturbed and poor colony growth ensues. In addition, orphaned colonies are

445 predicted to be particularly prone to reproductive conflicts in polyandrous species (Châline,  
446 Arnold, Papin, & Ratnieks, 2003; Chéron, Monnin, et al., 2011; Hughes & Boomsma, 2008),  
447 especially in species where workers can reproduce by thelytokous parthenogenesis (Greeff,  
448 1996). Our experiment under semi-natural conditions shows that in the thelytokous ant *C.*  
449 *cursor*, orphaned colonies lost a larger ratio of workers than queenright colonies, yet  
450 produced many gynes as well as new incipient nests. This is to our knowledge the first  
451 unambiguous demonstration that orphaned *C. cursor* colonies can requeen and fission under  
452 quasi-natural conditions even though worker reproduction was costly. The results also suggest  
453 the occurrence of cheating patriline at a low frequency, in both orphaned and queenright  
454 colonies, as well as the occurrence of intra-specific social parasitism, with some workers from  
455 one orphaned colony drifting into the paired queenright colony and producing gynes.

456

457         Thelytokous worker reproduction allows requeening of colonies that become  
458 queenless during overwintering. However, orphaned colonies lost a larger ratio of workers  
459 than queenright colonies, suggesting that their functioning was impaired. It is likely that many  
460 workers attempted to produce gynes following orphanage and that this was costly. In the  
461 laboratory, orphanage results in many workers laying eggs and the production of a huge  
462 amount of eggs (Cagniant, 1980; Clémencet et al., 2008). How the classic  
463 reproductive/survival trade-off (Harshman & Zera, 2007; Stearns, 1992) applies at the  
464 individual level in social insect is not clear (Kramer, Schrempf, Scheuerlein, & Heinze, 2015),  
465 yet within the worker caste the high investment in reproduction may reduce survival.  
466 Moreover, conflicts over reproduction may be costly at the colony level (Bocher et al., 2008;  
467 Gobin, Heinze, Strätz, & Roces, 2003). For instance, the time devoted to reproduction cannot  
468 be used for colony maintenance and laying workers may avoid the risk of foraging outside  
469 (Roth et al., 2014), which could lead to a lack of resources. Such ergonomic costs of worker

470 reproduction are intuitive but hard to demonstrate (e.g. Bourke, 2011). Some indirect  
471 evidence comes from the fact that colonies control worker reproduction in clonal species  
472 reproducing asexually, where worker reproduction has no genetic cost (Hartmann, Wantia,  
473 Torres, & Heinze, 2003; Teseo, Kronauer, Jaisson, & Châline, 2013). Also, in another species  
474 workers are not policed but refrain from reproducing in incipient colonies, presumably  
475 because the ergonomic costs of worker reproduction would be prohibitively costly in such  
476 small colonies (Moore & Liebig, 2013). Direct costs of conflicts and of reproduction on  
477 worker survival or on colony resources may therefore explain why orphaned colonies suffered  
478 a higher worker loss than queenright colonies.

479

480         The number of new colonies that can be produced by colony fission is more limited by  
481 the number of workers available than by the number of gynes (Cronin, Molet, Doums,  
482 Monnin, & Peeters, 2013). In *C. cursor*, colonies fission into  $4.0 \pm 1.3$  (mean  $\pm$  SD) colonies  
483 in the field (Chéron, Cronin, et al., 2011), or into  $2.35 \pm 0.88$  colonies in our experimental  
484 enclosures where competition for resources may be more severe owing to the limited space  
485 (Cronin et al., 2012). In spite of this, orphaned colonies produced twice as many gynes in the  
486 current experiment (36 on average) than colonies fissioning in the field (14 on average,  
487 Doums, Cronin, et al. 2013). This suggests that they produced more gynes than as required for  
488 requeening and colony fission. We argue that this is because worker thelytoky allows  
489 requeening but also results in reproductive competition between workers, with the effect of an  
490 excess production of gynes. Consequently, most gynes die when monogyny is restored in new  
491 colonies, or else many new colonies are produced but they are small hence have reduced  
492 competitive abilities. Either way, the mass production of gynes appears non-optimal at the  
493 colony level for queenless colonies. This may be because of the conflict over reproduction

494 between workers, or because selection for an efficient requeening strategy is too low which  
495 could occur for instance if orphanage is rare.

