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## Ambient light and mimicry as drivers of wing transparency in Lepidoptera

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1 **Ambient light and mimicry as drivers of wing transparency in Lepidoptera**

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15 **Abstract**

16 Transparency reduces prey detectability by predators. While the proportion of  
17 transmitted light in aquatic species is higher as light availability increases, less is  
18 known about such variation in terrestrial species. Transparency has evolved several  
19 times in the typically opaque winged Lepidoptera order (moths and butterflies),  
20 displaying a large diversity of degrees. Using two complementary approaches, we  
21 explore how the evolution of the differences in light transmittance relates to habitat  
22 openness, daytime activity and mimicry syndrome (bee/wasp versus dead-leaf  
23 mimic). First, by exposing artificial moth-like prey to wild avian predators in open  
24 and closed habitats, we show that survival increases at higher proportions of  
25 transmitted light in open habitats. Second, by analysing the evolution of wing

26 features and ecological traits in 107 clearwing species, we confirm that diurnal open-  
27 habitat species show higher light transmittances than diurnal closed-habitat species.  
28 Additionally, bee/wasp mimics are more often diurnal and have higher and less  
29 variable light transmittances than dead-leaf mimics, which are more often nocturnal.  
30 Bright conditions, such as open habitats during the day, and mimicry of insects with  
31 transparent wings seem to promote high light transmittance. Habitat openness,  
32 daytime activity and species interactions play a crucial role in determining  
33 transparency design.

34

35 **Keywords:** transparency, irradiance, mimicry, nocturnality, Lepidoptera, Batesian  
36 mimicry, habitat openness

37

## 38 **Introduction**

39 Transparency is common in aquatic environments where it reduces detectability by  
40 predators, especially in the pelagic environment where there is nowhere to hide  
41 (Johnsen 2014). However, the amount of light that is transmitted by transparent  
42 tissues varies between organisms. Based on the observation of 29 zooplankton  
43 species, Johnsen and Widder (1998), found that light transmittance could range from  
44 50 to 90%, with the most transparent species living in lighter, shallower places. In a  
45 theoretical approach, they show that efficiency at detecting transparent species  
46 depends on visual performance (for instance, minimum contrast that predator can  
47 detect, also known as contrast threshold), which varies with ambient light  
48 conditions: in shallow places with bright light conditions, high visual performance  
49 (low contrast threshold values) selects for high transmittance, and only highly  
50 transparent organisms are effectively undetected. Instead, at deeper areas with  
51 dimmer light conditions, visual systems are less performing (high contrast threshold  
52 values), thus organisms can be poorly transparent and be effectively undetected  
53 (Ruxton et al. 2018, Figure S1). On land, studies in primates have also shown higher  
54 visual performance at brighter light conditions as the retinal cells increase their  
55 neural response more strongly when mean luminance is higher (Purpura et al. 1988;  
56 Ghim and Hodos 2006). Similarly, visual performance increases with ambient light  
57 luminance in other terrestrial vertebrates such as birds (Hodos et al. 1976; Kassarov  
58 2003; Lind et al. 2013). Given the pervasive property of variation of visual  
59 performance with light availability, selection should favour different transmittance  
60 levels in different light environments on land.

61 On land, transparency is present in only a handful of lineages, including  
62 Centrolenidae frogs, *Gaeotis* semi-slugs, and insects, where transparent wings are

63 common. Transparency also reduces detectability of prey on land (Arias et al. 2019,  
64 2020; McClure et al. 2019). Recently, Gomez et al (2020) reported that transparency  
65 has evolved multiple times independently in Lepidoptera (butterflies and moths),  
66 order of mostly opaque winged species, where it is produced by a large diversity of  
67 structures and configurations conferring different transmittance levels. Although  
68 this study did not investigate the links between transparency and habitat, it  
69 suggested in several aspects an important role of visual predators in driving the  
70 evolution of transparency (for instance diurnal species were reported to transmit  
71 more light than nocturnal species). Hence, we expect diurnal terrestrial transparent  
72 species that live in more open habitats - with brighter light conditions - to transmit  
73 more light compared to species flying at night and/or living in more closed habitats -  
74 with dimmer light conditions-. In addition, at low light availability, different levels of  
75 transmittance can confer similar protection against predators. Therefore, nocturnal  
76 and/or closed-habitat species might show larger variation in light transmittance, as  
77 neither high nor low transmittance levels are strongly selected.

78         Predation risk can be reduced not only by reducing detectability, but also by  
79 mimicking inedible elements such as leaves (masquerade, Skelhorn et al. 2010) or  
80 unprofitable prey (batesian mimicry, Bates 1862), and transparency might help  
81 achieving such mimicry. Several clearwing Lepidoptera exhibit brownish colorations  
82 that combined with transparent surfaces that presumably perceived as “holes” can  
83 resemble dead leaves (example of a potential dead-leaf mimic in Fig. 1a). Other small  
84 clearwing moths and butterflies exhibit yellow and dark stripes on their bodies and  
85 highly transparent wings (example in Fig. 1b), resembling harmful species for  
86 predators, such as bees and wasps. Mimicry syndrome could concur in driving  
87 transmittance differences to have different optima in bee/wasp and leaf mimics, but

88 whichever factor (light availability versus mimicry) is driving its evolution is still  
89 unknown. Bees and wasps often live in open habitats (Grundel et al. 2010; Yamaura  
90 et al. 2012), and their mimics should do as well. High light transmittance should be  
91 selected in bees, wasps and their mimics because the reduction of detectability  
92 already conferred by their small body sizes, can be enhanced by higher levels of  
93 transparency (Gomez et al. 2020), and because light conditions are brighter in open  
94 habitats. By contrast, dead-leaf mimics might show a larger variation in body size,  
95 may more often live in closed habitats, where more leaves fall down and should  
96 therefore exhibit a broader diversity of light transmittance, as a range of  
97 transmittance levels can contribute to mimic leaves in decomposition and confer  
98 similar protection against predators. The expected differences in light transmittance  
99 should also be associated to variations in morphology and coloration of wing scales,  
100 with absent or reduced scales for bee/wasp mimics and classically shaped scales for  
101 leaf mimics.

102         Here, we investigate whether differences in transmittance found in  
103 Lepidoptera clearwing species are related to light availability and/or mimicry using  
104 two complementary approaches. First, we tested whether the efficiency of different  
105 transmittance levels at reducing detectability changes according to light availability  
106 in terrestrial environments, by carrying out a fieldwork experiment with artificial  
107 moth-like prey. Second, using actual specimens of butterflies and moths, we tested  
108 whether differences in the proportion of transmitted light could be explained by  
109 species daytime rhythm, habitat and/or mimicry, by conducting comparative  
110 analyses at broad interspecific level. We took advantage of the large dataset of  
111 Lepidoptera species analysed by Gomez et al (2020) to add species ecological traits  
112 (habitat, daytime rhythm and mimicry, known for 107 species) and relate them to

113 clearwing optical and structural traits. Together, these analyses help understanding  
114 the evolution of interspecific differences in the proportion of transmitted light on  
115 land.

