



Ecdysteroids affect female reproductive status and outcome of contest over hosts in the parasitoid wasp *Eupelmus vuilleti*

Anthony G.E. Mathiron, Charly Dixneuf, Nathalie Mondy, Charlotte Lécureuil, Ryan Earley, Marlène Goubault

► To cite this version:

Anthony G.E. Mathiron, Charly Dixneuf, Nathalie Mondy, Charlotte Lécureuil, Ryan Earley, et al.. Ecdysteroids affect female reproductive status and outcome of contest over hosts in the parasitoid wasp *Eupelmus vuilleti*. *Hormones and Behavior*, 2020, 125, pp.104819. 10.1016/j.ybeh.2020.104819 . hal-02971516

HAL Id: hal-02971516

<https://univ-lyon1.hal.science/hal-02971516>

Submitted on 22 Aug 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Ecdysteroids affect female reproductive status and outcome of contest**
2 **over hosts in the parasitoid wasp *Eupelmus vuilleti***

3
4 Anthony G.E. Mathiron¹, Charly Dixneuf¹, Nathalie Mondy², Charlotte Lécureuil¹, Ryan L. Earley^{3*}
5 and Marlène Goubault^{1*}

6 ¹Institut de Recherche sur la Biologie de l'Insecte, UMR 7261 CNRS - Université de Tours, Parc Grandmont, 37200
7 Tours, France

8 ² Laboratoire d'Ecologie des Hydrosystèmes Naturels et Anthropisés, CNRS, UMR 5023 - LEHNA, Université Lyon 1, 3
9 rue Raphaël Dubois, 69622 Villeurbanne

10 ³Department of Biological Sciences, The University of Alabama, 300 Hackberry Lane, Box 870344, Tuscaloosa, AL
11 35487, United States

12 *Authors contributed equally

13

14 **Author for correspondence:**

15 Anthony Mathiron

16 E-mail: anthony.mathiron@sfr.fr

17

18 **Abstract.** Ecdysteroids are a family of insect hormones that may play a role in modulating
19 aggressive behavior in reproductive contexts. In Hymenoptera, the few studies investigating the link
20 between ecdysteroid titers, reproduction and aggressiveness during contests concern solely eusocial
21 species. Here, we explored whether ecdysteroid titers influenced female reproductive status as well
22 as aggressiveness and resolution of conflict in a solitary ectoparasitoid, *Eupelmus vuilleti*
23 (Hymenoptera: Eupelmidae). *Eupelmus vuilleti* females parasitize and feed upon juvenile stages of
24 *Callosobruchus maculatus* (Coleoptera: Bruchidae). When two *E. vuilleti* females are simultaneously
25 present on a patch, they tend to protect the host they exploit by displaying aggressive behaviors

26 towards conspecific competitors. To our knowledge, nothing is known about the association between
27ecdysteroids and aggressiveness or the outcome of contests for host access in solitary insects. First,
28we quantified ecdysteroid titers that naturally circulate in females without fighting experience and
29after a contest over host access. Ecdysteroid titers measured after the contest did not correlate with
30female aggressiveness during the contest, but winner wasps had higher titers than both losers and
31females that did not fight. Then, we manipulated hormone titers via injection: ecdysone favored egg
32maturation (i.e., gonadotropic effect) within 24h and increased almost immediately the females'
33probability of winning host access without affecting their aggressiveness. Our results represent an
34important step in understanding how hormones, such as ecdysteroids, mediate insect behavior during
35intraspecific competition.

36

37**Key words:** ecdysteroids, egg maturation, aggressive behaviors, conflict resolution, hymenopteran
38parasitoid

39

40 **1. Introduction**

41 Intraspecific competition for indivisible resources may lead to direct interactions between
42individuals during contests (Kokko, 2013; Hardy and Briffa, 2013). Winning a contest generally
43provides profound fitness benefits to animals as they can get access to food (Barton, 1993; Vogel,
442005), a sexual partner (West-Eberhard, 1979; Schwagmeyer and Woontner, 1985; Simmons, 1986),
45dominance status (Chase, 1974) or a territory (Festa-Bianchet *et al.*, 1990). Because aggressiveness
46may help individuals to obtain such resources, many vertebrate and invertebrate taxa commonly
47exhibit aggressive behaviors during contests (Collias, 1944; Breed and Bell, 1983; Hardy and Briffa,
482013). For example, in parasitoid insects, females compete to lay their eggs on hosts from which
49their offspring develop, and aggressive interactions between females for host access have been
50observed in different parasitoid species (Hughes *et al.*, 1994; Petersen and Hardy, 1996; Field and

51 Calbert, 1999; Goubault *et al.*, 2007; Mohamad *et al.*, 2013, Mathiron *et al.*, 2018). However, being
52 aggressive can also be costly, as associated physical injuries can lead to death (Palombit, 1993;
53 Innocent *et al.*, 2011) and the inherent decrease in vigilance may increase predation risk (Jakobsson
54 *et al.*, 1995; Díaz-Uriarte, 1999).

55 Hormones function, in part, to allow animals to match their physiology to the situations they face
56 and adjust their behavior accordingly. Males of many vertebrates respond to social challenges from
57 conspecific with a rapid increase in androgen titers such as testosterone, which supports and
58 stimulates the expression of aggressive behaviors (reviewed in Wingfield *et al.*, 1990; Moore *et al.*,
59 2019). In insects, there is growing evidence that hormones may respond to social challenge in ways
60 that parallel androgens in vertebrates (reviewed in Tibbetts and Crocker, 2014; Tibbetts *et al.*, 2019),
61 such as in male and female burying beetles *Nicrophorus orbicollis* (Scott, 2006), male lobster
62 cockroaches *Nauphoeta cinerea* (Kou *et al.*, 2008, 2019) and female wasps *Polistes dominulus*
63 (Tibbetts and Huang, 2010). The majority of studies investigating how hormones mediate insect
64 behaviors in competitive contexts have focused on juvenile hormone (JH), but another important
65 class of hormones are the ecdysteroid hormones (ESH) – mainly ecdysone and 20-hydroxyecdysone
66 (20E). In adults, ESH are produced by the fat body, gonads or epidermis (Festucci-Buselli *et al.*,
67 2008; Bloch *et al.*, 2009) and act in almost all body tissues, such as central nervous system, fat body,
68 midgut and reproductive tissues in both males and females (reviewed in Schwedes and Carney,
69 2012). Similar to androgens, ESH pass into the cell and bind to nuclear receptors: in this case, a
70 heterodimer composed of the ecdysone receptor (EcR) and the Ultraspireacle (USP; Thomas *et al.*,
71 1993, Yao *et al.*, 1992). Finally, the receptor–hormone complex binds to specific sequences of the
72 DNA to regulate gene transcription (Bloch *et al.*, 2009; Roy *et al.*, 2018).

73 In adult females, ESH are mainly involved in the control of reproduction and reproductive
74 behaviors (reviewed in Nijhout, 1994; Elekonich and Robinson, 2000; Ringo, 2002). For example, in
75 eusocial Hymenoptera, *Bombus terrestris*, egg-laying mated queens have higher ESH titers than

76 virgin queens (Bloch *et al.*, 2000; Geva *et al.*, 2005), and ESH titers are higher in egg-laying worker
77 honeybees than in both nurses and foragers, and even higher in egg-laying queens (Robinson *et al.*,
78 1991). By contrast, Hartfelder *et al.* (2002) found no difference between virgin queens and mated
79 egg-laying queens of the stingless bee, *Melipona quadrifasciata*. In addition, ESH have rapid actions
80 on cell-membrane properties that might be particularly relevant for understanding their role as
81 behavioral mediators during intraspecific competition (Bloch *et al.*, 2009), but the few studies
82 measuring links between ESH titers and the expression of behaviors such as aggressiveness have
83 found inconsistent results. In eusocial hymenopterans, ESH titers are elevated in highly aggressive,
84 high-ranking workers relative to low-ranking workers in the queenless ant *Strebognathus peetersi*
85 (Brent *et al.*, 2006). In *Polistes dominula*, overwintered foundresses females injected with 20E in the
86 pre- and early-nesting phases were more likely to become dominant (i.e., displaying the highest
87 number of aggressive behaviors). In contrast, 20E titers in the haemolymph are very low and are not
88 associated with dominance rank of females in the late pre-emergent stage in the same species, as well
89 as in the South African species *Polistes smithii* (Kelstrup *et al.*, 2015).

90 Here, we explored how ESH mediate female reproductive status, aggressive behaviors during
91 contests over host access and the outcome of such contests in the parasitoid wasp *Eupelmus vuilleti*
92 Crawford (Hymenoptera: Eupelmidae). *E. vuilleti* is a solitary ectoparasitoid (i.e., only one offspring
93 can develop per host, with supernumerary juveniles being killed during larval competition; Fisher,
94 1961) that parasitizes and feeds upon larvae and pupae of the cowpea seed beetle *Callosobruchus*
95 *maculatus* (Coleoptera: Bruchidae), which infest seeds of *Vigna unguiculata* (Fabaceae). Female *E.*
96 *vuilleti* are known to protect the host they exploit by displaying aggressive behaviors towards
97 conspecific competitors (Mohamad *et al.*, 2010; Mathiron *et al.*, 2018). Previous studies have shown
98 that one major factor affecting aggressiveness and contest outcomes in *E. vuilleti* females is their
99 number of mature eggs (i.e., egg load): females are usually more aggressive and are more likely to
100 win contests when they have a greater egg load (Mohamad *et al.*, 2010, 2012; Mathiron *et al.*, 2018,

101 2019). Moreover, Mathiron *et al.* (2019) showed that wasps fighting over host access were more
102 aggressive when they had more ready-to-lay eggs, and this effect was stronger when females were
103 injected with JH. Finally, it is known that ecdysone is the main ESH secreted by reproductively
104 active females (Bodin *et al.*, 2007, 2009), and that simple contact with a host can trigger an increase
105 in its levels, correlated with the maturation of a single egg within 24 hours (Casas *et al.*, 2009).
106 Altogether, these results indicate the potential of ESH as a behavioral mediator in *E. vuilleti*.
107 Surprisingly, nothing is known about the role of this hormone family in aggressiveness and contest
108 outcome during competition for host access.

