The evolution of red colour vision is linked to coordinated rhodopsin tuning in lycaenid butterflies

Marjorie A. Liénard[a,b,*], Gary D. Bernard[c], Andrew A. Allen[a], Jean-Marc Lassance[b], Siliang Song[b], Richard Rabideau Childers[b], Nanfang Yu[d], Dajia Ye[b], Adriana Stephenson[b], Wendy A. Valencia-Montoya[b], Shayla Salzman[b], Melissa R.L. Whitaker[b], Michael Calonje[e], Feng Zhang[a], Naomi E. Pierce[b,*]

[a] The Broad Institute of MIT and Harvard, Cambridge, MA 02142, USA.

[b] Department of Organismic and Evolutionary Biology and Museum of Comparative Zoology, Harvard University, Cambridge, MA 02138, USA.

[c] Department of Electrical & Computer Engineering, University of Washington, Seattle, WA, USA.

[d] Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027, USA

[e] Montgomery Botanical Center, 11901 Old Cutter Road, Miami, FL 33156, USA.

Present addresses:

Department of Biology, Lund University, Lund, Sweden (MAL), Department of Ecology and Evolutionary Biology, University of Michigan, 500 S. State Street, Ann Arbor, MI 48109, USA. (SiSo), Department of Biology, University of Pennsylvania, PA 19104, USA (DY); Gene therapy program, University of Pennsylvania, PA 19104, USA (AS); School of Integrative Plant Sciences, Section of Plant Biology, Cornell University, 502 Mann Library, Ithaca, NY 14853, USA (ShSa); Entomological Collection, Department of Environmental Systems Science, ETH Zürich, Zürich, Switzerland (MRLW)

[*]Corresponding authors:

Marjorie A. Liénard, Biology Department, Lund University, Sölvegatan 35B, 22362 Lund, Sweden, marjorie.lienard@biol.lu.se

Naomi E. Pierce, Department of Organismic and Evolutionary Biology, MCZ laboratories 4th floor, Harvard University, 26 Oxford Street, Cambridge, MA 02138, USA, npierce@oeb.harvard.edu

ORCIDs in alphabetical order by last name:

GDB: 0000-0001-7460-5123, RRC: 0000-0002-7137-3192, JML: 0000-0002-3675-6956, MAL: 0000-0003-3193-3666, WVM: 0000-0001-9246-2330, NEP: 0000-0003-3366-1625, SSa: 0000-0001-6808-7542, MRLW: 0000-0002-8774-8518, NY: 0000-0002-9462-4724

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Abstract

Colour vision is largely mediated by changes in number, expression, and spectral properties of rhodopsins, but the genetic mechanisms underlying adaptive shifts in spectral sensitivity remain largely unexplored. Using *in vivo* photochemistry, optophysiology, and *in vitro* functional assays, we link variation in eye spectral sensitivity at long wavelengths to species-specific absorbance spectra for LW opsins in lycaenid butterflies. In addition to loci specifying an ancestral green-absorbing rhodopsin with maximum spectral sensitivity (λ_{max}) at 520-530 nm in *Callophrys sheridanii* and *Celastrina ladon,* we find a novel form of red-shifted LW rhodopsin at λ_{max} = 565-570 nm in *Arhopala japonica* and *Eumaeus atala.* Furthermore, we show that *Ca. sheridanii* and *Ce. ladon* exhibit a smaller bathochromic shift at BRh2 (480-489 nm), and with the ancestral LW rhodopsin, cannot perceive visible red light beyond 600 nm. In contrast, molecular variation at the LW opsin in *A. japonica* and *E. atala* is coordinated with tuning of the blue opsin that also shifts sensitivity to longer wavelengths enabling colour discrimination up to 617 nm. We then use *E. atala* as a model to examine the interplay between red and blue spectral sensitivity. Owing to blue duplicate expression, the spatial distribution of opsin mRNAs within an ommatidium defines an expanded retinal stochastic mosaic of at least six opsin-based photoreceptor classes. Our mutagenesis *in vitro* assays with BRh1 (λ_{max} = 435 nm) chimeric blue rhodopsins reveal four main residues contributing to the 65 nm bathochromic shift towards BRh2 (λ_{max} = 500 nm). Adaptations in this four-opsin visual system are relevant for discrimination of conspecific reflectance spectra in *E. atala*. Together, these findings illustrate how functional changes at multiple rhodopsins contribute to the evolution of a broader spectral sensitivity and adaptation in visual performance.