116

## 117 **Material and Methods**

### 118 1. Field experiment

#### 119 1.a. Artificial butterfly Elaboration

120 To test for the efficiency of light transmittance at reducing detectability in habitats  
121 with different light availability, we elaborated plain grey artificial butterflies with  
122 paper wings and a malleable edible body. Following the general methodology  
123 described in Arias *et al* (2020), butterflies did not replicate any real local butterfly,  
124 but mimicked a general grey moth with closed wings (i. e., a triangular shape). The  
125 rather cryptic butterfly colour was chosen based on 120 reflectance measures of  
126 green oak *Quercus ilex* trunks. Reflectance measurements were taken using a  
127 spectrophotometer (Starline Avaspec-2048 L, Avantes) and a deuterium halogen  
128 lamp (Avalight DHS, Avantes) emitting in the 300-700 nm range, including UV, to  
129 which some predators of butterfly and moths, such as birds, are sensitive (Chen and  
130 Goldsmith 1986). Measurements were done relative to a white reference (lights  
131 turned on with no sample) and a dark reference (light turned off with no sample).  
132 For reflectance measurements, we used an optic probe (FC-UV200-2-1.5 x 100,  
133 Avantes) merging illumination and collection angles. Grey wings (R=155, G=155,  
134 B=155) were printed on sketch paper Canson using a HP Officejet Pro 6230 printer.  
135 Paper wings were laminated with a Polyester Opale Mat 75µm poach. Four forms of  
136 artificial butterflies were used, here listed in order of increasing proportion of light  
137 transmittance: completely opaque butterfly “C”; poorly transparent butterfly with 6

138 layers of transparent film “T6”; highly transparent butterfly with a single layer of  
139 transparent film “T1”; and fully transparent butterfly with no film in the transparent  
140 zones “T0”. For the butterflies that included transparent elements, triangular  
141 windows of 234mm<sup>2</sup> were cut down from the grey triangle and the remaining part  
142 was put on top of one or six layers of transparency film 3M for inkjet printing. This  
143 transparent film was chosen as it is highly transparent, even in the UV range of the  
144 spectrum, and going from 1 to 6 transparent layers permitted a reduction of 50% of  
145 the transmittance between treatments (Fig. S2). Such transparent layer was coated  
146 with a transparent mate varnish to reduce its shininess. For transparency  
147 measurements, we measured specular transmittance from 300 to 1100nm, using a  
148 deuterium-halogen lamp (Avalight DHS, Avantes), optical fibres (FC-UV200-2-1.5 x  
149 100, Avantes) and a spectrometer (Starline Avaspec-2048 L, Avantes). Fibres were  
150 separated, aligned and 5mm apart and the wing sample was placed perpendicular  
151 between them at equal distance (light spot of 1mm diameter). Spectra were taken  
152 relative to a dark (light off) and to a white reference (no sample between the fibres)  
153 measurement. On top of butterfly wings, we added an artificial grey body. Butterfly  
154 bodies were prepared with flour (428 g), lard (250 g) and water (36 g), following  
155 Carrol & Sherratt (2013). Yellow, red and blue food edible colourings were used to  
156 dye the pastry in grey, imitating artificial wing colour. Such malleable mix permits to  
157 register and distinguish marks made by bird beaks from insect jaws. Both paper  
158 wings and artificial bodies were measured in spectrometry, similarly to how trunk  
159 reflectance was measured (Fig. S2). Bodies could attract predator attention, but it  
160 has been previously shown that wingless bodies had the same attractiveness as that  
161 of butterflies with large transparent elements (Arias et al. 2020). Artificial butterflies  
162 and bodies were pinned to green oak *Quercus ilex* trunks. To avoid ant attacks,

163 Vaseline and a piece of highly sticky double-faced transparent tape were stuck in  
164 between the wings and the trunk.

165

#### 166 1.b. Experimental set up

167 Predation experiments were performed in May and June 2018 at the zoological park  
168 of Montpellier (43.64°, 3.87°) and at La Rouvière forest (close to Montarnaud city  
169 43.65°, 3.64°). This experiment overlapped with the breeding season of local great  
170 (*Parus major*) and blue tit (*Cyanistes caeruleus*) populations, when birds are  
171 intensively looking for food, which can maximise the number of attacks on our  
172 artificial prey. Artificial prey items were pinned every 10 metres on oak trunks of at  
173 least 10 cm of diameter and with few or no moss cover. Prey order was randomized  
174 by blocks of eight items, two per treatment, before starting the experiment. Initially,  
175 prey were evenly disposed in closed and open areas. However, throughout the  
176 experiment a stronger predation rate was detected in open areas (see Results  
177 section). Therefore, we increased the number of artificial prey released on closed  
178 areas to compensate for the differential predation pressure and try to get more  
179 similar numbers of attacked prey items in closed and open habitats. We analysed  
180 results for both the whole dataset, including larger sample size in closed habitats,  
181 and 20 reduced datasets, including each time a different random subset of the closed  
182 habitat of the same amount of artificial prey as for the open habitat. Prey were  
183 mostly disposed facing north and as perpendicular to the floor as possible, to reduce  
184 direct sunlight reflection on them. Prey were checked every 24h. After 96h all prey  
185 were removed. When V- or U- marks were detected, or when the body was missing  
186 without signals of invertebrate attacks (i.e. no body scraps left on the wings or  
187 around the butterfly on the trunk) prey were considered as attacked and wings or

188 pins where removed. Instead, if invertebrate attacks were detected, or when prey  
189 was missing, it was replaced. Non-attacked prey were considered as censored data.

190 Canopy cover was used to classify places in open and closed habitat. We took  
191 pictures each 20 meters in the trails that were used for the experiment (at forest  
192 edges for the open habitat, inside the forest for the closed habitat, examples Fig. S3),  
193 using a Canon EOS 550D camera and a fisheye lens. Canopy cover was further  
194 quantified using Fiji software (Schindelin et al. 2012). Although canopy cover  
195 distribution is unimodal (Hartigans' dip test:  $D = 0.01$ ,  $p\text{-value} = 0.6$ ), we used a  
196 discrete classification, comparable to the one used for real species in the second part  
197 of our study. We assumed that places with cover larger than the mean were closed  
198 habitats and places with lower covers were open habitats (see Fig. S3 for the  
199 distribution of canopy cover in the experimental sites).

200 To test how different treatments survive along the experiment on both open and  
201 closed habitats, Cox proportional hazard regression (Cox 1972) were applied, first  
202 for all data points including form, habitat openness and their interaction as  
203 explanatory variables, and then, Cox regression were independently applied for each  
204 habitat using the different treatments as factors, to further explore the effect of form  
205 within each habitat. Overall significance was measured using a Wald test. Statistical  
206 analyses were performed in R (R Foundation for Statistical Computing 2014) using  
207 the *survival* package (Therneau and Lumley 2009).

208

## 209 2. Comparative analyses of museum specimens

### 210 2. a. Species selection and phylogeny

211 To explore the association of light transmittance with different conditions across  
212 multiple species we performed phylogenetic comparative analyses, since species are

213 not independent. We used the phylogeny of clearwing species by Gomez et al.  
214 (2020). In our analyses we included 107 species out of the 123 species included by  
215 Gomez et al, for which information about the openness of their habitat was available.  
216 These species spanned 31 of the 124 existing Lepidoptera families.