109 We designed a first experiment to quantify natural ESH titers circulating in *E. vuilleti* females
110 both without a host and after fighting over a host, and the extent to which contest aggressiveness and
111 outcome relate to these titers. We expected post-contest ESH titers to vary positively with the
112 number of aggressive behaviors displayed by females, and that winner females would have higher
113 titers than losers. Another common method that enables understanding of how hormonal change
114 affects individual responses is hormone manipulation via administration of a given amount of
115 hormones (Tibbetts and Izzo, 2009). We therefore set up a second experiment to determine the effect
116 of ESH, at different titers and time delays, on the number of mature eggs. This permitted us to define
117 the ESH injection conditions to study aggressive behavior independent of a gonadotropin effect. We
118 then studied whether aggressiveness and outcome of contest between wasps were influenced by
119 ecdysone treatment. We expected that individuals treated with ecdysone would display more
120 aggressive behaviors, and would ultimately be more likely to win contests for hosts than control
121 females (i.e., treated with vehicle).

122

123 **2. Material and Methods**

124 **2.1. Laboratory breeding**

125 We collected *E. vuilleti* on cowpea seeds infested by the bruchid beetle *Callosobruchus maculatus*
126 in Togo (West Africa) in 2007. According to the methodology described by Jaloux *et al.* (2004), we
127 then bred parasitoids in the laboratory (IRBI, University of Tours, France) on larvae and pupae of *C.*
128 *maculatus*. We dissected cowpea seeds to collect hosts for *E. vuilleti*, which were then placed
129 individually in a standard transparent gelatin capsule (length: 2 cm, diameter: 0.6 cm). By mimicking
130 a cowpea seed, this system facilitates observation of the number of eggs laid by females, without
131 significantly altering oviposition behavior (Gauthier and Monge, 1999). Previous studies have shown
132 that after a period of acclimation, parasitoid females behave in the same manner to the presence of
133 hosts inside seeds and capsules (Gauthier and Monge, 1999; Jaloux *et al.*, 2004), although the
134 number of eggs laid on hosts is slightly lower inside capsules (Damiens *et al.*, 2001).

135
136 2.2. Females' preparation for behavioral observations

137 During the following three experiments, we isolated parasitoid females directly at their emergence
138 to prevent them from having any previous experience of oviposition and competition. We then
139 placed them individually in petri dishes (diameter: 8.5 cm; height: 2.7 cm), provided with a piece of
140 cotton soaked in water and one pupa of *C. maculatus* located in a gelatin capsule that was renewed
141 each day preceding the experiments. *E. vuilleti* is a synovigenic parasitoid species (Jervis *et al.*,
142 2008): emerging females only have a few ready-to-lay eggs and they mature additional eggs
143 throughout their adult life (oviposition activity increases over time and peaks three days after
144 emergence; Jaloux *et al.*, 2004). We also provided females with one male during the first day for
145 mating and oogenesis stimulation (Terrasse and Rojas-Rousse, 1986). We carried out all
146 experimental procedures in a climate-controlled room at 30°C, 12:12 h light: dark and constant 70%
147 relative humidity.

148

149 2.3. Experiment 1: ESH titers, aggressiveness and outcome of contests

150 2.3.1. *Experimental procedure*

151 To facilitate wasps' identification during contests, we marked them on the dorsal part of their
152 thorax with a dot of bright yellow or bright red acrylic paint. On the day of behavioral observations,
153 we deprived females of hosts for at least 2h before the experiment so that they were more ready to
154 oviposit. All females were of the same age (3 days old), and marked with different colors. Paint color
155 did not affect contest outcomes (red-painted wasps won 15 of 25 contests; binomial test: $P = 0.42$).
156 At the beginning of the observation, we simultaneously introduced wasps into an arena consisting of
157 a plastic block made of three chambers linked by a narrow channel (adapted from Petersen and
158 Hardy, 1996; see Mathiron *et al.*, 2019). Females could freely move throughout the entire arena.

159 We placed either one ($N = 31$) or two females ($N = 30$) in the central chamber already containing
160 a 4th instar larva of *C. maculatus* previously placed in a capsule. A previous study showed that
161 females that experienced oviposition on *C. maculatus* pupae are more motivated to get access to a
162 4th instar larva (Mathiron *et al.*, 2018). In a patch with hosts, females often stop their behavioral
163 oviposition sequence after detecting a conspecific (females raised their antennae in the direction of
164 their opponent; Mohamad *et al.*, 2010). Wasps then either simply kick their opponent with their legs
165 without taking their ovipositor out of the capsule (defensive behavior) or can escalate to a full attack,
166 in which case one female generally chases her opponent away from the capsule, hits her with her
167 head or mounts her (Mathiron *et al.*, 2018). Chasing, hitting and mounting can lead to the loser
168 leaving the central chamber of the arena. We therefore recorded oviposition during all tests, which
169 contestant female displayed first oviposition behavior, and aggressive behaviors displayed by each
170 contestant female. All observations lasted 1h or were stopped when i) one contestant female pushed
171 her opponent out of the central chamber, ii) one exited the central chamber for at least 2 min or iii)
172 neither contestant female touched the host nor displayed agonistic interactions for at least 2 min.
173 When both contestant females stayed in the central chamber during the whole time of observation,

174 the winning female was determined as the one displaying oviposition behaviors (N = 22; mean ± S.E.
175 eggs laid: 1.32 ± 0.19).

176 We immediately froze wasps at -20°C after the experiments, weighed them using an electronic
177 balance (Ohaus Discovery® model, accuracy: 0.01mg), and stored them at -20°C until sample
178 preparation for hormonal quantification. Due to the small body of *E. vuilleti* females (mean body
179 mass ± S.E. = 1.52 ± 0.03 mg; N = 91), we were not able to collect the hemolymph from individuals
180 both before and after behavioral observations. In order to keep as much biological material as
181 possible for subsequent ESH quantification, we also did not dissect females to determine their egg
182 load.

183

184 *2.3.2. ESH quantification using Enzyme Immunoassays*

185 We placed each parasitoid in a 1.5 mL conical microcentrifuge tube with 0.5 mL of methanol
186 (99% HPLC grade), and we crushed them with a polypropylene pestle. After one hour at ambient
187 temperature, we centrifuged samples (10,000 $\times g$ for 5 min), and we transferred the supernatant
188 methanol into a new tube. We dried down these extracts in a SpeedVac (AES 1010 Thermo Savant),
189 and we then stored them at -20°C, until resuspending the samples in 0.180 mL of phosphate buffer
190 (0.01 M) before quantification of ESH titers.

191 Immunoassays (EIA) used for quantification of ESH were conducted according to the method of
192 Porcheron *et al.* (1989) modified for the use of a peroxidase conjugate of 20E as a tracer (De Reggi
193 *et al.*, 1992) and adapted for *E. vuilleti* (Bodin *et al.*, 2007). The L2 polyclonal antibody (gift from
194 Dr. Delbecque, University of Bordeaux, France) is very sensitive to ecdysone, 2-deoxyecdysone and
195 3-dehydro-ecdysone, but ca. six times less sensitive to 20E. Because ecdysone is the main compound
196 found in reproductive *E. vuilleti* female, ESH titers are expressed in ecdysone equivalents (E-eq.,
197 expressed in units of pg/ mg of female parasitoid), as this compound was used for reference curves.
198 To verify the reproducibility of our results, each sample measured by EIA was analyzed in duplicate.

199

200 2.4. Experiment 2: Effect of ecdysone on females' reproductive status

201 To investigate the influence of ecdysone manipulation on female reproductive status, we
202 randomly assigned two-day old wasps to one of four treatments: they received either 0.04 µL of
203 HPLC grade methanol (no female died due to methanol injection during this experiment) or 0.04 µL
204 of three different quantities of ecdysone (i.e. α -ecdysone, purity \geq 90.0 %, purchased from Sigma-
205 Aldrich, Inc.) dissolved in methanol (14, 64 or 120 pg). Immediately after being immobilized on a
206 plate that was cooled by ice, we injected wasps into the abdomen through the intersegmental
207 membrane using the nanoliter injector Nanoject III (Drummond Scientific Company). We then
208 placed females individually in a petri dish and we froze them at -20°C, either 4h (N = 59, 60, 59 and
209 57 for injection of 0, 14, 64 and 120 pg, respectively) or 24h (N = 68, 67, 67 and 62 injection of 0,
210 14, 64 and 120 pg, respectively) after injection. We deprived wasps of hosts so that no mature eggs
211 could be laid during this period. Finally, after weighing all females, we dissected them (N = 119 and
212 118 for 4h and 24h post-injection treatment, respectively) to count mature (i.e., ready-to-lay)
213 oocytes.