Keywords

molecular evolution, ecological adaptation, visual system/vision, rhodopsin, spectral sensitivity, insects, Lepidoptera

Significance Statement

Rhodopsins are photosensitive protein molecules that absorb specific wavelengths of incoming light and convey colour information in the visual system. We show that molecular evolution in a green insect opsin gene resulted in a shift in its maximal absorbance peak, enabling some lycaenid butterflies to use spectral energy of longer wavelengths (LW) to discriminate colours in the red spectrum better than relatives bearing ancestral green LW rhodopsins. Lycaenids also evolved a duplicate blue opsin

gene, and we illustrate an example where species equipped with red LW rhodopsins shifted their blue sensitivity peak to longer wavelengths due to changes in several blue-tuning residues that have evolved repeatedly in different insect lineages. We demonstrate how changes at multiple vision genes in the insect eye effectively create a coordinated mechanism expanding spectral sensitivity for visually guided behaviours such as selecting host plants and mates.

Introduction

Multiple studies have demonstrated the important contributions of gene duplication and protein-coding changes in the evolution of novelty in lineage-specific phenotypic traits (1-3). For instance, gene duplication combined with modifications leading to functional divergence has contributed to gene family expansion, ultimately increasing transcriptional and functional diversity across lineages (2, 4). Recent examples show that specialization of ancestral functions (5-7) or cooperation between encoded products of duplication (8) are common mechanisms resolving constraints in existing eukaryotic gene networks (9). Genomic segmental duplications have also been shown to promote repeated allelic fixation, linking adaptive duplicated loci to convergent evolutionary pathways (10).

However, structural, functional, or gene network constraints can impose evolutionary trade-offs if there is limited variation for alternative biochemically stable encoded products among duplicated loci within multigene families (9, 11). Characterizing the molecular patterns of evolution within multigene families, and identifying the functional role of mutations at lower taxonomic scales is needed to distinguish the multiple sources of molecular variation. This includes the relative roles of gene duplication, expression changes, protein sequence divergence and convergence, or cellular relocalization of encoded gene products that contribute to new or convergent phenotypes within lineages (2, 7, 8, 12, 13).

Opsins belong to a diverse multigene family of G protein-coupled receptors, offering a robust framework to study how molecular changes can ultimately cause changes in behaviour and favour diversification (14). Opsins bind to a small non-protein retinal moiety derived from vitamin A to form photosensitive rhodopsins and enable vision across animals (15-18). The evolution of vision across the animal kingdom has long been linked to independent opsin gene gains and losses (19-23), genetic variation across opsins (15, 24-26), and spectral tuning mutations within opsins (27, 28). These molecular mechanisms, together with alterations in visual regulatory networks (29), have been shown to contribute to rhodopsin adaptation and the diversification of spectral sensitivity phenotypes in insects (18, 30, 31) and vertebrates including fish, birds, bats and primates (32-36). Thus multiple levels of organization, including the evolutionary

diversification of opsin subfamilies, their functional properties and regulatory networks constitute the mechanistic basis for organisms to discriminate light sources of varying wavelengths and ultimately interpret them as colours, yet how multiple changes across opsin paralog repertoires impact spectral sensitivity at small taxonomic scales has been understudied.

The evolution of insect colour vision in particular shows how a complex sensory trait can play a central role in adaptations involving signalling and mate communication (18, 31, 37, 38). Whereas the ancestral repertoire of insects involved three types of light-absorbing rhodopsin genes: ultraviolet (UVRh, 350nm), blue (BRh, 440 nm) and green, also called long-wavelength (LWRh, 530nm) (18), today's genomes harbor smaller or larger rhodopsin repertoires with strong experimental evidence for repeated functional convergence toward UV, Blue and LW spectral sensitivities across lineages. For example, beetles lost their ancestral blue opsin gene 300 million years ago, and compensated for the loss of blue sensitivity via either UV or LW gene duplication across lineages (23, 39). Blue opsin duplications occurred independently in pierid and lycaenid butterflies (27, 30, 40-42); and extend photosensitivity into the UV/blue in *Heliconius* spp. with λ_{max} = 355 nm and 398 nm (21) and into the violet/blue, in *Pieris rapae* with λ_{max} = 420 and 450 nm (27). UV and LW duplications occurred in butterflies, hemipterans and dragonflies (20, 22, 26, 30, 43-45). In butterflies, LW opsin duplications have been identified in two papilionids, *Papilio xuthus* (31) and *Graphium sarpedon* (46) as well as a riodinid *(Apodemia mormo)* (20, 47), and contribute to extend spectral sensitivity into the far red.