217

## 218 2. b. Ecological data on species habitat, daytime activity and mimicry type

219 Ecological information was collected from the literature, Lepidoptera experts and  
220 our own knowledge for a total of 107 species for activity rhythm (57% of species are  
221 diurnal (day-active) species), habitat (56% of species living in open habitats), and  
222 mimicry status (14 species were bee/wasp mimics, 12 species were leaf mimics,  
223 while the remaining 81 did not fall in either of those categories (hereafter referred to  
224 as non-mimics, Table S1 and Fig S4). The selected 107 species do not include species  
225 that were reported to live in both open and closed habitats, or to fly at day and night.  
226 Visual predators are mostly active during the day and are supposed to be the main  
227 selective agents in the evolution of visual signals related to anti-predator defences  
228 (Ruxton et al. 2018), thus, nocturnal species are unlikely to face similar selective  
229 pressures as diurnal species although both could fly in similarly open habitats.  
230 Therefore, daytime rhythm and habitat were coded as a single variable with 4  
231 states (diurnal open habitat, diurnal closed habitat, nocturnal open habitat and  
232 nocturnal closed habitat). Bee and wasp mimics were grouped together in the same  
233 mimicry category, as both exhibit the striped pattern with black and yellow that  
234 advertise their unpalatability (Plowright and Owen 1980) and they exhibit similar  
235 body sizes. Butterflies and moths mimicking bees and wasps have forewings longer  
236 than their hindwings, and often, strong delimitations of their wing borders and veins  
237 by dark coloration, as the hornet moth *Sesia apiformis* (*api* - bee, *formis* -shaped) or

238 the broad-bordered bee hawk-moth *Hemaris fuciformis* (Fig 1b). Dead-leaf mimics  
239 include brownish moths and butterflies with small or large transparent surfaces and  
240 that could touch or not the wing borders (Fig. 1a). *Rotschildia lebeau* has been  
241 proposed as a leaf mimic (Janzen 1984) but such mimicry is controversial  
242 (Hernández-Chavarría et al. 2004). *Rotschildia ericina* was therefore not considered  
243 as a leaf mimic for the analyses.

244

## 245 2. c. Wing structural and optical measurements

246 Wing structural and optical measurements were taken from Gomez et al, using the  
247 following methods. Museum specimens were photographed using a D800E Nikon  
248 camera equipped with a 60mm lens, placed on a stand with an annular light. Photos  
249 were then analysed using ImageJ (Schneider et al. 2012) to extract descriptors of  
250 wing macrostructure: wing length (mm), wing surface (mm<sup>2</sup>), and clearwing area  
251 (the surface of transparent area in mm<sup>2</sup>), for the forewing and hindwing separately.  
252 We defined and computed proportion of clearwing area as the ratio clearwing  
253 area/wing surface, i.e. the proportion of the total wing area occupied by  
254 transparency.

255 For optical measurements, we followed the same procedure described above  
256 for measuring transmittance in artificial prey. For each species and wing, we took  
257 five measurements in the transparent zone. We analysed spectral shape using Avicol  
258 v6 (Gomez 2006) to extract the mean transmittance over [300-700] nm, which  
259 described the level of transparency.

260

## 261 2. d. Physical properties of transparent wings

262 Gomez et al (2020) described a large diversity in transparent wing surface  
263 characteristics. Using binocular imaging (Zeiss Stereo Discovery V20) and digital  
264 microscopic imaging (Keyence VHX-5000), these authors found that transparency  
265 could be achieved either with nude membranes or with membranes covered by  
266 scales of various types (either classical scales, hair-like scales or both) that could be  
267 coloured or transparent, and erected or flat according to their insertion on the wing  
268 membrane. Different combinations of structures and configurations are related to  
269 different light transmission levels. Therefore, we also explored the evolution of these  
270 characteristics and their relationship with mimicry syndrome.

271

## 272 2. e. Analyses of transmittance differences between habitats and mimics

273 To explore whether differences in the proportion of transmitted light are related to  
274 variation in habitat and mimicry we fitted both 1) a linear mixed model including  
275 107 species for which we found data on habitat preference and 2) a Bayesian  
276 phylogenetic mixed model, including the phylogeny of the 107 species. Comparisons  
277 between the first and the second analysis allowed us to assess the influence, if any, of  
278 phylogenetic relationships on the observed trends. Light availability, mimicry and  
279 morphological traits were included as explanatory variables in our model. We  
280 defined ActHab, a variable combining daytime activity and habitat openness with  
281 four levels (diurnal open, diurnal closed, nocturnal open, nocturnal closed) and three  
282 contrasts (diurnal vs. nocturnal, open vs. closed habitats, and diurnal open habitat  
283 vs. diurnal closed habitat). The variable mimicry has three levels (bee-wasp mimics,  
284 leaf mimics and non-mimics) and we tested two contrasts (bee/wasp mimics vs. all  
285 other species, and leaf mimics vs. non- mimics). Other explanatory variables  
286 included: wing length (as a proxy of butterfly size), proportion of clearwing surface

287 and fore-/hindwing, reported by Gomez et al (2020) as correlated to light  
288 transmittance. Wing transmittance, wing length and clearwing proportion were  
289 obtained from Gomez *et al* (2020). As five measurements per wing (fore- and  
290 hindwing), thus ten measurements per species were included in our dataset, wing  
291 measures nested in species was considered as a random effect. We fitted different  
292 models including different combinations of two- and three-factor interactions and  
293 we compared them using the AIC criterion to select the best model. To better  
294 understand the effect of each of the included variables, we reported and compared  
295 the full model without interactions and the best model including interactions (Table  
296 1). Additionally, we fitted Bayesian phylogenetic mixed models with Markov chain  
297 Monte Carlo analyses using the ‘mulTree’ R package (Guillerme and Healy 2014).  
298 Using the best formulated linear mixed model, uninformative priors were chosen,  
299 with variance and belief parameter set to 1 for random effects and 0.002 for residual  
300 variances (Hadfield 2010). Models were run using two chains of 600,000 iterations,  
301 a thinning interval of 300 and a burn-in of 10,000. Fixed effects were considered  
302 statistically significant when the probabilities in the 95% credible intervals did not  
303 include zero. As Bayesian phylogenetic mixed models consider no interactions  
304 between factor levels, several submodels were fitted to test the interactions from the  
305 best model obtained according to AIC criterion.

306         Additionally, we performed several phylogenetic generalised least square  
307 (PGLS) analyses (1 observation per species) to test for potential correlations  
308 between size, proportion of clearwing surface, daytime activity, habitat and mimicry,  
309 and between wing ratio (forewing length/hindwing length, usually high in bees and  
310 wasps) and mimicry. Using BayesTraits (Pagel and Meade 2013) we additionally  
311 explored character coevolution between mimicry and ActHab and between habitat

312 and daytime as well as between mimicry and scale characteristics:  
313 absence/presence of scales, scale insertion (flat or erected), scale coloration  
314 (coloured or transparent) and scale type (hair-like scales and classic scales). When  
315 analysing physical wing properties and mimicry evolution, independent analyses  
316 were performed for anterior and posterior wings, as differences between wings have  
317 been reported by Gomez et al (2020). We calculated the likelihood of the dependent  
318 and independent models of evolution of each pair of binary characters, using a  
319 Markov-Chain Monte-Carlo approach. We then estimated the likelihood ratio test  
320 between them and compared it to a chi-square distribution with 4 degrees of  
321 freedom to obtain their statistical significance (Pagel 1994). As this approach can  
322 only be applied to binary characters, and mimicry has three factors, models were run  
323 including the different possible pairwise combinations to explore: a. evolution of  
324 dead-leaf mimicry (including non-mimics and dead-leaf mimics); b. evolution of  
325 bee/wasp mimics (including non-mimics and bee/wasp mimics) and c. differences in  
326 the evolution of dead-leaf and bee/wasp- mimics (including bee/wasp and dead-leaf  
327 mimics). Similarly, for the composed variable ActHab we compared (i) diurnal and  
328 nocturnal species flying in open habitats, and (ii) nocturnal species flying in open  
329 and in closed habitats. We calculated  $\delta$ , a new metric inspired in the phylogenetic  
330 analog of the Shannon entropy to measure phylogenetic signal in categorical non-  
331 ordered data (Borges et al. 2019), for testing for phylogenetic signal in ActHab,  
332 daytime activity and mimicry evolution.  $\delta$  is useful to detect whether the coevolution  
333 between traits are homologies (characteristics are shared within a clade) or  
334 convergences (characteristics evolved independently but jointly and several times  
335 along the phylogeny). For each trait, we compared its evolution in our data with the  
336 evolution of a randomly sorted trait (assuming it has no phylogenetic signal), using

337  $\lambda = 0.1$ , standard deviation of 0.5, 10000 iterations, keeping the 10<sup>th</sup> iterate  
338 and burning-in 100 iterates, parameters from the example script proposed by  
339 Borges *et al* (2019). In case of homology,  $\delta$  should be higher for the real data than for  
340 the randomly sorted data.