496

497         Reproductive cheating occurred in three out of nine orphaned colonies, where some  
498 patriline produced more gynes than their fair share. A similar proportion (3/13) had  
499 previously been observed under laboratory conditions and at an earlier pupal stage (Chéron,  
500 Monnin, et al., 2011). Comparison of patriline distribution in workers and gynes is not  
501 sufficient to clearly demonstrate cheating. Other factors such as differential survival of  
502 patrilines in workers (Clémencet et al., 2008) or queen turnover could also generate  
503 differences in patriline distribution. The latter probably occurs in nest 2-QL-a, where 14  
504 patrilines were detected with clear difference between worker and gyne patrilines distribution.  
505 Cheating is also suggested by the occurrence of worker reproduction in one queenright  
506 colony. These results are in apparent contrast with another study where workers produced no  
507 gyne in presence of the queen (all gynes were queen-produced, by sex or thelytoky, Doums,  
508 Cronin, et al. 2013), even though attempts of worker reproduction nevertheless occurred as  
509 revealed by the presence of worker-produced diploid males (Doums, Ruel, et al., 2013).  
510 Interestingly, the queenright colony where workers reproduced was the only one with a higher  
511 rate of workers loss than in the paired queenless colony (Figure 2, enclosure 4). This suggests  
512 that worker reproductive conflicts may have occurred in this colony, as it did in queenless  
513 colonies. Overall, our results thus suggest the occurrence of cheating at low frequencies, and  
514 in both queenright and queenless contexts. This is expected on relatedness grounds because  
515 the pattern of selection for gyne production through worker thelytoky parallels that for male  
516 production in polyandrous species (Ratnieks, 1988; Wenseleers & Ratnieks, 2006). Workers  
517 are collectively not expected to reproduce because they are equally or more related to queen-  
518 produced gynes (by sex,  $r=0.4$ ; by thelytoky,  $r=0.5$ ) than to worker-produced gynes ( $r=0.4$ )

519 (Doums, Cronin, et al., 2013). However, cheaters can occur at a low frequency because they  
520 are more related to clonal female offspring of their patriline (0.75) than to any other female  
521 offspring (own patriline > mother queen > other patrilines). Because cheaters exploit the  
522 benefits of cooperation they should increase in frequency, until they reach an equilibrium with  
523 cooperators if the fitness of cheaters is negatively frequency dependent, or until they invade  
524 the population and cooperation stops, at which points cheaters cease to exist as such as there  
525 is no more sociality to exploit (Ghoul et al., 2014). Here, the benefits of cheaters are clearly  
526 frequency dependent in regards of relatedness, and they would decrease if too many workers  
527 were to reproduce. Consistently with this, the cheating lineages detected so far have always  
528 been found to be rare in colonies and/or in populations (Härtel et al. 2006; Hughes and  
529 Boomsma 2008; Chéron, Monnin, et al. 2011, this study). Another factor limiting the  
530 frequency of cheaters is that they likely trade-off their investment in colony maintenance and  
531 brood rearing towards reproduction (Roth et al., 2014). This cost may be negligible when  
532 cheaters are rare but may become important if they increase in frequency. One factor that may  
533 favour cheaters is that they may be more likely to engage in social parasitism than other  
534 lineages, in which case they would provide some inclusive fitness to the other worker  
535 patrilines.

536

537         Our experiment showed that workers from one orphaned colony (nest 4-QL-a) drifted  
538 into the paired queenright colony (4-QR-a) where they produced gynes (Figure 1). This is the  
539 first unambiguous demonstration of intra-specific social parasitism in *C. cursor* under natural  
540 conditions, and it corroborates the finding of a previous study under laboratory conditions in  
541 which foreign workers present in one colony produced a disproportionably high number of  
542 gynes (Chéron, Monnin, et al., 2011). The drifting of workers into unrelated colonies is well  
543 known in social insects, including in *C. cursor* (Chéron, Monnin, et al., 2011; Doums, Cronin,