Although duplicated LW opsins have never been detected in the families Nymphalidae, Pieridae or Lycaenidae (25, 40, 41), photoreceptor types with sensitivity peaks in the red have been identified in these groups (40, 41). This supports the hypothesis that additional mechanisms such as lateral filtering and/ or molecular variation of ancestral LW opsin genes also contribute to modify long-wavelength sensitivity.

For example, photostable lateral filtering pigments are relatively widespread across butterfly lineages (e.g. *Heliconius* (21)*, Papilio (45), Pieris* (48), *Colias erato* (49), and some moths (*Adoxophyes orana,* (50)*; Paysandisia archon* (51)). These pigments

104 act as long-pass filters, absorbing short wavelengths and pushing the sensitivity peak of
105 LW photoreceptors into the red, to create distinct spectral types that can contribute to
106 colour vision (19, 31, 40, 48, 52, 53). Lateral filtering can shift peak sensitivity to longer
107 wavelengths while reducing peak amplitude, but cannot *extend* photoreceptor sensitivity
108 into the far red beyond the exponentially decaying long-wavelength rhodopsin
109 absorbance spectrum (52). Molecular variation of ancestral LW opsin genes could
110 potentially extend photoreceptor sensitivity, but this mechanism has remained difficult to
111 disentangle from the effects of filtering granules using classical electrophysiological
112 approaches (31, 53, 54).

113 The molecular underpinnings of mammalian MWS/ LWS spectral tuning has
114 been studied using mutagenesis experiments and led to the identification of critical
115 amino acid replacements and their interactions at key residues (55, 56). Most
116 mammalian lineages possess long-wavelength sensitive (LWS) cone opsins that specify
117 Medium (M, λ_{max} 510-540 nm) and Long (L, λ_{max} > 540 nm) rhodopsins. In humans,
118 trichromatic vision is conferred through the use of Short (S, λ_{max} = 414 nm), and tandem
119 duplicate M (λ_{max} = 530 nm) and L (λ_{max} = 560 nm) cone rhodopsins (34), that collectively
120 allow us to discriminate longer wavelengths of light as green-red colours (57, 58). In
121 birds, tetrachromatic vision is based on two SWS cone opsins, together with a green M
122 opsin (λ_{max} = 497-514 nm) and a red-sensitive LWS opsin (λ_{max} = 543-571 nm) (reviewed
123 in 59). In insects, the evolution of red receptors occurred independently multiple times
124 (30) but the possible contribution of molecular variation to insect LW opsin gene
125 diversification has remained elusive, notably due to difficulties in expressing LW opsins
126 *in vitro* (27, 60, 61, but see 62). Red receptors are intriguingly very common in butterflies
127 compared to other insect groups such as bees or beetles (30), raising the possibility that
128 perception of longer wavelengths plays an important role in the context of foraging (31,
129 46, 63), oviposition (64, 65) and mate recognition (25) for species equipped with them.

130 Lycaenids comprise the second largest family of butterflies, representing almost
131 thirty percent of all species, and exhibiting considerable ecological and morphological
132 diversity (66, 67). Pioneering work showed that species of Lycaenidae in the genera
133 *Lycaena* and *Polyommatus* have expanded spectral sensitivity at long wavelengths, and
134 this has been postulated to arise from filtering pigments, modified opsins or both (19, 40,

41). Here, by combining physiological, molecular and functional approaches, we identify additional lycaenid species with red photoreceptors and elevated spectral sensitivity at long wavelengths, and show that their LW opsin locus specifies a novel type of LW rhodopsin with red-shifted maximal absorbance. We focus on the Atala hairstreak (*Eumaeus atala*) as a suitable model to show the interplay between regulatory and adaptive changes at multiple opsin loci in the evolution of red spectral sensitivity and link the evolution of finely tuned four-opsin vision to relevant visually guided behaviours in these butterflies.