341 Finally, we predicted higher variance in light transmittance for those  
342 conditions where different levels of transparency might be equally efficient as would  
343 be the case for butterflies and moths that are active during the night, that live in  
344 closed habitats and/or that are dead-leaf mimics. We applied Fligner-Killeen tests of  
345 homogeneity of variance in R to test for difference in variance between (i) diurnal  
346 and nocturnal species living in open and in close habitats, and (ii) bee/wasp mimics,  
347 leaf mimics and no mimic species. As Gomez et al (2020) reported that transmittance  
348 is closely related to wing size, we also tested for differences in the variation of wing  
349 length between habitat, daytime activity and mimicry using the test mentioned  
350 above.

351

## 352 Results

### 353 Fieldwork experiment

354 In total, 1149 artificial butterflies were used during the experiment and 243 prey  
355 were attacked (21.14 %). When data from both open and closed habitats were  
356 analysed together, survival was lower in open than in closed areas. In closed areas  
357 651 prey were released, 110 attacked, with an attack rate of 16.89% while in open  
358 areas, 498 prey were released, 133 attacked, with an attack rate of 26.71% (Wald  
359 test = 34.39, df = 7,  $p < 0.001$ ). Results are similar when including the “reduced”  
360 datasets (random subsample of the closed habitat set and of the same sample size as  
361 the set released in open habitats, Table S2). Additionally, in open habitats the opaque

362 form was more attacked than the other forms that had transparency ( $z = 2.15$ ,  
363  $p = 0.031$ ), but when including the “reduced” dataset, such difference was only  
364 detected in 6 out of the 20 random subsets Table S2). When data was analysed  
365 independently in each habitat, all prey treatments were similarly attacked in closed  
366 areas (Fig. 2a, Wald test = 0.9,  $df = 3$ ,  $p = 0.825$ , and for the reduced dataset Wald test  
367 = 0.5,  $df = 3$ ,  $p = 0.5$ ), in contrast to open areas (Fig. 2b, Wald test = 9.86,  $df = 3$ ,  $p =$   
368 0.02). In open areas, opaque artificial butterflies were more attacked than all the  
369 other treatments ( $z = 2.68$ ,  $p = 0.007$ , Fig. 2b); artificial butterflies with six layers of  
370 transparency were marginally more attacked than those with a single transparency  
371 layer ( $z = 1.839$ ,  $p = 0.066$ , Fig. 2b), while artificial butterflies with or without a  
372 single transparent layer were similarly attacked and reported the lowest number of  
373 attacks ( $z = -1.61$ ,  $p = 0.11$ , Fig. 2b).

374

### 375 Comparative analyses

#### 376 Relationships between light transmittance, habitat and daytime activity

377 Habitat and daytime activity partly explain the variations found in light  
378 transmittance. Species flying in closed habitats transmit slightly more light than  
379 species flying in open habitats (model without interactions  $t = -1.67$ ,  $df = 101$ ,  $p = 0.08$ ;  
380 model with interactions  $t = -3.29$ ,  $df = 101$ ,  $p = 0.001$  Table 1). However, diurnal  
381 species flying in open habitats transmit more light than diurnal species flying in  
382 closed habitats (model with interactions  $t = 2.05$ ,  $df = 101$ ,  $p = 0.043$ , Table 1, Fig. 3).  
383 Transmittance decreases with wing length in diurnal species, but increases with  
384 wing length in nocturnal species (interactions between wing length and ActHab:  
385  $DO > DC$   $t = -3.46$ ,  $df = 484$ ,  $p < 0.001$ ;  $D > N$   $t = -2.33$ ,  $df = 484$ ,  $p = 0.02$ ;  $O > C$   $t = 2.68$ ,  $df =$   
386 484,  $p = 0.01$ ; Fig. 3). Transmittance increases with the proportion of clearwing

387 surface at a similar rate for both wings in most species (Interactions between  
388 proportion of clearwing surface and ActHab: D0>DC  $t = -2.55$ ,  $df = 484$ ,  $p = 0.01$ ; D>N  
389  $t = 1.11$ ,  $df = 484$ ,  $p = 0.27$ ; O>C  $t = 3.51$ ,  $df = 484$ ,  $p = <0.001$ ). More results were  
390 significant when phylogenetic effect was excluded, suggesting some phylogenetic  
391 signal in open/close habitat. Results were similar for most Linear and Bayesian  
392 mixed models, but differed when testing transmittance in diurnal/nocturnal species  
393 (Table 1 for Linear mixed model results and Tables S2 for Bayesian mixed  
394 submodels testing interactions included in linear mixed models). Actually, daytime  
395 activity has some phylogenetic signal ( $\delta = 0.58$  for real data vs.  $\delta = 0.42$  for  
396 randomised data), but ActHab not ( $\delta = 0.56$  for real data vs.  $\delta = 0.57$  for randomised  
397 data). No difference in wing length or the proportion of clearwing surface was  
398 detected between diurnal and nocturnal species nor species flying in closed or open  
399 habitats (Table S3).

400

401 Relationships between light transmittance, transparency structural basis and  
402 mimicry

403 Mimicry explains a large portion of the variation found in light transmittance.  
404 Bee/wasp mimics transmit more light than other clearwing species (model without  
405 interactions:  $t = 1.77$ ,  $df = 101$ ,  $p = 0.08$ ; model with interactions:  $t = 3.52$ ,  $df = 101$ ,  
406  $p < 0.001$ , Table 1, Fig. 4). Light transmittance for bee/wasp mimics is higher at larger  
407 proportions of clearwing surfaces ( $t = 2.24$ ,  $df = 484$ ,  $p = 0.03$ ) and at smaller wing  
408 lengths ( $t = -6.39$ ,  $df = 484$ ,  $p < 0.001$ ), in contrast to leaf mimics that exhibit higher  
409 transmittance at smaller proportions of clearwing surface ( $t = 3.67$ ,  $df = 484$ ,  
410  $p < 0.001$ ) and marginally, at larger wing lengths ( $t = -1.88$ ,  $df = 484$ ,  $p = 0.06$ , Table 1,  
411 Fig. 4).

412           Regarding the relationship between mimicry and wing characteristics, leaf  
413 mimics have smaller hindwings than non-mimics (PGLS forewing:  $t=1.66$ ,  $p = 0.1$ ;  
414 hindwing:  $t=1.99$ ,  $p = 0.05$ , Figure 4b), and the length ratio forewing/hindwing is  
415 larger for bee/wasp mimics than for any other clearwing species (PGLS  $t=4.51$ ,  $p$   
416  $<0.001$ , Fig. 4e). Additionally, the proportion of clearwing surface is larger for non-  
417 mimics and for bee/wasp mimics (PGLS forewing:  $t=4.005$ ,  $p < 0.001$ ; hindwing:  
418  $t=2.86$ ,  $p=0.005$ , Fig. 4c). Mimicry syndrome and daytime have likely coevolved:  
419 most bee/wasp mimics are diurnal while most leaf mimics are nocturnal  
420 (BayesTraits daytime activity and bee/wasp or leaf mimics: LRT=9.5,  $df = 4$ ,  $p=0.05$ ,  
421 Table 2, Fig S4 & Fig S6).