214

215 2.5. Experiment 3: Effect of ecdysone on female aggressiveness and contest outcome

216 To investigate the influence of ecdysone manipulation on female aggressive behavior and their
217 probability of winning a contest, we randomly assigned three-day old wasps to two different
218 injection treatments: either with 0.04 µL of ecdysone diluted in methanol (quantity = 64 pg) or 0.04
219 µL of methanol alone (no female died due to methanol injection during this experiment). We marked
220 wasps the day before behavioral observations to allow individual identification during contests. We
221 deprived females of hosts for at least 1h before the start of the contest so that they were more ready
222 to oviposit. Based on our results from Experiment 2 (see section 3.1.), we observed contests between
223 females from 1h to 3h post-injection to avoid an effect of ecdysone treatment on females' mature egg

224 load. As described in experiment 1, we then simultaneously introduced two wasps into the central
225 chamber of the contest arena at the beginning of the observation.

226 We ran contests between either i) one control female (i.e., injected with methanol only) and one
227 test female (i.e., injected with ecdysone; N = 28), or ii) between two control females (N = 25),
228 challenging for a 4th instar larva of *C. maculatus* located in gelatin capsule and previously placed in
229 the central chamber of the contest arena. Contests occurred between females of the same age (3 days
230 old), marked with different colors and visually matched for size; post-experiment data analysis
231 confirmed that contestants of the same dyad did not differ significantly in body mass (paired t-test:
232 $t_{52} = 0.42$, $P = 0.68$). Both females could freely move throughout the entire contest arena.
233 Observations lasted 1h maximum. During all tests, we recorded oviposition behaviors, which
234 contestant female displayed first such behaviors, and attack behaviors displayed by each female.
235 When both females of a dyad stayed in the central chamber during the whole time of observation, we
236 determined the winning female as the one exhibiting oviposition behaviors (N = 44; mean \pm S.E.
237 eggs laid: 0.65 ± 0.1).

238 After each contest, we counted the number of eggs laid on the host by the winning female, and we
239 froze all wasps at -20°C. We finally weighed them and dissected them to count the number of mature
240 eggs in their ovaries. The initial mature egg load of winning females was calculated as the number of
241 mature eggs in their ovaries + the number of eggs laid on the host.

242

243 2.6. Statistical analysis

244 We performed data analyses with the software Rstudio (RStudio Team, 2016), using $\alpha = 0.05$.
245 Our general approach was to use, when possible, parametric analyses in which the assumed
246 distribution of residuals was matched to the data rather than transforming data to fit standard
247 assumptions (Wilson and Hardy, 2002; Hardy and Briffa, 2013). However, we used non-parametric
248 tests when parametric conditions were not satisfied.

249 Experiment 1: For the 30 contests that we observed during experiment 1, 25 contests were
250 resolved (i.e., there was a clear winner and loser female). Therefore, we only considered these
251 contests in the analysis. We first randomly assigned one of the 2 contestant females of each replicate
252 as the focal female, using the ALEA function of Microsoft Excel. We then performed a generalized
253 linear model (GLM) assuming a quasi-Poisson distribution of errors (link function = ‘log’) to test the
254 association between post-trial ESH titers of focal females and their contest experience (i.e., no
255 contest, winner or loser). Pairwise *post hoc* comparisons (function ‘emmeans’) were used to
256 determine significant difference between treatments. We ran the same procedure to test the effect of
257 an interaction between after ESH titers of focal contestant females and ESH of their opponent on the
258 number of attacks displayed by focal contestant females. Then we calculated the relative number of
259 attacks of focal contestant females as the ratio: ‘number of attacks of the focal female / (number of
260 attacks of the focal female + number of attacks of the opponent)’ and the relative difference of post-
261 contest ESH titers between contestant females as the ratio: ‘(post-contest ESH titer of the focal
262 female – post-contest ESH titer of the opponent) / (post-contest ESH titer of the focal female + post-
263 contest ESH titer of the opponent)’. We also defined contest outcome as a binary response: 0 = the
264 focal contestant female lost, 1 = the focal contestant female won. We ran a GLM assuming a
265 binomial distribution of errors (link function = ‘logit’) to investigate whether the interaction between
266 the relative number of attacks of focal females and the relative difference in post-contest ESH titers
267 between females affected the probability of the focal female winning. We used the same procedure to
268 test whether the probability of being first to display oviposition behavior (binary response: 0 = the
269 focal female was not first to display oviposition behavior, 1 = the focal female was the first to
270 display oviposition behavior) was significantly associated with the relative difference in post-contest
271 ESH titers between contestants.

272 Experiment 2: We first investigated whether the number of mature eggs differed significantly
273 between females receiving different ecdysone quantities, 4h after injection, by performing a GLM

274 assuming a quasi-Poisson distribution of errors (link function = ‘log’). We then ran a generalized
275 polynomial model (GPM) with a Poisson distribution of errors (link function = ‘log’) to explore the
276 effect of ecdysone treatments on the number of mature eggs 24h after injection.

277 Experiment 3: Of the 74 contests that we observed during experiment 3, 53 contests were clearly
278 resolved. We only considered these contests in the following analysis. We first verified that initial
279 egg load did not differ between ecdysone-treated females ($N = 28$; mean egg load \pm S.E.: 2.6 ± 0.3)
280 and control females ($N = 78$; mean egg load \pm S.E.: 2.4 ± 0.2 ; Mann-Whitney test: $U = 1197.5$, $P =$
281 0.44). We then ran a GLM with a quasi-Poisson distribution of errors (link function = ‘log’) to test
282 the effect of injection treatment, initial egg load of focal females, initial egg load of opponent
283 females and two-way interactions between these variables on the number of attacks displayed by
284 focal females. We also calculated the relative number of attacks of focal females as described for
285 experiment 1, and we determined the relative difference in initial mature egg load between females
286 as the ratio: ‘(initial egg load of the focal female – initial egg load of the opponent) / (initial egg load
287 of the focal female + initial egg load of the opponent)’. We then performed a GLM with a binomial
288 error distribution (link function = ‘logit’) to explore the influence of injection treatment, the relative
289 number of attacks of focal females and the relative difference in egg load between females on the
290 probability of the focal female winning. The model included the three main effects and the two-way
291 interactions between variables. We used the same procedure to investigate whether the probability of
292 being first to display oviposition behavior varied with the injection treatment received by focal
293 females.

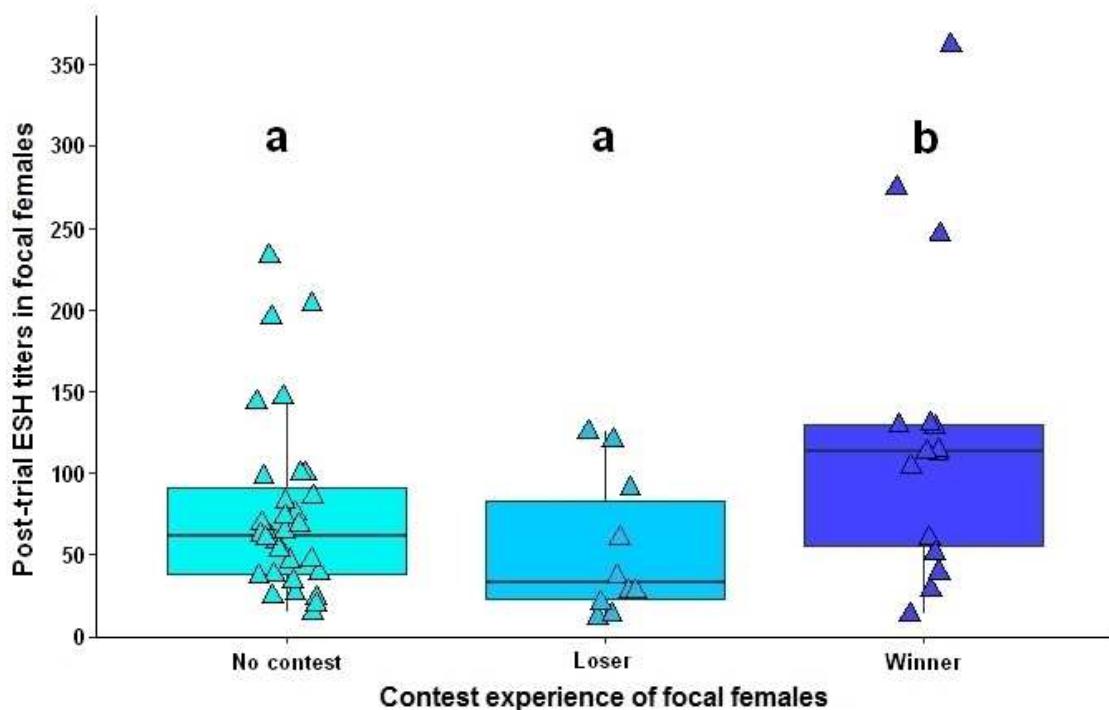
294 For all analyses, likelihood ratio and F statistics were calculated using the ‘Anova’ function
295 (package car), which performs type 2 analysis of variance for GLM models, that is, invariant to the
296 order in which effects are entered into the model (Fox and Weisberg, 2019).

297

298 **3. Results**

299 3.1. Experiment 1: ESH titers, aggressiveness and outcome of contests

300 We found a significant difference in post-trial ESH titers between focal females with different
301 contest experience (GLM with quasi-Poisson distribution of residuals: $F_{2,53} = 4.48, P = 0.02$; **Fig. 1**):
302 winner females had significantly higher post-trial ESH titers (mean \pm S.E. = 127.2 ± 25.2 pg E-eq /
303 mg of female) than losers (mean \pm S.E. = 53.6 ± 13.6 pg E-eq / mg of female; pairwise *post hoc*
304 comparisons: $P = 0.029$) and females with no contest experience (mean \pm S.E. = 77 ± 9.9 pg E-eq /
305 mg of female; pairwise post-hoc comparisons: $P = 0.047$). However, post-trial ESH titers were not
306 significantly different between loser females and females with no contest experience (pairwise post-
307 hoc comparisons: $P = 0.519$).