Results

Hairstreak butterflies with elevated sensitivity at long wavelengths express red-shifted rhodopsin receptors

A photographic series at distinct elevations in the eye revealed dramatic differences in eyeshine colouration between two pairs of lycaenids (Fig. 1 insets and Fig. S1). The Spring Azure, *Celastrina ladon* (subfamily Polyommatinae) and Sheridan's green hairstreak, *Callophrys sheridanii* (subfamily Theclinae), present homogeneous green and orange eyeshine in their dorsal eyes at 30° elevation, with a relatively small number of red ommatidia (*Ce. ladon*, 5%; *Ca. sheridanii*, 16%) (Fig. S1A-B). By contrast, the Japanese Oakblue, *Arhopala japonica,* and the Atala Hairstreak, *Eumaeus atala* (both subfamily Theclinae), share high levels of saturated red eyeshine in the dorso-equatorial region, due at least in part to species-specific differences in rhodopsin content (Fig. 1, Fig. S1B).

We partially bleached eyeshine of *A. japonica* and *E. atala* using repeated white-light flashes to reveal two types of ommatidia. Some ommatidia were resistant to bleaching and maintained their red eyeshine owing to lateral filtering by cherry-red pigment granules located distally within the photoreceptor cells of those ommatidia. The rest of the ommatidia were bleached, suggesting the presence of red sensitive opsin-based photoreceptors in these two species (Fig. S1C).

To test for the presence of red sensitive receptors, we performed analyses of *in vivo* photochemical rhodopsin bleaching measurements of adult butterflies. These experiments revealed long wavelength (LW) spectral sensitivities in dark-adapted eyes of *A. japonica* with λ_{max} ± standard error at 571 ± 2.45 nm ($CI_{95\%}$ = 566 to 576 nm) (Fig. 1A) and *E. atala* with λ_{max} at 563 nm ± 0.9 nm ($CI_{95\%}$ = 561 to 566 nm), respectively (Fig. 1B). We found that the two other lycaenid species we studied, *Ca. sheridanii* and *Ce. ladon,* were difficult subjects for our *in vivo* methods. In *Ca. sheridanii,* a noisy difference spectra obtained by photochemistry provided an estimate at LW λ_{max} = 518 nm ± 3.7 nm for ($CI_{95\%}$ = 511 to 526 nm) (Fig. 1C). Similarly, in *Ce. ladon,* partial LW bleaches were not measurable due to low LW rhodopsin densities,.

173 We chose to examine in detail the *in vivo* and *in vitro* contributions of all
174 rhodopsin pigments in *E. atala*, a multi-brooded and abundant hairstreak butterfly
175 naturally occurring throughout the year in Florida (USA) (68). Unlike most lycaenids, *E.*
176 *atala* larvae are extreme specialist herbivores on New World cycads in the genus *Zamia*
177 and show an unusually bright aposematic colouration advertising toxins they sequester
178 from their hosts (69). Conversely, the adult is a striking velvety black butterfly with bright
179 blue and red colours on the wings and the abdomen (Fig. 1) and can collect nectar from
180 43 species across 20 plant families (69)

181 We first analyzed epi-microspectrophotometric difference spectra obtained after
182 intense ommatidial flashing from a series of interference filters, which in addition to
183 identifying R565 (LW rhodopsin, Fig. 1B) allowed us to narrow down a blue rhodopsin at
184 R440 (Fig. 2A). Optophysiology measurements confirmed that neither the R565 LW nor
185 the R440 blue sensitive rhodopsins could be responsible for the high sensitivity around
186 360 nm, which instead was due to UV-receptors (Fig. 2B, Table S2). Finally, a
187 densitometric analysis of male and female eyes (Fig 2C-D, Tables S3-S4), showed that
188 these physiological data are best fit using least-squares regression by a model in which
189 four rhodopsins are present in the eye with λ_{max} values matching the LWRh rhodopsin as
190 well as UVRh 360 nm, BRh1 441.3 nm ± 4.7 nm ($CI_{95\%}$ = 431.7 to 450.9 nm, Table S2)
191 and a second blue rhodopsin BRh2 494.2 ± 1.2 nm ($CI_{95\%}$ = 492 to 497 nm) (Fig. 2E-F,
192 Tables S3-4).

193

194 ***Red sensitivity is due to functional variation at long-wavelength opsin loci***

195 Transcriptomic mRNA profiling of *E. atala* yielded only a single LW opsin (Table S6),
196 which is in line with earlier molecular evidence showing that lycaenid species possess
197 one LW opsin gene (30, 40, 53). Accordingly, eye cDNA library screening using
198 degenerated oligonucleotide primers followed by RACE cDNA amplification led to the
199 characterization of single orthologous LW cDNA sequences in *Ce. ladon*, *Ca. sheridanii*
200 and *A. japonica* (Fig. 3). We optimized an *in vitro* HEKT293 cell culture assay to
201 reconstitute heterologous rhodopsin pigments (27, 61, 70, 71) by using a newly
202 engineered heterologous vector to increase expression levels, and improving purification