544 et al., 2013). However, it remains largely unclear whether it is an accidental phenomenon, as  
545 in the thelytokous Cape honey bees (reviewed in Goudie and Oldroyd 2014), or an active  
546 process, as in *Bombus terrestris* (Blacher et al., 2013). Orphaned colonies may be more  
547 susceptible to social parasitism by foreign workers. They are weakened by the loss of many  
548 workers and disorganised by the onset of worker reproduction, so that foreign workers may  
549 succeed entering colonies more often. In addition, orphaned colonies stop policing worker  
550 reproduction hence foreign workers that have succeeded entering the colony are more likely  
551 to reproduce unchecked. In our experiment, orphaned colonies did not suffer more from social  
552 parasitism as we found only one foreign worker in one of the nine orphaned colonies, which  
553 is less than in the field where foreign workers occurred in 6 out of 13 colonies (Chéron,  
554 Monnin, et al., 2011). This may be because colonies react to orphanage by tightening the  
555 scrutiny of individuals entering the nest, as occurs in orphaned honeybee colonies that face a  
556 similar threat from social parasitism and respond by being more discriminatory against  
557 foreign workers (Chapman, Makinson, et al., 2009). Alternatively, orphaned colonies may be  
558 a source of social parasitic workers if the intense reproductive conflicts between workers  
559 result in some workers absconding or being expelled from the colony. That is, social  
560 parasitism may be a side effect of the massive worker reproduction in orphaned colonies  
561 rather than an evolved parasitic strategy (Blacher et al., 2013). Our data support this  
562 hypothesis to some extent as we found gynes produced by workers from the orphaned colony  
563 in one of the four queenright colonies that produced gynes (colony 4-QR-a).

564

565         Finally, our results could also shed some light on the potential factors affecting the  
566 evolution of thelytokous parthenogenesis in this species. In general, thelytoky provides some  
567 benefits compared to sexual reproduction, such as the avoidance of the twofold cost of sex, a  
568 reproductive insurance under low population density and the maintenance of co-adapted gene



569 pool (Bell, 1982; Hurst & Peck, 1996; Meirmans, Meirmans, & Kirkendall, 2012). These  
570 benefits also occur in social organisms if the queen reproduces through thelytoky, but other  
571 selective forces come into play when workers use thelytoky as in *C. cursor*. At the colony  
572 level, worker thelytoky is beneficial by allowing requeening after the death of the queen  
573 (Lenoir et al., 1988). Our results show that this factor could indeed play a role in *C. cursor*,  
574 even though the frequency of colony orphanage is unknown. Queens are often replaced by  
575 young queens during colony fission (Chéron, Cronin, et al., 2011) so we surmise that old  
576 queens may be relatively rare and hence orphanage may be relatively uncommon. Assuming  
577 that colonies collected queenless result from natural orphanage and not from the loss of the  
578 queen during collection, we can estimate an upper limit to the frequency of orphanage at the  
579 end of hibernation. Based on this paper and on two other field collections carried out in  
580 March, we found 5.5% of queenless colonies at collection (2/18 queenless colonies in 2011  
581 (this paper); 0/13 in 2013; 1/19 in 2015 (Doums & Monnin, n.d.)). Whether worker thelytoky  
582 could allow requeening or survival of colonies that become orphaned at other times than early  
583 spring, when sexuals are produced, is unclear because gynes would remain virgin. Orphaned  
584 colonies would thus have to produce the workers necessary for their survival by thelytoky (of  
585 gynes and/or workers) until the next mating season, but the high worker loss experienced by  
586 orphaned colonies in our experiment suggests this is unlikely. Therefore, the benefits obtained  
587 by requeening may be insufficient to explain the evolution of worker thelytoky. At the  
588 individual level, worker thelytoky may be favoured by the benefits obtained by cheating,  
589 allowing workers to rewind the tape of social evolution in some ways (Gadagkar, 1997).  
590 However, worker reproduction in presence of the queen and cheating patriline in queenless  
591 colonies are less frequent than in the Cape honey bees (Allsopp et al., 2010; Goudie &  
592 Oldroyd, 2014; Moritz et al., 2011). Ultimately, worker thelytoky may be better explained by  
593 the benefits thelytoky confers to the queen caste (Doums, Cronin, et al., 2013; Pearcy, Aron,

594 et al., 2004). Indeed, intercaste genetic correlations could constrain the evolution of queen-  
595 worker dimorphism such that worker thelytoky may be a nonadaptive “caste load” from  
596 positively selected thelytoky in queens (Holman et al 2013). More studies are required to  
597 confirm the cost and benefits of thelytoky in both castes.  
598

599 DATA ACCESSIBILITY STATEMENT

600 Genetic analyses reported in this article can be reproduced using the data published in  
601 Mendeley (doi:10.17632/83j7xtw6fm.2).