422           We found that transmittance varies less in bee/wasp mimics than in leaf-  
423 mimics (Fligner-Killeen test for forewing: 15.6,  $df= 1$ ,  $p<0.001$ , for hindwing: 36.14,  
424  $df = 1$ ,  $p<0.001$ ), or in other clearwing species (Fligner-Killeen test for forewing:  
425 16.38,  $df=1$ ,  $p<0.001$ ; for hindwing: 36.34,  $df = 1$ ,  $p<0.001$ ), but there is no difference  
426 in the transmittance variation in leaf mimics and non-mimic species (Fligner-  
427 Killeen test for forewing: 2.02,  $df=1$ ,  $p= 0.155$ ; for hindwing: 0.00005,  $df = 1$ ,  
428  $p=0.995$ ). Likewise, wing length varies less in bee/wasp mimics than in leaf mimics  
429 (Fligner-Killeen test for forewing: 18.91,  $df=1$ ,  $p<0.001$ ; for hindwing: 39.86,  $df = 1$ ,  
430  $p<0.001$ ) or in other clearwing species (Fligner-Killeen test for forewing: 39.06,  
431  $df=1$ ,  $p<0.001$ ; for hindwing: 59.15,  $df = 1$ ,  $p<0.001$ ). Leaf and non-mimics show  
432 similar variations in wing length (Fligner-Killeen test for forewing: 0.58,  $df=1$ ,  
433  $p=0.447$ ; for hindwing: 2.46,  $df = 1$ ,  $p=0.117$ ).

434           Some scale characteristics are correlated to mimicry evolution. Scales are  
435 more often absent and less often coloured when present in hindwings of bee/wasp  
436 mimics in comparison to non-mimics wings (BT LRT presence = 24.55,  $df=4$ ,

437  $p < 0.001$ , Table S4 & Fig S7; BT LRT colour = 16.14,  $df = 4$ ,  $p = 0.003$ , Table S4 & Fig S7).  
438 Similarly, leaf mimics have less often coloured scales in comparison to non-mimics  
439 both in forewing (BT LRT = 11.62,  $df = 4$ ,  $p = 0.02$ ) and hindwing (LRT = 12.87,  $df = 4$ ,  
440  $p = 0.012$ , Table S4 & Fig S7). Moreover, leaf mimics only exhibit classic scales in  
441 contrast to bee/wasp mimics and non-mimics (LRT = 9.33,  $df = 4$ ,  $p = 0.053$ , Table S4 &  
442 Fig S7). These similarities are likely to be evolutionary convergences as mimicry has  
443 no phylogenetic signal ( $\delta = 0.99$  for real data vs.  $\delta = 1.002$  for randomised data).

444

## 445 **Discussion**

446 Fieldwork experiments using artificial prey that differed in their proportion of  
447 transmitted light suggest that variation in transparency can be detected only in  
448 brighter light conditions, similar to what has been suggested for aquatic  
449 environments (Johnsen and Widder 1998). Poorly transparent prey types survived  
450 less than highly transparent ones in open environments, while they performed  
451 similarly in closed areas. Additionally, less artificial moths were attacked in closed  
452 habitats, even after increasing the number of artificial prey in closed habitats to  
453 compensate for the higher predation rate often reported for open habitats such as  
454 forest edges (Barbaro et al. 2014). By controlling for differences in predation rate  
455 between habitats by increasing the number of prey placed in closed habitat our  
456 results suggest that selective pressure towards an increase in transmittance is  
457 higher in open than in closed habitats.

458 Our experimental results suggest that if transparency has mostly evolved as a  
459 detectability reducer, high transmittance should be more common in open habitats.  
460 In comparative analyses, when analysing only diurnal species, clearwing species  
461 flying in open habitats transmit indeed more light than species flying in closed

462 habitats, in agreement to what would be selected according to the high visual  
463 performance of visual predators under bright conditions (Johnsen and Widder  
464 1998). However, overall butterflies and moths living in closed habitats (including  
465 both diurnal and nocturnal) transmit similar to slightly more light than species living  
466 in open habitats. Gomez et al (2020) reported that poor light transmittance is  
467 associated to small proportions of clearwing surface and large wing sizes. Diurnal  
468 species flying in closed habitats show higher proportion of clearwing surface than  
469 those living in open habitats (Table 1, Fig. 3), probably contributing to the  
470 similar/slightly higher values of light transmittance in closed habitats in comparison  
471 to the open habitats. Species living in open habitats undergo higher risks of tissue  
472 damage by higher exposure to UV light, more wind or higher exposure to direct  
473 rainfall, conditions that have been reported as important at shaping moth and  
474 butterfly segregation in different habitats (Brown Jr and Hutchings 1997). In case  
475 transparency entails costs related to one or several of these factors, selection may  
476 promote lower proportions of clearwing surfaces in open habitats, decreasing the  
477 vulnerability of clearwing Lepidoptera species to these abiotic effects.

478         Transparency can decrease prey detectability but it is also involved in  
479 mimicry of bees or wasps, and differences in light transmittance seem to be closely  
480 associated to mimicry evolution. When mimicry is included in the analysis, we found  
481 that bee/wasp mimics have higher transmittance levels, frequently associated to the  
482 absence of scales in their wings, and are more often restricted to open habitats, in  
483 agreement to our fieldwork results and confirming that high transmittance in open  
484 habitats can be a visual optimum in terrestrial environments. As this is not the case  
485 for all clearwing species, this highlights the strong effect of biotic and abiotic

486 interactions in shaping adaptive peaks, thus the segregation of species under  
487 different conditions and the evolution of different features.

488         We also found that bee/wasp mimics are diurnal (similar to most bees,  
489 Somanathan et al. 2009), and have smaller wing sizes and smaller hindwings in  
490 comparison to their forewings (as has been reported for wasps and bees, Wootton  
491 1992; Lindauer 2019). Insects that mimic bees or wasps resemble their harmful  
492 counterparts in body colour, body shape and flight pattern (for butterflies (Skowron  
493 Volponi et al. 2018)) but also in activity patterns (for Diptera (Howarth et al. 2004)).  
494 Convergence in high light transmittance along with reduction in variation in wing  
495 size and the presence of long and narrow forewings and small hindwings (large  
496 fore/hindwing ratio) can contribute to such multicomponent mimicry, that improves  
497 prey chances at deceiving a larger set of predators, in case several traits are similarly  
498 salient for them (Kazemi et al. 2015) or when different predator species find  
499 different cues as salient (Kikuchi et al. 2016). As chitin, primary component of  
500 insects exoskeleton, is transparent, clearwings in insects are likely the basal state in  
501 absence of selection for colour evolution. However, the evolution of highly  
502 transparent wings in diurnal and very active insects, such as pollinators could have  
503 been driven by their higher mobility and the openness of the habitat where the  
504 majority of nectar sources frequently occurs (van Halder et al. 2011; Baude et al.  
505 2016). This suggest that bees, wasps and their Batesian mimics combine highly  
506 transparent wings as they can enhance their crypsis while being highly mobile and  
507 also exhibit warning colours that advertise their (potential) harmfulness once they  
508 are detected/approached by predators, similar to unpalatable clearwing Ithomiini  
509 species (Mcclure et al. 2019). In aquatic environment, transparent forms of *Hippolyte*  
510 *obliquimanus* shrimps are more mobile and exploit a larger diversity of habitats,

511 probably because they are cryptic on several backgrounds (Duarte et al. 2016).  
512 Whether transparency is also related to higher mobility in insects remains to be  
513 properly tested.