308

309 **Figure 1.** Post-trial ESH titers (pg E-eq / mg of female) in focal females with different contest experience (no
310 contest: N = 31, loser: N = 10 or winner: N = 15). *: $P < 0.05$. Different letters indicate significant statistical
311 differences.

312

313 We found that the number of attacks displayed by focal contestant females was independent of
314 their post-contest ESH titers (GLM with quasi-Poisson distribution of residuals: $F_{1,21} = 0.01$, $P =$
315 0.91), their opponent's post-contest ESH titers ($F_{1,21} = 0.32$, $P = 0.58$) or the interaction between
316 these variables ($F_{1,21} = 0.03$, $P = 0.86$).

317 The probability of a female winning a contest was not significantly affected by the interaction
318 between the relative number of attacks and the relative difference in post-contest ESH titers between
319 females (**Table 1**). However, it was significantly influenced by both factors independently (**Table 1**):
320 winner females displayed significantly more attacks (mean \pm S.E. = 18 ± 3 attacks) than their
321 opponent (mean \pm S.E. = 9 ± 2 attacks) compared to loser females (mean \pm S.E. = 9 ± 2 attacks) with
322 their opponent (mean \pm S.E. = 21 ± 7 attacks; **Fig. 2A**). In addition, focal females were more likely
323 to win contest when they had higher post-contest ESH titers (mean \pm S.E. = 127.3 ± 25.2 pg E-eq /
324 mg of female) than their opponent (mean \pm S.E. = 74.9 ± 8.8 pg E-eq / mg of female) compared to
325 loser females (mean \pm S.E. = 53.6 ± 13.8 pg E-eq / mg of female) with their opponent (mean \pm S.E. =
326 95 ± 24.3 pg E-eq / mg of female; **Fig. 2B**).

327

328 **Table 1.** Effect of relative number of attacks and relative difference in post-contest ESH titers on winning
329 probability over host of focal females.

Factors affecting contest outcomes	Estimates	d.f.	G	P
Intercept	-5.782			
Relative attacks	13.81	1	13.9	< 0.001
Relative difference in after contest ESH titers	-2.638	1	4.57	0.03
Relative attacks x Relative difference in after contest ESH titers	13.31	1	2.35	0.12

Residuals

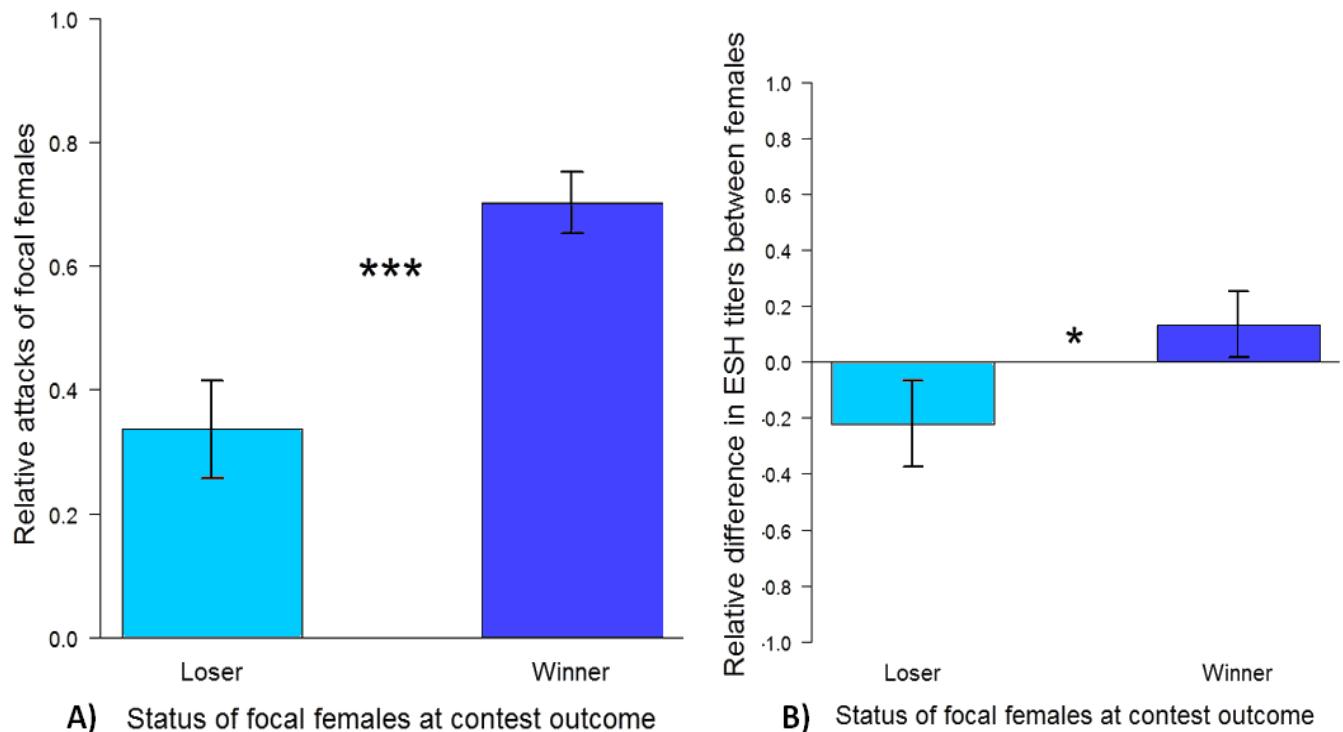
21

Total

24

330 *P*-values of significant explanatory variables are highlighted in bold font.

331



332

333 **Figure 2.** Status of focal females (loser: N = 10 or winner: N = 15) after conflict resolution (N = 25). A) Mean
334 (\pm S.E.M.) relative attacks of focal females. ***: $P < 0.001$. B) Mean (\pm S.E.M.) relative difference in post-
335 contest ESH titers (pg E-eq / mg of female) between females. *: $P < 0.05$.

336

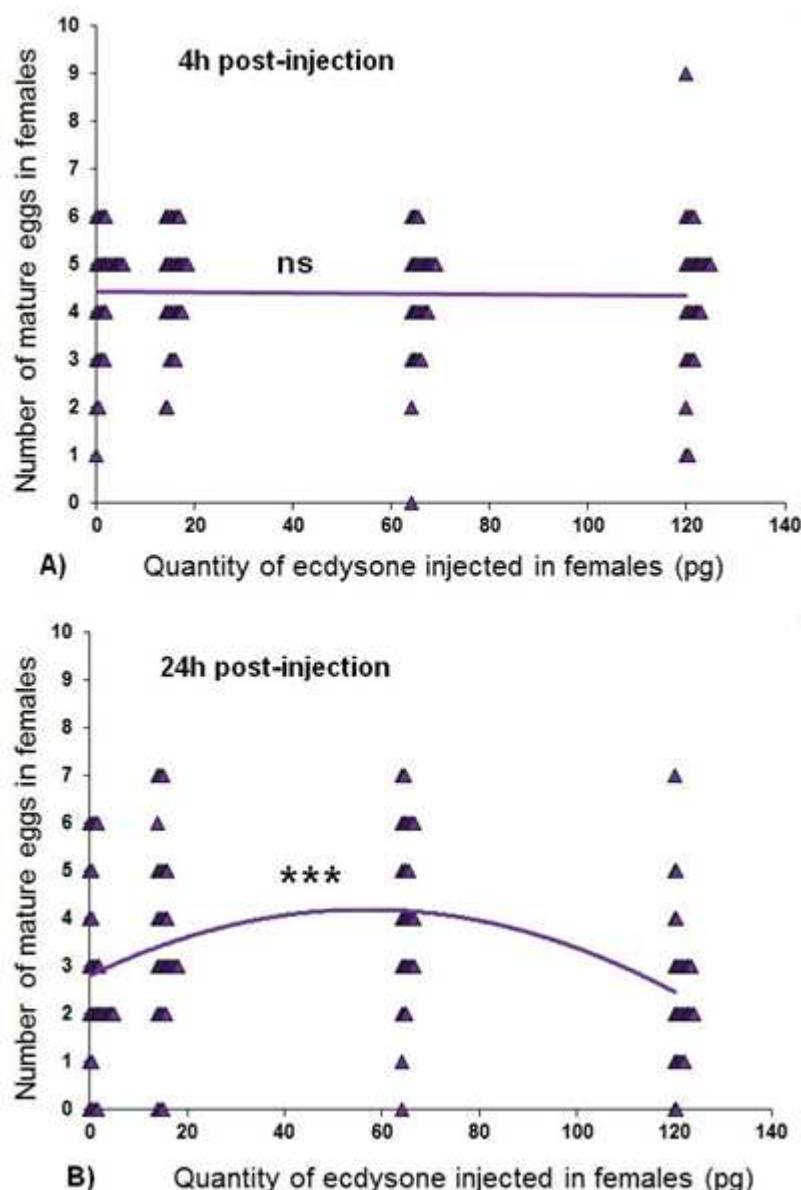
337 The probability of focal females being first to display oviposition behavior was significantly
338 associated with the relative difference in post-contest ESH titers between contestants (GLM with
339 binomial distribution of error: $G_1 = 4.58$, $P = 0.03$). Focal females were more likely to be first to
340 display such behavior when they had higher ESH titers than their opponent.

341

342 3.2. Experiment 2: Effect of ecdysone treatment on females' reproductive status

343 The number of mature eggs in females did not vary across treatments 4h after injection ($F_{1,117} =$
344 0.09, $P = 0.77$; **Fig. 3A**). However, egg load was significantly influenced by treatment 24h after
345 injection, with a dose-dependent effect of ecdysone injection on egg maturation reaching the highest
346 positive effect at 64 pg ($G_1 = 14.33$, $P < 0.001$; **Fig. 3B**).