602

603

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825

826 FIGURE CAPTIONS

827 Figure 1: The nine enclosures are depicted as black rectangles with their number between  
828 parentheses (enclosure #7 was not used). Circles represent colonies. In each enclosure, the  
829 two circles at the top of the rectangle are the two transplanted colonies. The red and crowned  
830 circle is the queenright colony and the green circle is the orphaned colony (# identify the two  
831 colonies that were collected queenless). Queenright and orphaned colonies were identified by  
832 the presence of the queen and by their large production of gynes, respectively. Smaller circles  
833 show propagules with the same colour than their mother colony (as determined by genetic  
834 analysis, see Results). The areas of circles are proportional to colony size at the time of  
835 recollection, and are standardised relative to the largest nest within each enclosure. The  
836 number of sexuals collected in each colony is given in light orange for gynes, light and dark  
837 blue for haploid and diploid males, respectively (all diploid males were produced by  
838 thelytoky), and grey for foreign males. All sexuals from queenright colonies were produced  
839 asexually by the queen except in enclosure 4 where they were non clonal (\*) and where seven  
840 were worker-produced, including three originating from the queenless nest. \*\* shows worker-  
841 produced gynes.

842

843

844 Figure 2: Worker loss ratio (a) and gynes production (b) in queenright (QR) and queenless  
845 (QL) colonies. Worker loss ratio is the ratio of the number of workers lost during the 11  
846 weeks spent in the enclosures divided by the initial colony size. Each dot represents one  
847 enclosure labelled with its number (enclosure #7 was not used). Dotted lines correspond to an  
848 equal ratio of worker loss and of gyne production, i.e. dots below the lines correspond to  
849 enclosures where QR colonies had higher worker loss (a) or higher gyne production (b) than  
850 QL colonies (and conversely above the lines).

851 Figure 3: Distribution of patriline in workers (dark grey) and gynes (light grey) for the eight  
852 orphaned colonies and for the queenright colony of enclosure 4. The data are depicted as the  
853 number of workers or gynes for each nest. The probability value of the Fisher test testing the  
854 null hypothesis of no difference in patriline distribution is given between parentheses in the  
855 title for each nest. In nest 4-QR-a, patriline 4AP1 (marked with \*\*\*\*) corresponds to patriline  
856 1 of neighbouring nest 4-QL-a.

857

858

859 **Table A1:** Size and composition of colonies.

Enclosure	Nests	Workers implanted	Workers recollected	Worker genotyped	Sexuals recollected
<b>1</b>	<b>QRa</b>	<b>1,570</b>	<b>824</b>	<b>0</b>	<b>86</b>
	QLa	1,868	465	20	66
	QLb		167	2	1
	QLc		61	2	1
	QLd		82	2	0
<b>2</b>	<b>QRa*</b>	<b>884</b>	<b>632</b>	<b>0</b>	<b>0</b>
	<b>QRb</b>		<b>448</b>	<b>2</b>	<b>7</b>
	QLa	1,298	665	20	75
<b>3</b>	<b>QRa</b>	<b>886</b>	<b>484</b>	<b>0</b>	<b>52</b>
	<b>QRb</b>		<b>38</b>	<b>2</b>	<b>2</b>
	QLa <sup>#</sup>	960	277	20	36
	QLb		45	2	2
	QLc		60	2	1
<b>4</b>	<b>QRa</b>	<b>652</b>	<b>267</b>	<b>20 (1 from A-QL)</b>	<b>12</b>
	QLa	682	320	20	6
<b>5</b>	<b>QRa</b>	<b>505</b>	<b>221</b>	<b>0</b>	<b>5</b>
	<b>QRb</b>		<b>53</b>	<b>2</b>	<b>1</b>
	QLa	1,048	462	21	67
	QLb		9	2	0
<b>6</b>	<b>QRa</b>	<b>606</b>	<b>410</b>	<b>0</b>	<b>0</b>
	QLa <sup>#</sup>	427	135	20	13
<b>8</b>	<b>QRa</b>	<b>1,760</b>	<b>1073</b>	<b>0</b>	<b>41</b>