514 On the other hand, we found that leaf mimics are larger, are more often found  
515 in closed habitats and in contrast to the trends for all other clearwing species,  
516 transmit more light at larger wing sizes and lower proportions of clearwing surfaces.  
517 Some fully opaque fallen leaf mimic species, such as the comma butterfly (*Polygonia*  
518 *c-album*) exhibit a distinctive pale mark that might decrease their predation by being  
519 perceived as ‘distractive marks’ preventing predators from recognise the prey, thus  
520 enhancing background matching (Dimitrova et al. 2009; Olofsson et al. 2013),  
521 although it is controversial (Troscianko et al. 2018). Either way, reduced and highly  
522 transparent zones as those found in *Orthogonioptilum violascens* might produce a  
523 similar appearance to those markings given their high transmittance that might be  
524 highly reflective and be perceived as a white mark, conferring thus the potential  
525 benefits of the “comma mark” when seen for a given angle, as well as the full crypsis,  
526 when no reflections can be perceived. Whether highly transparent windows work as  
527 other highly visible elements displayed in cryptic species such as eyespots that deter  
528 predators (Stevens et al. 2008, 2009) and that are also important in mate choice  
529 (Robertson and Monteiro 2005) remains to be tested.

530 Other dead-leaf mimics include large transparent surfaces that can expand to  
531 the wings edges, as for *Bertholdia* species, or not, as for *Pseudasellodes fenestraria*. In  
532 both cases, transparency surfaces are likely disrupting prey shape (as in the first  
533 case) and/or prey surface (as in the second example (Costello et al. 2020)), thereby  
534 reducing their detectability. Disruptive coloration, especially when touching prey  
535 borders, has been broadly studied as it is common in fully opaque cryptic species

536 (Cuthill et al. 2005; Schaefer and Stobbe 2006; Stevens and Cuthill 2006; Fraser et al.  
537 2007). Whether transparent surfaces touching wing edges, work as disruptive  
538 marks regardless of their transmittance, decreasing even more prey detectability  
539 remains to be tested.

540

#### 541 **Conclusion**

542 Both light availability (daytime activity and habitat openness) and mimicry can  
543 concur to fostering variations in light transmittance on land. Our results opens up  
544 new questions that need to be investigated in the future, in particular the eventual  
545 cost of transparency regarding irradiance, wind and direct rainfall, needed to better  
546 understand the evolution and the constraints imposed on transparency on land.

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## Figures and tables

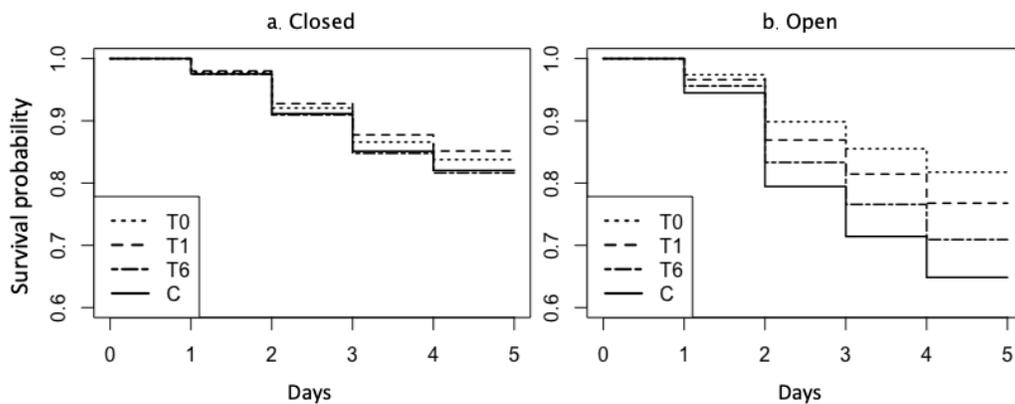
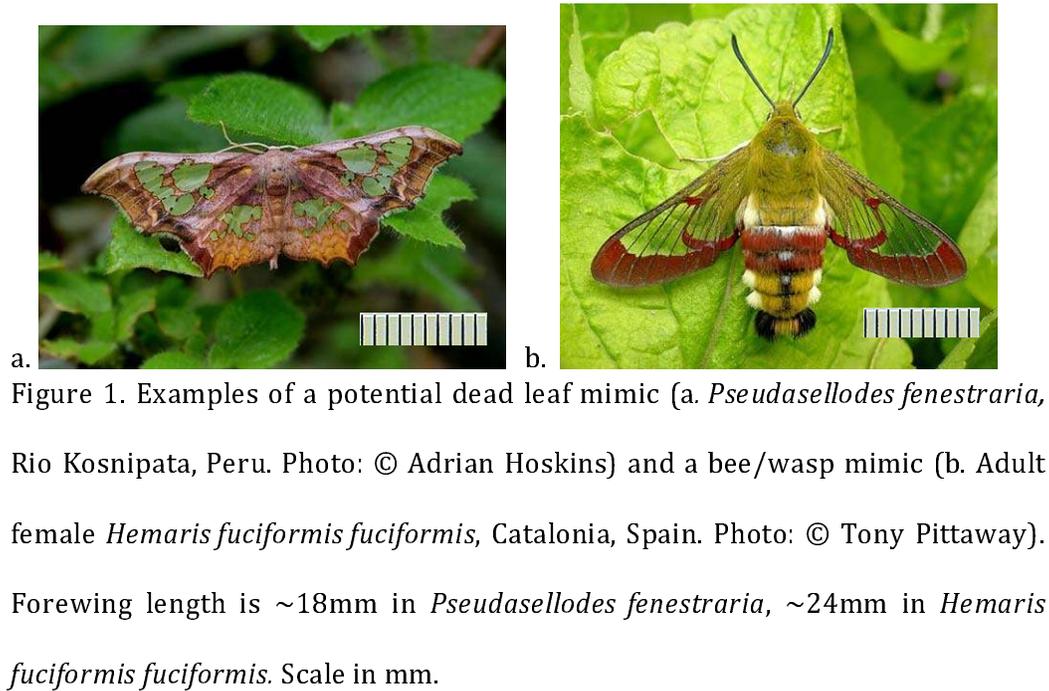


Figure 2. Survival of artificial prey in (a.) closed and (b.) open areas, without any transparent area (C), and with transparent elements covered by 6 (T6), 1 (T1) or non (T0) transparent film layers. Prey placed on tree trunks were monitored for 'survival' every day for 4 days.