347



348

349 **Figure 3.** Number of mature eggs in females injected with different quantities of ecdysone. A) 4h after
350 injection. ns: non-significant. B) 24h after injection. ***: $P < 0.001$. Data points have been horizontally
351 displaced from their position to show the numbers of observations.

352

353 3.3. Experiment 3: Effect of ecdysone treatment on female aggressiveness and contest
354 outcome

355 The number of attacks displayed by females was not influenced by injection treatment, initial egg
356 load of females, initial egg load of their opponent, or any interactions between these variables (**Table**
357 **2**).

358

359 **Table 2.** Effect of injection treatment, initial egg load of focal females and initial egg load of the opponent
360 females on the number of attacks of focal females.

Factors affecting aggressiveness	Estimates	df	F	P
Intercept	1.5133			
Injection treatment (control)	-0.6853	1	3.0776	0.09
Egg load of focal females	0.3183	1	3.0297	0.09
Egg load of opponent females	0.0833	1	2.8708	0.10
Injection treatment (control) x Egg load of focal females	0.0402	1	0.0303	0.86
Injection treatment (control) x Egg load of opponent females	-0.0241	1	0.0090	0.92
Egg load of focal females x Egg load of opponent females	-0.0983	1	1.2683	0.27
Residuals			46	

Total	52
-------	----

361 Focal females: ecdysone-treated: N = 28; methanol-treated: N = 25)

362

363 The probability of females winning contests over hosts did not vary significantly with the
 364 difference in egg load between contestants but was significantly influenced by ESH injection (**Table**
 365 **3**): wasps injected with ecdysone were more likely to win contests than females injected with vehicle
 366 alone (**Fig. 4**). Moreover, there was an interaction between the relative attacks of females and the
 367 relative difference in egg load between contestants. Aggressive females had a greater chance of
 368 winning the contest, and this probability increased further when they had more ready-to-lay eggs
 369 than their opponent (see **Table 3**). There were no significant interactions between injection and
 370 either relative attacks or difference in egg load on winning probabilities (**Table 3**).

371

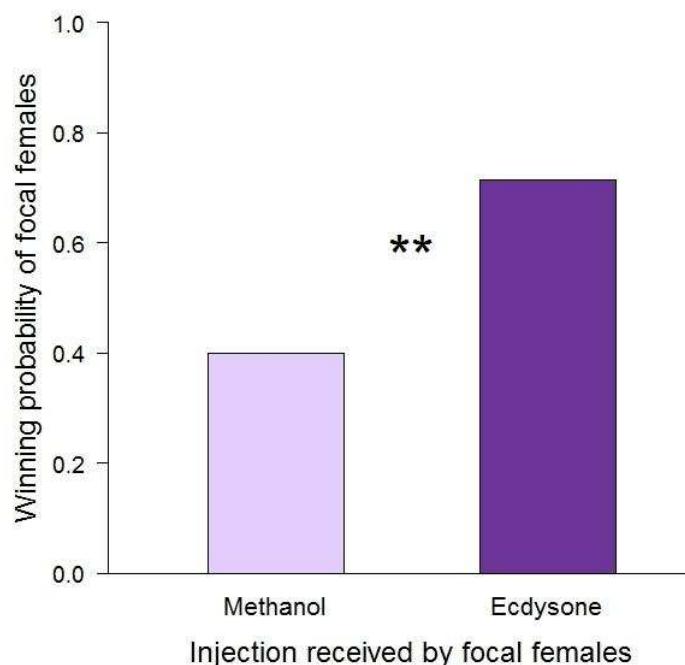
372 **Table 3.** Effect of injection treatment, relative number of attacks and relative difference in egg load on the
 373 winning probability over host of focal females.

Factors affecting contest outcomes	Estimates	df	G	P
Intercept	-1.8814			
Injection treatment (control)	-0.4766	1	9.88	0.002
Relative attacks	8.8585	1	19.1	< 0.001
Relative diff. in egg load	-2.9157	1	0.04	0.84
Injection treatment (control) x Relative attacks	-5.9728	1	3.78	0.05
Injection treatment (control) x Relative diff. in egg load	1.8775	1	1.08	0.30

Relative attacks x Relative diff. in egg load	7.7581	1	4.70	0.03
Residuals	46			
Total	52			

374 *P*-values of significant explanatory variables are highlighted in bold font. Focal females: ecdysone-treated: N
 375 = 28; methanol-treated: N = 25)

376



377

378 **Figure 4.** Winning probability of focal females according to the injection treatment they received before a
 379 contest (methanol (control): N = 25 or ecdysone in methanol: N = 28). **: *P* < 0.01

380

381 The probability of a contestant displaying first oviposition behavior varied significantly with
 382 injection treatment (GLM with binomial distribution of error: $G_1 = 4.66$, $P = 0.03$): females injected
 383 with ecdysone were more frequently the first to display such behavior (16/28 contests) than control
 384 females (7/25 contests).

385

386 **4. Discussion**

387 Our work aimed to explore the role of ESH in female aggressiveness and conflict resolution over
388 oviposition sites (hosts) in the solitary ectoparasitoid *E. vuilleti*. First, we showed no link between
389 naturally circulating post-contest ESH titers in females and their aggressiveness when fighting for
390 host access, but winner females had higher ESH titers than losers after the contest and females that
391 did not experience contest. Second, when measuring how ecdysone manipulation affects egg
392 maturation, we found that ecdysone injection had a dose-dependent gonadotropin effects at 24h post-
393 injection. Finally, ecdysone injections had no effect on female aggressiveness during contests over a
394 host, but ecdysone-injected females were more likely to win contests over a host.

395

396 **4.1. ESH, aggressiveness and outcome of contest over host**

397 One main finding of our study – supported by both hormone quantification and hormone
398 manipulation – is that ESH are involved in the outcome of contests over hosts in *E. vuilleti*. First, we
399 found that females that won fights over hosts had higher post-contest ESH titers than both loser
400 females and females that did not experience a contest. This agrees with previous works in
401 bumblebees (Bloch *et al.*, 2000; Geva *et al.*, 2005) and queenless ants, *Streblognathus peetersi*
402 (Brent *et al.*, 2006), showing that ESH titers are higher in high-ranking than in low-ranking workers.
403 Here, we are not able to determine whether ESH titers were already high in eventual winner prior to
404 the contests or ESH titers increased as a result of winning. Supporting one hypothesis than another
405 would need hormones quantification both before and after contest, which is not yet technically
406 feasible in small animals such as *E. vuilleti*. Nevertheless, our results demonstrate that ESH titers are
407 associated with the outcome of contests over hosts. Moreover, in our study, contestant females
408 injected with ecdysone were more likely to win compared to control females. In the only one
409 experiment that directly tested the effect of ESH injection on contests between conspecific
410 individuals in insects, Röseler *et al.* (1984) also found that injecting 20E in females of the eusocial

411 wasp *Polistes dominula*, alone or coupled with JH-I, increased the probability of attaining dominant
412 status compared to control individuals. To our knowledge, our study shows, for the first time, the
413 importance of ESH in outcomes of intraspecific competition for the access to an indivisible resource
414 in a solitary insect species.

415 In both vertebrate and invertebrate taxa, it is well known that individuals displaying higher levels
416 of aggressiveness during intraspecific competition are more likely to win access to indivisible
417 resources (Breed and Bell, 1983; Hsu *et al.*, 2006; Hardy and Briffa, 2013; but see Scott, 2006).
418 Here, we also found such a relationship between aggressiveness and contest outcome, with *E. vuilleti*
419 females being more likely to win when showing relatively more attacks. However, this link appeared
420 to be independent of ESH titers. Indeed, post-contest ESH titers in fighting wasps did not correlate to
421 their level of aggressiveness and the relative number of attacks displayed by contestants did not vary
422 significantly with the injection treatment they received. Similarly, Kelstrup *et al.* (2014a, b) showed
423 no relationship between ESH titers and aggressive behaviors, neither in females of the caste-flexible
424 epiponine wasp *Synoeca surinama*, nor in queens and workers of the swarm-founding eusocial wasp
425 *Polybia mycans*. Altogether, these data support the idea that ESH are not involved in modulating
426 aggressive behaviors in these insects. In *E. vuilleti*, such agonistic behaviors are mediated by JH
427 (Mathiron *et al.*, 2019). Although we still lack information about the interplay between both families
428 of hormones, our present work might suggest that ESH did not stimulate JH sufficiently to mediate
429 female aggressiveness within the time frame of our experiments (under 3 hours).

430

431 4.2. ESH, egg load and contest outcome

432 As observed in many other insect species (reviewed in Nijhout, 1994; Swevers and Iatrou, 2009),
433 ecdysone has a gonadotropin effect in *E. vuilleti* females. By manipulating ESH levels, we showed
434 that wasps' egg load increased with the quantity of ESH injected after 24h, with the greatest effect at
435 64 pg. The absence of a measurable response of egg load to ecdysone injection at the highest dose

436 (i.e., 120 pg) may result from negative feedback driven by ecdysone binding its receptors (Beydon
437 and Lafont, 1983; Parvy *et al.*, 2014). Interestingly, this gonadotropin effect was observed 24h after
438 injection but not 4h post-injection, suggesting that egg maturation takes longer than 4h in *E. vuilleti*
439 (see also Mathiron *et al.*, 2019). By observing wasps fighting over hosts between 1h and 3h post-
440 injection in our last experiment, we were thus able to disentangle the effects of ecdysone and egg
441 load on aggressiveness and contest outcome.