203 procedures to obtain higher yields of actively reconstituted LW rhodopsins. Our
204 expression cassette derives from the pcDNA5 plasmid and expresses coding opsin
205 sequences tagged with a C-terminal FLAG epitope under a strong CMV promoter.
206 Directly downstream the FLAG epitope, a short peptide linker plus a T2A cleavage
207 cassette enable co-transcription of a fused cytoplasmic fluorescent mRuby2 coding
208 sequence (Fig. 3A). This expression cassette proved to be efficient at detecting
209 monomeric units of ultraviolet, blue and long-wavelength (LW) heterologous *E. atala*
210 opsin proteins *in vitro* (Fig. S2A). It is also successful at reconstituting and purifying
211 active LW rhodopsins, *i.e*. in *A. japonica, E. atala, Ca. sheridanii* and *Ce. ladon* lycaenid
212 butterflies (Fig. 3B-F, Fig. S2B, Table S5).

213 When purified from large-scale HEK293T cell cultures and reconstituted *in vitro* in
214 the dark in the presence of 11-*cis*-retinal, we found that the LW rhodopsin from *A.*
215 *japonica* absorbs maximally at λ_{max}= 574 ± 4 nm ($CI_{95\%}$ = 570-586 nm) (Fig. 3C) whereas
216 that of *E. atala* absorbs maximally at λ_{max}= 569 ± 2 nm ($CI_{95\%}$ = 565-573 nm) (Fig. 3D).
217 The peak of absorbance of purified LW rhodopsin measurements is within confidence
218 intervals of the best fit for LW linear absorbance estimates *in vivo* and supports the
219 hypothesis that the LW rhodopsin limb of absorbance in these two species pushes red
220 sensitivity above 600 nm. The LW rhodopsin pigment from *Ca. sheridanii* absorbs
221 maximally at λ_{max} = 519.2 nm ± 1.1 ($CI_{95\%}$ = 517-521 nm) (Fig. 3E), which is in
222 accordance with photochemical measurements (Fig. 1C), whereas *Ce. ladon* LW
223 rhodopsin absorbs maximally at λ_{max}= 531.7 ± 1.5 nm ($CI_{95\%}$ = 529-535 nm) (Fig. 3F,
224 Table S5).

225 In summary, these findings indicate that our expression system can be used
226 successfully to assess the functionality of LW rhodopsins outside of the complex eye
227 environment and demonstrate that at least some hairstreaks (Theclinae) express a new
228 functional type of far-red shifted visual opsin.

229

230 ***Blue opsin mRNA expression patterns lead to enhanced eye spectral richness***

231 Following photochemical and densitometric evidence that *E. atala* butterflies likely
232 possess four rhodopsins including contributions from two blue rhodopsins, we identified

233 two differentially expressed blue opsin-like transcripts from the eye transcriptome,
234 namely BRh1 and BRh2 (Table S6). We then examined their respective mRNA
235 expression patterns in photoreceptor cells, aided by the histological reconstruction of
236 photoreceptor organization in a typical ommatidium (Fig. 4).

237 We found that *E. atala* hairstreaks have a straight, 480-micron long rhabdom
238 composed of eight longitudinal photoreceptor cells (Fig. 4A-B (a-g)) and a ninth cell
239 close to the basement membrane (Fig. 4A-B (h)). The two most distal R1-R2
240 photoreceptor cells contribute the majority of microvillar extensions from 0 to 160
241 microns, whereas R3-R4 distal cells contribute a majority of microvilli from 140 to 300
242 microns, thereby overlapping partially with R1-R2 in the distal rhabdom tier. The
243 proximal R5-R8 cells contribute most microvilli in the last rhabdom tier up to 440
244 microns, a depth where the photoreceptor cells no longer bear any microvilli and the
245 ninth cell becomes visible (Fig. 4A-B (i)).

246 This rhabdomeric analysis provided the spatial morphological insights necessary
247 to subsequently identify photoreceptor cells expressing each opsin mRNA across
248 different eye regions. Using double fluorescent *in situ* hybridization experiments in
249 transverse and longitudinal eye sections of males and females of *E. atala*, we showed
250 that LWRh is expressed in all ommatidia in the six photoreceptor cells R3 to R8 (Fig. 5),
251 which is typical of many butterfly species (25, 29). No fluorescent signal was detected for
252 the long-wavelength opsin in R1-R2 cells (Fig. 5D-F). We next examined the cellular
253 localization of the short UV and medium blue opsin mRNAs in transverse sections in the
254 dorsal eye. Using probes targeting LWRh in combination with cRNA probes for UVRh,
255 BRh1 or BRh2 mRNAs, our data provide evidence that the latter rhodopsin mRNAs can
256 be expressed in either or both R1-R2 receptor cells forming single ommatidia (Fig 5A-F).