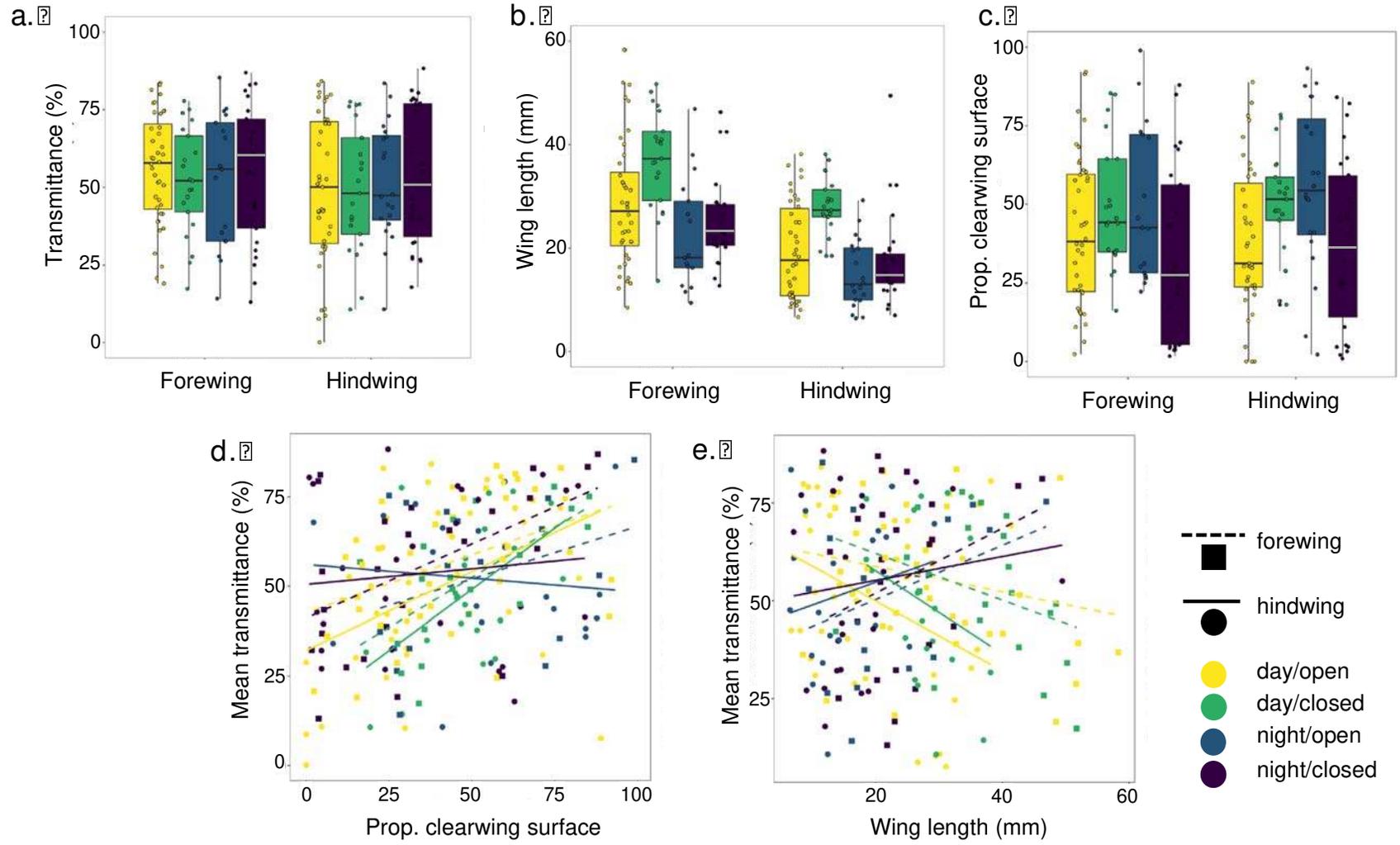


Figure 3: Variation between diurnal/open (yellow), diurnal/closed (green), nocturnal/open (blue) and nocturnal/closed (purple) in a) mean light transmittance, b) wing length, c) proportion of clearwing surface; and the relationship between transmittance, wing (forewing: square/dashed and hindwing: circle/plain) and d) proportion of clearwing surface or e) wing length. Plotted lines in d. and e. correspond to linear regressions per wing and ActHab level. Values larger than 60 mm were not plotted for clarity reasons but were included in the analyses.

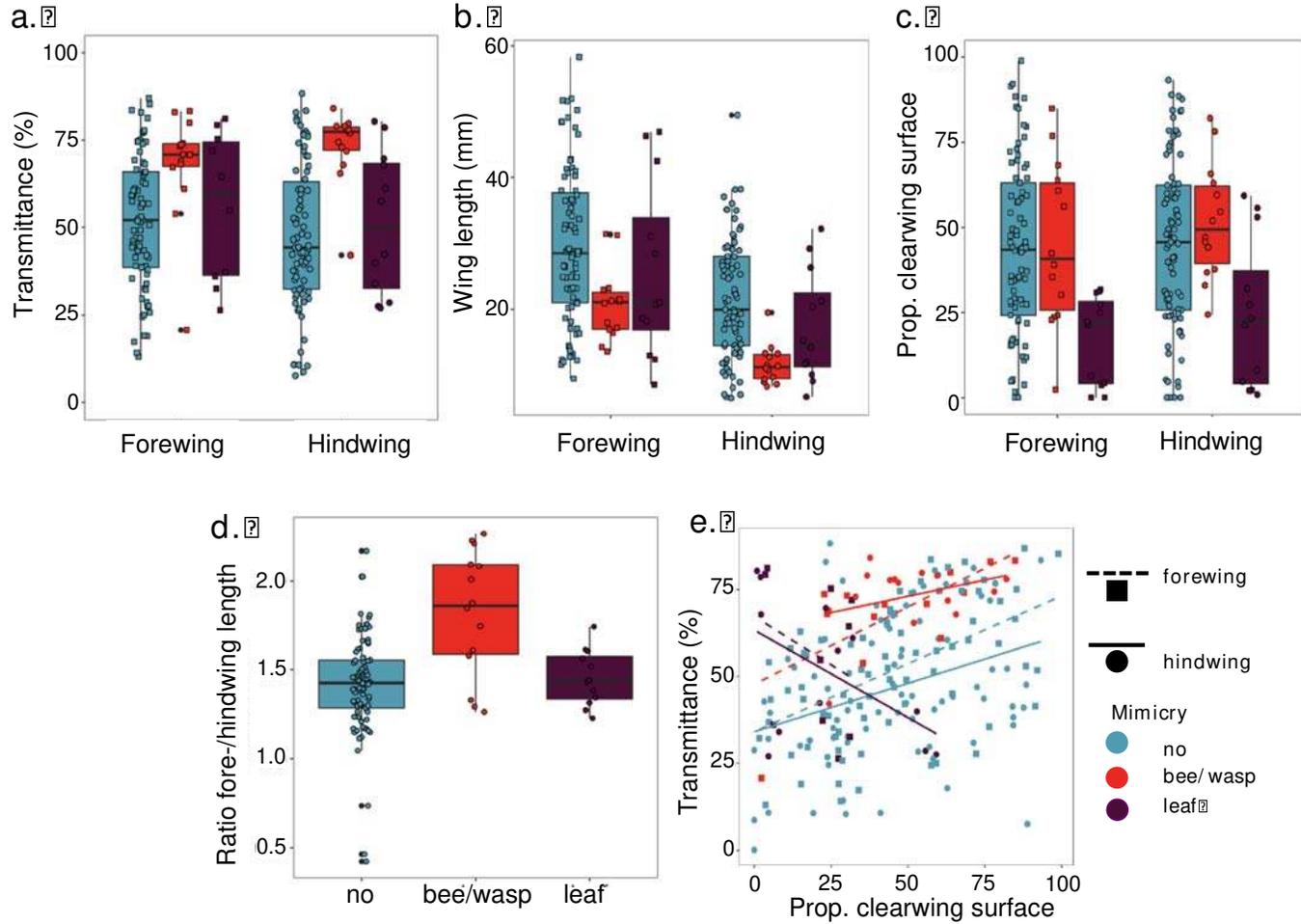


Figure 4: Variation between bee/wasp mimics (red), leaf mimics (purple) and no mimics (blue) in a) mean light transmittance, b) wing length, c) proportion of clearwing surface, d) Ratio between length of forewing and hindwing per mimicry group and e) in the relationship between wing size and mean light transmittance. Plotted lines in e. correspond to linear regressions per wing and mimicry level.

Table 1. Variation of mean proportion of transmitted light according to mimicry, habitat, daytime activity, wing size, wing and proportion of clearwing surface excluding (in the left) or including interactions between them (in the right). For Bayesian estimations see Tables S2 a, b, c and d.