	QLa	2,101	298	23 (1 foreign)	41
	QLb		433	2	9
	QLc		41	2	0
	QLd		13	2	0
<b>9</b>	<b>QRa</b>	<b>511</b>	<b>298</b>	<b>0</b>	<b>0</b>
	QLa	564	309	20	27
<b>10</b>	<b>QRa</b>	<b>429</b>	<b>269</b>	<b>0</b>	<b>0</b>
	QLa	562	290	20	11

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860 The table gives the number of workers implanted in enclosures in March (enclosure #7 was  
861 not used), recollected from enclosures in May and genotyped, as well as the number of  
862 sexuals collected (all sexuals were genotyped). Nests recollected in enclosures were assigned  
863 to the corresponding implanted queenright (QR) or queenless (QL) colony based on the  
864 presence of the marked queen or on the genetic analysis of workers (see M&M). Queenright  
865 colonies and the new nests they produced are highlighted in bold. \* this nest was not found in  
866 may but collected in September. # these nests were collected orphaned.  
867



868 **Table A2:** genotypes of the queens of nests 4QRa and 4QLa, of their mates inferred from worker genotypes, and of the 10 gynes produced by  
 869 nest 4QRa.

<b>Individuals</b>	<b>L46</b>	<b>L51</b>	<b>L11</b>	<b>L58</b>	<b>L61</b>	<b>L99</b>	<b>L100</b>	<b>L65</b>	<b>origin</b>
<b>Nest 4QRa</b>									
Queen	161/161	196/198	225/245	150/150	245/255	126/126	189/193	248/248	
Mate1	153	216	235	150	265	128	195	248	
Mate2	153	206	235	171	253	128	177	248	
Mate3	153	198	235	150	217	130	193	256	
Mate4	157	204	235	150	241	118	193	248	
Mate5	153	196	235	150	225 or 245	130	193	256	
Mate6	161	188	239	171	251	126	177	250	
Mate7	155	198	225 or 245	150	225	126	191	250	
<b>Gyne G1</b>	<b>153/161</b>	<b>198/198</b>	<b>235/235</b>	<b>165/178</b>	<b>231/253</b>	<b>118/130</b>	<b>191/195</b>	<b>248/250</b>	<b>4QL mate1</b>
<b>Gyne G9</b>	<b>157/157</b>	<b>198/200</b>	<b>235/235</b>	<b>165/178</b>	<b>?/?</b>	<b>118/118</b>	<b>191/191</b>	<b>248/250</b>	<b>4QL mate3</b>
<b>Gyne G11</b>	<b>153/153</b>	<b>196/198</b>	<b>235/259</b>	<b>165/178</b>	<b>231/243</b>	<b>118/130</b>	<b>191/195</b>	<b>246/248</b>	<b>4QL mate1</b>
Gyne G10	<u>161/161</u>	198/216	235/245	150/150	?/?	126/128	189/195	248/248	<u>4QR mate1</u>

Gyne G2	155/161	196/198	<u>245/245</u>	150/150	225/255	126/126	189/191	248/250	<u>4QR mate7</u>
Gyne G4	153/161	198/216	235/245	150/150	255/265	<u>128/128</u>	193/195	248/248	<u>4QR mate1</u>
Gyne G5	153/161	196/216	<u>225/225</u>	150/150	255/265	126/128	193/195	248/248	<u>4QR mate1</u>
Gyne G6	157/161	196/204	225/235	150/150	241/255	118/126	189/193	248/248	4QR mate4
Gyne G7	<u>161/161</u>	198/216	235/245	150/150	??	126/128	193/195	248/248	<u>4QR mate1</u>
Gyne G8	153/161	198/216	235/245	150/150	245/265	126/128	193/195	248/248	4QR mate1

**Nest 4QLa**

Queen	153/157	196/198	235/259	165/171	243/253	118/118	185/191	250/246
Mate1	161	198	235	178	231	130	195	248
Mate2	157	200	235	178	233	118	191	248
Mate3	157 or 153	196	235	150	253	118	193	248
Mate4	153	200	235	150	233	138	193	248
Mate5	157 or 153	196 or 198	235 or 239	150	255	116	193	250 or 246

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870 All gynes were sexually produced. Three were daughters of workers from the queenless nest 4QLa (highlighted in bold), five were probably  
871 produced by workers of the queenright nest 4QRa, and two could have been produced either sexually by the queen or by workers of the  
872 queenright nest 4QRa. The homozygous genotypes showing that gynes were probably parthenogenetically produced by workers are underlined.