257 We also assessed the possibility that these opsins are co-expressed in R1 and
258 R2 cells using cRNA probes for UVRh and BRh1 (Fig. 5G), UVRh and BRh2 (Fig. 5H) or
259 BRh1 and BRh2 (Fig. 5I). We find that R1 and R2 follow a one-cell one-opsin regulation
260 pattern, with mutually exclusive expression of UVRh, BRh1 and BRh2 mRNAs (Fig. 5J).
261 Females exhibit a dorso-ventral expression gradient in which BRh2-expressing cells are
262 sparse in the dorsal eye region. In the ventral retina however, all three opsins (UVRh,
263 BRh1, BRh2) are found in addition to LWRh (R3-R8) (Fig. S3).

264 Cellular expression data therefore show that both of the duplicated blue opsin
265 mRNAs encode functional transcripts. Overall, the cellular localization of blue opsin
266 duplicates in adjacent photoreceptor cells creates multiple ways in which rhodopsins are
267 distributed within individual ommatidia, forming a local stochastic rhodopsin mosaic of at
268 least six opsin-based photoreceptor classes (UV-UV, B1-B1, B2-B2, UV-B1, UV-B2, B1-
269 B2, Fig. 5j). Additional structural features of the eye may also contribute to the diversity
270 of spectral sensitivity functions of individual photoreceptors, including the spectral
271 influence from lateral filtering granules found in distal rhabdomeres that add to the
272 spectral sensitivity of some photoreceptor cells.

273

274 ***BRh1 and Brh2 opsin duplicate loci encode blue and green-shifted rhodopsins***

275 We reconstituted active BRh1 and BRh2 rhodopsins *in vitro* and measured their spectral
276 sensitivities via spectroscopy as detailed in the methods. We determined that BRh1 λ_{max}
277 = 435 nm ± 2 nm and BRh2 λ_{max} = 500 nm ± 2 nm (Fig. 6A-B, Table S7), thereby
278 confirming that they encode the rhodopsins conferring the expanded blue to green
279 spectral sensitivity in *E. atala*. In addition to its LWRh red-shifted opsin (Fig. 3D), *E. atala*
280 uses a fourth rhodopsin that absorbs UV wavelengths *in vitro* at λ_{max}= 352 nm ± 3.5 nm
281 ($CI_{95\%}$ = 345-360 nm) (Fig. 3, Fig. S2d, Table S7).

282

283 ***Four spectral tuning sites and epistasis leads to bathochromic shifts between***
284 ***blue duplicates***

285 In order to understand the proximate mechanisms driving the 65 nm spectral shift
286 between blue opsin duplicates, we performed homology modeling against the
287 invertebrate squid rhodopsin (72). Along with their 380-aa long opsin protein sequences,
288 Eat-BRh1 and Eat-BRh2 exhibit 101 amino acid residue differences (corresponding to
289 73% similarity in aa sequence). Six variant sites were identified among 21 homologous
290 residues located within 5Å of any carbon forming the *cis*-retinal binding pocket (Fig.
291 6A,C). Two variant sites (S1 and S4) are shared with a blue/violet opsin duplication that
292 occurred independently in pierid butterflies, causing a UV-shift (VRh λ_{max} = 420 nm) from

293 the ancestral blue rhodopsin (BRh λ_{max} = 450 nm) (27), whereas four residues are
294 unique to duplicated blue opsins found in lycaenids (S2, S3,S5,S6).