442 Female fertility is known to strongly affect behavioral strategies during contests over hosts in *E.*
443 *vuilleti*, with wasps with a higher egg load than their opponent being more likely to win host access
444 (Mohamad *et al.*, 2010, 2012; Mathiron *et al.*, 2018, 2019). Game theory models predict that the
445 outcome of a conflict is influenced by the existing asymmetry between competitors in terms of
446 subjective resource value (Maynard Smith and Parker, 1976; Enquist and Leimar, 1987). Parasitoid
447 females with more ready-to-lay eggs should place a higher value in the hosts, which should lead
448 them to win more often, as observed in different parasitoid species (e.g. Stokkebo and Hardy, 2000;
449 Mohamad *et al.*, 2010; but see Goubault *et al.*, 2007). The underlying mechanisms remain, however,
450 unknown. Because ecdysone is produced by active ovaries and partially stored in the eggs of *E.*
451 *vuilleti* females (Mondy *et al.*, 2006; Bodin *et al.*, 2007), this effect of egg load asymmetry on
452 contest outcome may actually result from the action of ESH produced by mature eggs. In experiment
453 1, we thus quantified post-contest ESH titers in females without determining their initial egg load
454 (we could not dissect them without impairing ESH quantification). It is therefore possible that
455 winner females were the ones with more ready-to-lay eggs prior to the contest; these females may
456 have had higher ESH titers and attacked more to get access to the host. The fact that we did not
457 observe a relationship between the number of mature eggs and winning probability in our last
458 experiment also supports this idea: the ecdysone we injected in females bypassed the actions of
459 ecdysone naturally produced by eggs, masking the usual link between egg load and winning success.

460 As a result, ESH would not solely have an autocrine and/or paracrine action in the ovaries, but also
461 an endocrine role in the mediation of female *motivation* to get access to the host.

462

463 4.3. How can ecdysone increase the probability of winning contests?

464 The mechanism underlying the association between wasps with higher ESH titers and their
465 elevated winning probability remains to be determined. From our results, it appears to be
466 independent of the modulation of aggressive behaviors, because ESH did not drive variation in
467 aggressiveness in our experiments. An alternative explanation would be that ecdysone increases
468 female motivation to lay their eggs, leading them to exploit the host faster than control conspecifics.

469 This would lead them to win host access more often. Previous studies investigating the role of ESH
470 on *E. vuilleti* oogenesis found an increase in ecdysone titers after simply contacting a host, which
471 correlated with maturation of an egg within 24 hours (Bodin *et al.*, 2007, 2009; Casas *et al.*, 2009).

472 As such, females with higher ESH titers than their opponent would be more ready to lay eggs, and
473 would thus be more likely to be first to display oviposition behavior (i.e., before their opponent). In

474 the same way, ecdysone-injected wasps should be more likely to be the first female of the dyad to
475 display oviposition behavior than methanol-injected females. Our analyses seem to support these
476 expectations: focal females were more likely to be first to display oviposition behavior when they

477 have higher ESH titers than their opponent (Experiment 1). Moreover, females injected with
478 ecdysone were more frequently the first female of the dyad to display such behavior than control

479 females (Experiment 3). Even if in Experiment 1 we cannot determine whether the relative
480 difference in ESH titers between females after contest resulted from displaying oviposition behavior

481 or the oviposition behavior associated with winning host access resulted from difference in ESH
482 titers before contests, we hypothesize that ESH mediate female winning success by increasing their
483 propensity to display oviposition behavior quickly. While it is well known that *subjective resource*

484 *value* drives individuals' behavior during contests (Briffa & Hardy 2013), the underlying

485 mechanisms remain poorly investigated, particularly in insects. The endocrine action of ESH appears
486 to be one important pathway mediating contest behavior.

487

488 **5. Conclusion**

489 By testing the role of ESH on both fertility and behavioral decisions during contests over hosts in
490 female *E. vuilleti*, we have shown for the first time that ecdysone is involved in the outcome of
491 conflicts in a solitary insect. However, we found no evidence that ecdysone fuels aggressive
492 behaviors like JH does in this species (Mathiron *et al.*, 2019a). This suggests that the two family
493 hormones, ESH and JH, interact to mediate wasps' behavior during intraspecific competition for
494 reproductive resources. Interactions between JH and ESH are already known to play a central role in
495 different aspects of insect biology, such as metamorphosis in juveniles (reviewed in Riddiford, 2008)
496 and the regulation of vitellogenesis and ovarian development in adults (reviewed in Bloch *et al.*,
497 2009; Roy *et al.*, 2018; see also Santos *et al.*, 2019). In *E. vuilleti*, JH-III and ecdysone both favor
498 egg maturation (Mathiron *et al.*, 2019 and this study, respectively). Direct competition over host
499 access between *E. vuilleti* females is closely related to reproduction. Thus, ESH and JH effects on
500 behavioral strategies during contests may have been co-opted because of the joint role of these
501 hormones on reproductive status, but particular selective advantages and constraints may have
502 selected each one for the mediation of different behaviors. Future experiments exploring the relative
503 and/or joint action of ESH and JH in this species would broaden our understanding of the hormonal
504 mediation of aggressiveness and conflict resolution over indivisible resources in solitary insects.

505

506 **Funding**

507 This work was supported by the French Ministry of Research (2016-Bourse Ministérielle-44).

508

509 **Acknowledgement**

510 We are grateful to Joël Meunier for his numerous advices, and Adeline Dumet and Fabrice
511 Vannier for their technical assistance.

512

513 **References**

- 514 Barton, R.A. 1993. Sociospatial mechanisms of feeding competition in female olive baboons, *Papio anubis*. *Animal
515 Behaviour*, 46, 791–802.
- 516 Beydon, P., & Lafont, R. 1983. Feedback inhibition of ecdysone production by 20-hydroxyecdysone in *Pieris brassicae*
517 pupae. *Journal of Insect Physiology*, 29(6), 529–533. [https://doi.org/10.1016/0022-1910\(83\)90084-7](https://doi.org/10.1016/0022-1910(83)90084-7)
- 518 Bloch, G., Hefetz, A., & Hartfelder, K. (2000). Ecdysteroid titer, ovary status, and dominance in adult worker and queen
519 bumble bees (*Bombus terrestris*). *Journal of Insect Physiology*, 46(6), 1033–1040. [https://doi.org/10.1016/S0022-1910\(99\)00214-0](https://doi.org/10.1016/S0022-1910(99)00214-0)
- 520
- 521 Bloch, G., Shpigler, H., Wheeler, D.E., & Robinson, G.E. 2009. Endocrine Influences on the Organization of Insect
522 Societies. In S.E.F. and R.T.R. Donald W. Pfaff, Arthur P. Arnold, Anne M. Etgen (Ed.), *Hormones, Brain and
523 Behavior* (pp. 1027–1068). San Diego. <https://doi.org/10.1016/b978-012532104-4/50042-1>
- 524 Bodin, A., Jaloux, B., Delbecque, J.-P., Vannier, F., Monge, J.-P., & Mondy, N. 2009. Reproduction in a variable
525 environment: How does *Eupelmus villeti*, a parasitoid wasp, adjust oogenesis to host availability? *Journal of
526 Insect Physiology*, 55(7), 643–648. <https://doi.org/10.1016/j.jinsphys.2009.04.003>
- 527 Bodin, A., Jaloux, B., Mandon, N., Vannier, F., Delbecque, J.-P., Monge, J.-P., & Mondy, N. 2007. Host-Induced
528 Ecdysteroids in the Stop-and-Go Oogenesis in a Synovigenic Parasitoid Wasp. *Archives of Insect Biochemistry and
529 Physiology*, 65, 103–111. <https://doi.org/10.1002/arch>
- 530 Breed, M.D., & Bell, W.J. 1983. Hormonal influences on invertebrate aggressive behavior, in: Svare, B.B. (Ed.),
531 Hormones and Aggressive Behavior. Plenum Press, New York, NY, pp. 577–590.
- 532 Brent, C., Peeters, C., Dietmann, V., Crewe, R., & Vargo, E. 2006. Hormonal correlates of reproductive status in the
533 queenless ponerine ant, *Strebognathus peetersi*. *J. Comp. Physiol. A Neuroethol. Sensory, Neural, Behav. Physiol.*
534 192, 315–320. <https://doi.org/10.1007/s00359-005-0065-6>