	Estimate ± se	DF	t		Estimate ± se	DF	t		
Single factors	<b>(Intercept)</b>	<b>48.36±3.03</b>	<b>502</b>	<b>15.97</b>	<b>***</b>	<b>42.77±4.47</b>	<b>484</b>	<b>9.56</b>	<b>***</b>
	<b>% clearwing</b>	<b>0.27±0.02</b>	<b>502</b>	<b>10.91</b>	<b>***</b>	<b>0.27±0.08</b>	<b>484</b>	<b>3.57</b>	<b>***</b>
	<b>Mimicry:bee/wasp&gt;leaf+non-mimics</b>	<b>16.39±5.55</b>	<b>101</b>	<b>2.95</b>	<b>**</b>	<b>31.14±6.7</b>	<b>101</b>	<b>4.65</b>	<b>***</b>
	Mimicry:leaf<non-mimics	9.8±6.15	101	1.59		8.09±7.96	101	1.02	
	Wing length	<b>-0.43±0.07</b>	<b>502</b>	<b>-6.6</b>	<b>***</b>	<b>-0.07±0.14</b>	<b>484</b>	<b>-0.5</b>	
	ActHab (DayOpen>DayClosed)	3.18±3.78	101	0.84		<b>16.18±7.89</b>	<b>101</b>	<b>2.05</b>	<b>*</b>
	ActHab (Day>Night)	1.68±1.99	101	0.84		6.63±4.13	101	1.61	
	ActHab (Open>Closed)	-4.62±2.77	101	-1.67	~	<b>-17.26±5.24</b>	<b>101</b>	<b>-3.29</b>	<b>**</b>
	Wing (Forewing>Hindwing)	<b>3.67±0.39</b>	<b>502</b>	<b>9.45</b>	<b>***</b>	1.23±0.66	484	1.87	~
	Mimicry (bw>l+n.m): % clearwing	-	-	-		0±0.07	484	-0.06	
<b>Mimicry (leaf&lt;n.m): % clearwing</b>	-	-	-		<b>-0.37±0.1</b>	<b>484</b>	<b>-3.72</b>	<b>***</b>	
<b>Mimicry (bw&gt;l+n.m):W.length</b>	-	-	-		<b>-0.87±0.15</b>	<b>484</b>	<b>-5.85</b>	<b>***</b>	
Mimicry (leaf<n.m):W.length	-	-	-		0.33±0.19	484	1.76	~	
<b>ActHab (DO&gt;DC): % clearwing</b>	-	-	-		<b>-0.36±0.14</b>	<b>484</b>	<b>-2.55</b>	<b>**</b>	
ActHab (D>N): % clearwing	-	-	-		0.08±0.07	484	1.11		
<b>ActHab (O&gt;C): % clearwing</b>	-	-	-		<b>0.31±0.09</b>	<b>484</b>	<b>3.51</b>	<b>***</b>	
<b>ActHab (DO&gt;DC):Wing length</b>	-	-	-		<b>-0.89±0.26</b>	<b>484</b>	<b>-3.46</b>	<b>***</b>	
<b>ActHab (D&gt;N):Wing length</b>	-	-	-		<b>-0.32±0.14</b>	<b>484</b>	<b>-2.33</b>	<b>*</b>	
<b>ActHab (O&gt;C):Wing length</b>	-	-	-		<b>0.54±0.2</b>	<b>484</b>	<b>2.68</b>	<b>**</b>	
Interactions	% clearwing surf.:Wing length	-	-	-		0±0	484	-0.5	
	Wing length:Wing (F>H)	-	-	-		0.05±0.02	484	1.91	~
	ActHab (DO>DC):Wing (F>H)	-	-	-		0.55±0.93	484	0.58	
	<b>ActHab (D&gt;N):Wing (F&gt;H)</b>	-	-	-		<b>2.31±0.48</b>	<b>484</b>	<b>4.83</b>	<b>***</b>
	ActHab (O>C):Wing (F>H)	-	-	-		0.02±0.76	484	0.02	
	<b>ActHab (DO&gt;DC): % clearw :W. length</b>	-	-	-		<b>0.02±0.01</b>	<b>484</b>	<b>4</b>	<b>***</b>
	ActHab (D>N): % clearw :W. length	-	-	-		0±0	484	-0.48	
	<b>ActHab (O&gt;C): % clearw :W. length</b>	-	-	-		<b>-0.01±0</b>	<b>484</b>	<b>-2.99</b>	<b>**</b>

Linear mixed model with transmittance as dependent variable and the following explanatory variables: the combination between daytime activity and habitat type (ActHab: nocturnal-open/nocturnal-closed/diurnal-open/diurnal-closed), wing length in mm, proportion of clearwing area (% clearwing), mimicry syndrome (bee/wasp -, leaf - or non-mimics), wing (fore-/hindwing) and the interactions: mimicry syndrome and proportion of clearwing area, mimicry syndrome and wing size, proportion of clearwing area and habitat type, wing size and habitat type, wing size and proportion of clearing area, wing and wing length and proportion of clearwing area, wing length and habitat as explanatory variables. Wing measurements nested in species was considered as random effect. LMM p values below 0.05 are statistically significant. \*\*\* stands for p<0.001, \*\* for p<0.01, \* for p<0.05 and ~ for p<0.1.

Table 2. Results of coevolution tests between habitat, mimicry and daytime activity

Tested characters	Mimicry levels included	L.Dep.	L.Indep.	LR	df	p	
daytime activity/ mimicry	<b>bee/wasp &amp; leaf mimics</b>	<b>-29.13</b>	<b>-33.88</b>	<b>9.5</b>	<b>4</b>	<b>0.05</b>	*
	<b>No- &amp; leaf mimics</b>	<b>-91.21</b>	<b>-98.19</b>	<b>13.96</b>	<b>4</b>	<b>0.01</b>	***
	No- & bee/wasp mimics	-100.85	-100.86	0.02	4	1	
habitat / mimicry	bee/wasp & leaf mimics	-34.86	-36.78	3.85	4	0.43	
	No- & leaf mimics	-102.27	-102.34	0.13	4	1	
	No- & bee/wasp mimics	-99.73	-101.26	3.05	4	0.55	
habitat/daytime activity	No-, bee/wasp- & leaf mimics	-142.49	-145.1	5.22	4	0.26	
day.open vs night.open /mimicry	bee/wasp & leaf mimics	-17.57	-21.17	7.2	4	0.12	
	No- & leaf mimics	-45.89	-49.05	6.32	4	0.18	
	No- & bee/wasp mimics	-57.48	-57.82	0.68	4	0.95	
night.open vs night.closed /mimicry	bee/wasp & leaf mimics	-19.5	-19.52	0.04	4	1	
	No- & leaf mimics	-50.56	-50.57	0.02	4	1	
	No- & bee/wasp mimics	-36.86	-36.87	0.02	4	1	

Log-likelihood of dependent (L. Dep. Coevolution, 4 parameters estimated) and independent (L. Indep. 8 parameters estimated) evolution models between pairs of binary characters obtained from BayesTraits, log-likelihood ratio (LR), associated degree of freedom (df: difference in number of parameters) and corresponding p-value of the Likelihood Ratio Test. Because BayesTraits only take binary characters, when factors have more than 2 levels (mimicry and the composed character ActHab), we implemented pairwise comparisons of level. Coevolution between mimicry and diurnal species flying either in open or in closed habitats was not tested as no bee/wasp mimic is simultaneously diurnal and closed habitat dweller (Fig S4). A significant p-value means that the dependent model is significantly better than the independent model, indicating a correlated evolution between the traits. \*\* stands for statistical significance below 0.01 and \* for significance values below 0.05.