295 Given this combination of shared and unique yet limited number of variant sites,
296 we decided to test their possible involvement in blue spectral tuning by site-targeted
297 mutagenesis. Specifically, we first modified individual residues S1 to S4 and measured
298 their spectral tuning effect *in vitro* (Fig. 6E-G, Fig. S4). Chimeric opsins showing
299 bathochromic shifts were used sequentially to substitute adjacent variant sites following
300 two candidate evolutionary trajectories. We observed an additive bathochromic shift
301 totaling 40 nm (λ_{max} = 475 nm) by substituting A116S (S1) together with I120F (S2) and
302 Y177F (S4) (Fig. 6E). In a second tuning trajectory, we observed that Y177F alone
303 conferred a 79 nm bathochromic shift (λ_{max} = 514 nm), which could then be
304 compensated by a 6 nm hypsochromic shift (λ_{max} = 508 nm) by combining G175S and
305 A116S (Fig. 6G). A third evolutionary trajectory explored the contribution of two lycaenid-
306 specific cysteine substitutions (I106C, F207C) in helix 5 (Fig. S4). These changes
307 caused a strong green-wave spectral shift that was not compensated for by additional
308 candidate interacting residues in the quintuple mutant (S1,2,4,5,6; Fig. S5, Table S8).
309 G165S (S3) tested alone or in various double mutant combinations caused
310 bathochromic shifts, but we did not obtain the sextuple chimeric construct bearing
311 G175S (S3) and cannot therefore exclude the possibility that it also plays a role in this
312 case. The available results from all variants bearing cysteines in S5 and S6, however,
313 suggest that both cysteine residues on helix 5, which are absent in Pieridae blue opsins,
314 are unlikely to be the main evolutionary drivers of blue spectral shifts in lycaenid BRh2
315 loci.

316 Finally, our optophysiological density analyses showed that blue spectral
317 sensitivity differs between species equipped with green or red LW rhodopsins. Whereas
318 all species possess a blue photoreceptor with conserved absorbance with λ_{max} = 435-
319 440 nm, the second blue sensitivity peak in *A. japonica* and *E. atala* is at λ_{max} = 500 nm
320 (Fig. 2F, S5A) unlike λ_{max} = 489 in *C. ladon* (Fig. S6B, Table S9). These data suggest a
321 role for coordinated shifts between blue and LW rhodopsins in the evolution of red
322 spectral sensitivity.

323

324 ***Shifted Blue and LW rhodopsins tune colour vision in the context of conspecific***
325 ***recognition***

326 In order to investigate possible correspondence between *E. atala* visual spectral
327 sensitivities and colour traits that might be important in signalling and sexual selection,
328 we measured the reflectance spectra associated with specific wing patches (Fig. 7, SI
329 Dataset 2). For the butterfly to interpret colours, it must i) possess at least two spectral
330 types of receptors sensitive to the reflectance spectrum of incident visible light
331 illuminating the coloured area, and ii) be able to compare individual receptor responses
332 neurally to create an output chromatic signal (73). Although we did not take this analysis
333 to the second step of recording responses of different individual receptors to reflectance
334 spectra, we investigated in detail the first necessary condition by measuring and
335 comparing reflectance spectra of body and wing patches from males and females
336 including blue scales on the abdomen and thorax, as well as black, blue and red scales
337 on forewings and hindwings (Fig. 7A). In males, dorsal forewings are bright iridescent
338 blue in summer, whereas scales appear more generally green/ teal in winter generations
339 (68). Female dorsal wings, on the other hand, display a darker royal blue colour along
340 the edge of their upper forewings. Both sexes also have conserved wing and body
341 patterns, including regularly spaced rows of blue spots visible on folded and unfolded
342 hindwings, and a bright red abdomen with a large bright red spot on the mid-caudal
343 hindwing area that falls precisely along the abdomen in folded wings (Fig. 1A, inset).

344 First, epi-microspectrophotometry measurements from dark areas of male and
345 female wings (Fig. 7B) showed that black scales are only 1 % as reflective as adjacent
346 cyan scales in the blue/green band at 450 nm, with a reflectance maximum of 0.053
347 (female, *f*) and 0.041 (male, *m*) (SI datafile 2) compared to reflectance maxima at 510
348 nm of ventral hindwing blue scales 1.53 (*f*) and 1.76 (*m*) (Fig. 7B). This indicates that
349 brightness – which is a function of reflectance - in black regions decreases 100 fold
350 compared to adjacent coloured scales in both sexes.

351 Blue scales on the dorsal forewings have a maximal reflectance peak at 490 nm
352 in females and 510 nm in males, and blue scales on the ventral hindwings have a
353 maximal reflectance peak at 510 nm (*f*) and 530 nm (*m*) (Fig. 7B). Thorax scale

354 reflectance is 1.86 times and 2.88 times higher than dorsal wing reflectance in females
355 and males, respectively.