- 535 Briffa, M., Hardy, I.C.W., Gammell, M.P., Jennings, D.J., Clarke, D.D., & Goubault, M. 2013. Analysis of animal
536 contest data. In: Hardy I.C.W., Briffa M., editors. Animal contests. Cambridge (UK): Cambridge University Press.
537 p. 47–85.
- 538 Casas, J., Vannier, F., Mandon, N., Delbecque, J.-P., Giron, D., & Monge, J.-P. 2009. Mitigation of egg limitation in
539 parasitoids: Immediate hormonal response and enhanced after host use. *Ecology*, 90(2), 537–545.
540 <https://doi.org/10.1890/08-0507.1>
- 541 Chase, I.D. 1974. Models of hierarchy formation in animals societies. *Behav. Sci.* 19, 374–382.
- 542 Collias, N.E. 1944. Aggressive behavior among vertebrate animals. *Physiol. Zool.* 17, 83–123.
543 <https://doi.org/10.1086/physzool.17.1.30151832>
- 544 Damiens, D., Imbert, E., Bressac, C., Thibeauudeau, C., & Chevrier, C. 2001. Egg-laying, pre-imaginal growth dynamics,
545 and mortality in *Eupelmus orientalis* and *Dinarmus basalis*, two solitary ectoparasitoids of *Callosobruchus*
546 *maculatus*. *Entomologia Experimentalis et Applicata*, 99(1), 97–105. <https://doi.org/10.1023/A:1018954320519>
- 547 De Reggi, M., Pitoizet, N., Gharib, B., & Delbecque, J.-P. 1992. New Enzyme Immunoassays for Ecdysteroids Using
548 Peroxidase as Enzyme and Polyclonal or Monoclonal Antibodies. In: Abstract of the Xth Ecdysone Workshop, p.
549 91
- 550 Díaz-Uriarte, R. 1999. Anti-predator behaviour changes following an aggressive encounter in the lizard *Tropidurus*
551 *hispidus*. *Proc. R. Soc. B Biol. Sci.* 266, 2457–2464. <https://doi.org/10.1098/rspb.1999.0946>
- 552 Elekonich, M.M., & Robinson, G.E. 2000. Organizational and activational effects of hormones on insect behavior.
553 *Journal of Insect Physiology*, 46, 1509–1515.
- 554 Enquist, M., & Leimar, O. 1987. Evolution of fighting behaviour: The effect of variation in resource value. *J. Theor.*
555 *Biol.* 127, 187–205. [https://doi.org/10.1016/S0022-5193\(87\)80130-3](https://doi.org/10.1016/S0022-5193(87)80130-3)
- 556 Festa-Bianchet, M., Apollonio, M., Mari, F., & Rasola, G. 1990. Aggression among Lekking Male Fallow Deer (*Dama*
557 *dama*): Territory Effects and Relationship with Copulatory Success. *Ethology*, 85, 236–246.
- 558 Festucci-Buselli, R.A., Contim, L.A.S., Barbosa, L.C.A., Stuart, J., & Otoni, W.C. 2008. Biosynthesis and potential
559 functions of the ecdysteroid 20-hydroxyecdysone — a review. *Botany*, 86(9), 978–987.

- 560 Field, S.A., & Calbert, G. 1999. Don't count your eggs before they're parasitized: contest resolution and the trade-offs
561 during patch defense in a parasitoid wasp. *Behav. Ecol.* 10, 122–127. <https://doi.org/10.1093/beheco/10.2.122>
- 562 Fisher, R.C. 1961. A study in insect multiparasitism. I. Host selection and oviposition. *Journal of Experimental Biology*,
563 38(3), 267-275
- 564 Fox, J., & Weisberg, S. 2019. An R companion to applied regression (3rd ed.). New York, NY: Sage
- 565 Gauthier, N., & Monge, J.-P. 1999. Could the egg itself be the source of the oviposition deterrent marker in the
566 ectoparasitoid *Dinarmus basalis*? *J. Insect Physiol.* 45, 393–400. [https://doi.org/10.1016/S0022-1910\(98\)00138-3](https://doi.org/10.1016/S0022-1910(98)00138-3)
- 567 Goubault, M., Cortesero, A.M., Poinsot, D., Wajnberg, E., & Boivin, G. 2007. Does host value influence female
568 aggressiveness, contest outcome and fitness gain in parasitoids? *Ethology*, 113(4), 334–343.
569 <https://doi.org/10.1111/j.1439-0310.2006.01325.x>
- 570 Geva, S., Hartfelder, K., & Bloch, G. 2005. Reproductive division of labor, dominance, and ecdysteroid levels in
571 hemolymph and ovary of the bumble bee *Bombus terrestris*. *Journal of Insect Physiology*, 51(7), 811–823.
572 <https://doi.org/10.1016/j.jinsphys.2005.03.009>
- 573 Hardy, I.C.W., & Briffa, M. 2013. Animal contests. Cambridge University Press.
- 574 Hartfelder, K., Bitondi, M.M.G., Santana, W.C., & Simões, Z.L.P. 2002. Ecdysteroid titer and reproduction in queens
575 and workers of the honey bee and of a stingless bee: loss of ecdysteroid function at increasing levels of sociality?
576 *Insect Biochemistry and Molecular Biology*, 32, 211–216.
- 577 Hughes, J.P., Harvey, I.F., & Hubbard, S. F. 1994. Host-searching behavior of *Venturia canescens* (Grav.)
578 (Hymenoptera: Ichneumonidae): Interference-the effect of mature egg load and prior behavior. *Journal of Insect
579 Behavior*, 7(4), 433–454. <https://doi.org/10.1007/BF02025442>
- 580 Hsu, Y., Earley, R.L., & Wolf, L.L. 2006. Modulation of aggressive behaviour by fighting experience: Mechanisms and
581 contest outcomes. *Biological Reviews of the Cambridge Philosophical Society*, 81(1), 33–74.
582 <https://doi.org/10.1017/S146479310500686X>
- 583 Innocent, T.M., West, S.A., Sanderson, J.L., Hyrkkänen, N., & Reece, S.E. 2011. Lethal combat over limited resources:
584 Testing the importance of competitors and kin. *Behav. Ecol.* 22, 923–931. <https://doi.org/10.1093/beheco/arg209>

- 585 Jakobsson, S., Brick, O., & Kullberg, C. 1995. Escalated fighting behaviour incurs increased predation risk. *Anim. Behav.*
586 49, 235–239. [https://doi.org/10.1016/0003-3472\(95\)80172-3](https://doi.org/10.1016/0003-3472(95)80172-3)
- 587 Jaloux, B., Sanon, A., Huignard, J., & Monge, J.-P., 2004. Interspecific relationships between the solitary ectoparasitoid,
588 *Eupelmus villeti* (Crw.) (Eupelmidae), and its sympatric species, *Dinarmus basalis* (Rond.) (Pteromalidae), in the
589 presence of their host, *Callosobruchus maculatus* pic (Coleoptera Bruchidae). *J. Insect Behav.* 17, 793–808.
590 <https://doi.org/10.1023/B:JOIR.0000048989.36181.4d>
- 591 Jervis, M.A., Ellers, J., & Harvey, J.A. 2008. Resource acquisition, allocation, and utilization in parasitoid reproductive
592 strategies. *Annual Review of Entomology*, 53(1), 361–385. <https://doi.org/10.1146/annurev.ento.53.103106.093433>
- 593 Kelstrup, H.C., Hartfelder, K., Nascimento, F.S., & Riddiford, L.M. 2014a. Reproductive status, endocrine physiology
594 and chemical signaling in the Neotropical, swarm-founding eusocial wasp *Polybia micans*. *J. Exp. Biol.* 217, 2399–
595 2410. <https://doi.org/10.1242/jeb.096750>
- 596 Kelstrup, H.C., Hartfelder, K., Nascimento, F.S., & Riddiford, L.M. 2014b. The role of juvenile hormone in dominance
597 behavior, reproduction and cuticular pheromone signaling in the caste-flexible epiponine wasp, *Synoeca surinama*.
598 *Front. Zool.* 11, 1–19. <https://doi.org/10.1186/s12983-014-0078-5>
- 599 Kelstrup, H.C., Hartfelder, K., & Wossler, T.C. 2015. *Polistes smithii* vs. *Polistes dominula*: the contrasting
600 endocrinology and epicuticular signaling of sympatric paper wasps in the field. *Behav. Ecol. Sociobiol.* 69, 2043–
601 2058. <https://doi.org/10.1007/s00265-015-2015-9>
- 602 Kokko, H. 2013. Dyadic contests: modelling fights between two individuals. In: Hardy I.C.W., Briffa M, editors. *Animal*
603 contests. Cambridge (UK): Cambridge University Press. p. 5–32.
- 604 Kou, R., Chou, S.Y., Huang, Z.Y., & Yang, R.L. 2008 Juvenile hormone levels are increased in winners of cockroach
605 fights. *Horm. Behav.* 54, 521–527.
- 606 Kou, R., & Hsu, C.C. 2013. Mating enhances the probability of winning aggressive encounters in male lobster
607 cockroaches. *Hormones and Behavior*, 64(3), 546–556. <https://doi.org/10.1016/j.ybeh.2013.07.007>
- 608 Kou, R., Hsu, C.C., Chen, S.C., & Fang, S. 2019 Winner and loser effects in lobster cockroach contests for social
609 dominance. *Horm. Behav.* 107, 49 - 60.

- 610 Mathiron, A.G.E., Pottier, P., & Goubault, M. 2018. Let the most motivated win: resource value components affect
611 contest outcome in a parasitoid wasp. *Behav. Ecol.* 00, 1–8. <https://doi.org/10.1093/beheco/ary084>
- 612 Mathiron, A.G.E., Earley, R.L., & Goubault, M. 2019. Juvenile hormone manipulation affects female reproductive status
613 and aggressiveness in a non-social parasitoid wasp. *General and Comparative Endocrinology*.
614 <https://doi.org/10.1016/j.ygcen.2019.01.006>
- 615 Maynard Smith, J., & Parker, G.A. 1976. The logic of asymmetric animal contests. *Anim. Behav.* 24, 159–175.
- 616 Mohamad, R., Monge, J.-P., & Goubault, M. 2010. Can subjective resource value affect aggressiveness and contest
617 outcome in parasitoid wasps? *Anim. Behav.* 80, 629–636. <https://doi.org/10.1016/j.anbehav.2010.06.022>
- 618 Mohamad, R., Monge, J.-P., & Goubault, M. 2012. Wait or fight? Ownership asymmetry affects contest behaviors in a
619 parasitoid wasp. *Behav. Ecol.* 23, 1330–1337. <https://doi.org/10.1093/beheco/ars125>
- 620 Mohamad, R., Monge, J.-P., & Goubault, M. 2013. Do resource value and ownership status affect intensity and
621 resolution of contests in a parasitoid wasp? *Entomol. Exp. Appl.* 147, 99–109. <https://doi.org/10.1111/eea.12049>
- 622 Mondy, N., Corio-Costet, M.F., Bodin, A., Mandon, N., Vannier, F., & Monge, J.-P. 2006. Importance of sterols
623 acquired through host feeding in synovigenic parasitoid oogenesis. *Journal of Insect Physiology*, 52(9), 897–904.
624 <https://doi.org/10.1016/j.jinsphys.2006.03.007>
- 625 Moore, I. T., Hernandez, J., & Goymann, W. 2019. Who rises to the challenge? Testing the Challenge Hypothesis in fish,
626 amphibians, reptiles, and mammals. *Hormones and Behavior*. <https://doi.org/10.1016/j.yhbeh.2019.06.001>
- 627 Nijhout, H.F. 1994. Insect Hormones. Princeton University Press, Princeton.
- 628 Palombit, R.A. 1993. Lethal territorial aggression in a white-handed gibbon. *Am. J. Primatol.* 31, 311–318.
629 <https://doi.org/10.1002/ajp.1350310407>
- 630 Parvy, J.-P., Wang, P., Garrido, D., Maria, A., Blais, C., Poidevin, M., & Montagne, J. 2014. Forward and feedback
631 regulation of cyclic steroid production in *Drosophila melanogaster*. *Development*, 141(20), 3955–3965.
632 <https://doi.org/10.1242/dev.102020>
- 633 Petersen, G., Hardy, & I.C.W., 1996. The importance of being larger: parasitoid intruder – owner contests and their
634 implications for clutch size. *Anim. Behav.* 51, 1363–1373. <https://doi.org/10.1006/anbe.1996.0139>

- 635 Porcheron, P., Moriniere, M., Grassi, J., & Pradelles, P. 1989. Development of an enzyme immunoassay for ecdysteroids
636 using acetylcholinesterase as label. *Insect Biochemistry*, 19(2), 117–122. [https://doi.org/10.1016/0020-1790\(89\)90081-4](https://doi.org/10.1016/0020-1790(89)90081-4)
- 638 Richard, F.-J., & Hunt, J.H. 2013. Intracolony chemical communication in social insects. *Insectes Sociaux*, 60(3), 275–
639 291. <https://doi.org/10.1007/s00040-013-0306-6>
- 640 Riddiford, L.M. 2008. Juvenile hormone action: A 2007 perspective. *Journal of Insect Physiology*. 54, 895–901.
641 <https://doi.org/10.1016/j.jinsphys.2008.01.014>
- 642 Ringo, J.M. 2002. Hormonal Regulation of Sexual Behavior in Insects. In *Hormones, Brain and Behavior* (pp. 93–114).
643 Elsevier. <https://doi.org/10.1016/B978-012532104-4/50038-X>
- 644 Robinson, G.E., Strambi, C., Strambi, A., & Feldlaufer, M.F. 1991. Comparison of juvenile hormone and ecdysteroid
645 haemolymph titres in adult worker and queen honey bees (*Apis mellifera*). *Journal of Insect Physiology*, 37(12),
646 929–935. [https://doi.org/10.1016/0022-1910\(91\)90008-N](https://doi.org/10.1016/0022-1910(91)90008-N)
- 647 Röseler, P.F., Röseler, I., Strambi, A., Augier, R. 1984. Influence of insect hormones on the establishment of dominance
648 hierarchies among foundresses of the paper wasp, *Polistes gallicus*. *Behav. Ecol. Sociobiol.* 15, 133–142.
649 <https://doi.org/10.1007/BF00299381>
- 650 Röseler, P.F., Röseler, I., & Strambi, A. 1985. Role of ovaries and ecdysteroids in dominance hierarchy establishment
651 among foundresses of the primitively social wasp, *Polistes gallicus*. *Behavioral Ecology and Sociobiology*, 18(1),
652 9–13. <https://doi.org/10.1007/BF00299232>
- 653 Roy, S., Saha, T.T., Zou, Z., & Raikhel, A.S. 2018. Regulatory pathways controlling female insect reproduction. *Annual
654 Review of Entomology*. 63(1), 489–511. <https://doi.org/10.1146/annurev-ento-020117-043258>
- 655 Santos, C.G., Humann, F.C., & Hartfelder, K. 2019. Juvenile hormone signaling in insect oogenesis. *Current Opinion in
656 Insect Science*, 31, 43–48. <https://doi.org/10.1016/j.cois.2018.07.010>
- 657 Schwagmeyer, P.L., & Woontner, S.J., 1985. Mating Competition in an Asocial Ground-Squirrel, *Spermophilus
658 tridecemlineatus*. *Behav. Ecol. Sociobiol.* 17, 291–296. <https://doi.org/10.1007/BF00300149>

- 659 Schwedes, C.C., & Carney, G.E. 2012. Ecdysone signaling in adult *Drosophila melanogaster*. *J. Insect Physiol.*, 58(3),
660 293-302.
- 661 Scott, M.P. 2006. The role of juvenile hormone in competition and cooperation by burying beetles. *J. Insect Physiol.* 52,
662 1005–1011. <https://doi.org/10.1016/j.jinsphys.2006.04.006>
- 663 Swevers L., & Iatrou, K. 2009. Ecdysteroids and Ecdysteroid Signaling Pathways During Insect Oogenesis. In: Smagghe
664 G. (eds) Ecdysone: Structures and Functions. Springer, Dordrecht
- 665 Simmons, L. 1986. Intermale Competition and Mating Success in the Field Cricket, *Gryllus bimaculatus* (Degeer). *Anim.*
666 *Behav.* 34, 567–579. [https://doi.org/10.1016/S0003-3472\(86\)80126-9](https://doi.org/10.1016/S0003-3472(86)80126-9)
- 667 Stokkebo, S., & Hardy, I.C.W. 2000. The importance of being gravid: egg load and contest outcome in a parasitoid wasp.
668 *Anim. Behav.* 59, 1111–1118. <https://doi.org/10.1006/anbe.2000.1407>
- 669 Terrasse, P.C., & Rojas-Rousse, D. 1986. Distribution de la ponte et évitement du superparasitisme chez l'hyménoptère
670 solitaire *Bruchocida vuilleti* Cwf. (Hym., Eupelmidae), parasite des stades larvaires de son hôte, *Callosobruchus*
671 *maculatus* F. (Col., Bruchidae). *J. Appl. Entomol.* 101, 243–256. <https://doi.org/10.1111/j.1439-0418.1986.tb00855.x>
- 673 Tibbetts, E.A., & Crocker, K.C. 2014. The challenge hypothesis across taxa: Social modulation of hormone titres in
674 vertebrates and insects. *Anim. Behav.* 92, 281–290. <https://doi.org/10.1016/j.anbehav.2014.02.015>
- 675 Tibbetts, E.A., Fearon, M.L., Wong, E., Huang, Z.Y., & Tinghitella, R.M. 2018. Rapid juvenile hormone downregulation
676 in subordinate wasp queens facilitates stable cooperation. *Proceedings of the Royal Society B: Biological Sciences*,
677 285. <https://doi.org/10.1098/rspb.2017.2645>
- 678 Tibbetts, E.A., & Huang, Z.Y. 2010. The challenge hypothesis in an insect: juvenile hormone increases during
679 reproductive conflict following queen loss in *Polistes* wasps. *Am. Nat.* 176, 123–130.
- 680 Tibbetts, E.A., & Izzo, A.S. 2009. Hormones and Behavior Endocrine mediated phenotypic plasticity: Condition-
681 dependent effects of juvenile hormone on dominance and fertility of wasp queens. *Horm. Behav.* 56, 527–531.
682 <https://doi.org/10.1016/j.yhbeh.2009.09.003>
- 683 Tibbetts, E.A., Izzo, A., & Huang, Z.Y. 2011. Behavioral and physiological factors associated with juvenile hormone in
684 Polistes wasp foundresses. *Behavioral Ecology and Sociobiology*, 65, 1123–1131.

- 685 Tibbetts, E.A., Laub, E.C., Mathiron, A.G.E., & Goubault, M. 2019. The challenge hypothesis in insects. *Hormones and*
686 *Behavior.*
- 687 Thomas, H.E., Stunnenberg, H.G, & Stewart, A.F. 1993. Heterodimerization of the *Drosophila* ecdysone receptor with
688 retinoid X receptor and ultraspiracle. *Nature*. 362, 471–75.
- 689 Vogel, E.R. 2005. Rank differences in energy intake rates in white-faced capuchin monkeys, *Cebus capucinus*: The
690 effects of contest competition. *Behav. Ecol. Sociobiol.* 58, 333–344. <https://doi.org/10.1007/s00265-005-0960-4>
- 691 West-Eberhard, M.J. 1979. Sexual Selection, Social Competition, and Evolution. *Proc. Amercian Philos. Soc.* 123, 222–
692 234.
- 693 Wilson, K., & Hardy, I.C.W. 2002. Statistical analysis of sex ratios: an introduction, in: Hardy, I.C.W. (Ed.), Sex Ratios:
694 Concepts and Research Methods. Part 2. Statistical Analysis of Sex Ratio Data. Cambridge University Press, New
695 York, pp. 46–92.
- 696 Wingfield, J.C., Hegner, R.E., Dufty, A.M., & Ball, G.F. 1990. The challenge hypothesis -theoretical implications for
697 patterns of testosterone secretion, mating systems, and breeding strategies. *Am. Nat.* 136, 829–846
- 698 Yao, T.P., Segraves, W.A., Oro, A.E., McKeown, M., & Evans, R.M. 1992. *Drosophila* ultraspiracle modulates ecdysone
699 receptor function via heterodimer formation. *Cell*. 71, 63–72.