356 Red scales on male and female hindwings reflect maximally in the far red (750
357 nm), similarly to abdominal scales (Fig. 7B-C). Blue scales on the thorax have a maximal
358 reflectance peak at 490 nm in both sexes, overall indicating that male and female
359 reflectance spectra are similar for blue scales on the body, but not for blue scales on the
360 wings. We noted, too, that leaf surfaces of the butterfly's primary host cycad, *Zamia*
361 *integrifolia*, have a peak of reflectance at 550 nm and a red edge inflection point around
362 700 nm with high reflectance in the near infrared region (Fig. 7D). Altogether, our
363 analyses support that the butterfly's photoreceptor spectral sensitivities (Fig. 7E) can
364 efficiently discriminate between its host plant (for oviposition), the colours of male and
365 female conspecifics, and colour variation between sexes.

366 ## Discussion
367
368 ***Red opsin receptors contribute to far-red spectral sensitivity***

369 It has remained challenging to identify the contribution of different genetic mechanisms
370 that affect phenotypic variation amongst complex traits in nature, and ultimately an
371 organism's fitness. Opsins represent a robust system to link molecular changes to
372 phenotypic changes in animal colour vision as they are the first elements in
373 phototransduction cascade and have been shown to directly modulate the visual spectral
374 sensitivity of insects, primates and other vertebrates. .We have optimized a functional
375 assay to disentangle the contribution of the long-wavelength (LW) rhodopsin from
376 filtering pigment granules and variable eye reflectance properties in the eyes of lycaenid
377 butterflies. We discovered a novel functional form of LW rhodopsin with a red-shifted
378 maximal absorbance spectrum (λ_{max}) between 565 and 575 nm in two lycaenid species,
379 *A. japonica* and *E. atala,* that is further supported by microspectrophotometry (MSP) and
380 optophysiology data (Figs. 1-3, Fig S5). The red-shifted rhodopsins have a longer-
381 wavelength limb of absorbance than lycaenid green LW rhodopsins due to a
382 bathochromic shift in their λ_{max} (Figs. 1, 3), which elevates the photoreceptor response at
383 long wavelengths (Fig. 2F, S5A). Consequently, those two species have much greater
384 optophysiological sensitivity in the far red than the lycaenid species with photoreceptors
385 expressing green LW rhodopsins, whether or not surrounded by lateral filtering
386 pigments.

387 Red spectral sensitivity has previously been examined *in vivo* notably in a
388 species of cabbage white butterfly, *Pieris rapae*, where light perception above 600 nm
389 results from ommatidia expressing a single LW opsin together with two types of pigment
390 granules that confer three types of red photoreceptors (48). Methods employing cAMP-
391 dependent heterologous spectroscopy identified maximal peak absorptions at 540 nm
392 and 560nm for *Papilio* PxRh1 and PxRh3 LW opsins respectively (62), whereas earlier
393 electrophysiological λ_{max} estimates placed PxRh1 at 525 nm and PxRh3 at 575 nm (45).
394 Our assay provides quantifiable expression and yields to obtain accurate λ_{max} *in vitro*
395 outside of the complexity of the eye structure itself which circumvents potential
396 inaccuracy from optophysiological estimates measured *in vivo* in certain species due to
397 interfering lateral pigments or other properties of the eye itself. It also has the advantage

398 of functionally studying variation in orthologous rhodopsin genes independently from
399 inferences based on sequence data alone. Our study reconciles *in vivo* and *in vitro*
400 approaches to substantiate that higher visual performance in the far red is achieved by
401 modifying absorbance properties of long-wavelength rhodopsins.

402

403 ***Duplication, spectral tuning and adjacent cellular localization provide expanded***
404 ***photoreceptor types***

405 Opsin evolution has undergone recurrent events of gene duplication and loss across
406 animals including insects (16). From ancestral insect trichromatic colour vision (UV, blue,
407 green), insects that have lost one of these three rhodopsins are often found to have
408 compensated from that loss by recruiting a duplicate gene copy that has undergone
409 spectral tuning to shift the peak sensitivity, as seen in true bugs and beetles (23, 39). By
410 contrast, tetrachromatic insects that activate an additional rhodopsin are also known to
411 have acquired increased spectral sensitivity in ranges of visible light, as seen in
412 *Heliconius* duplicated UV opsins (21), or *Pieris* duplicated blue opsins (27). Lycaenid
413 species examined thus far have two blue opsins for which epi-microspectrophotometric
414 estimates previously yielded sensitivities of λ_{max} in the range 420-440 nm and 480-500
415 nm (40, 41).

416 Our results show that blue opsin loci in *E. atala* specify blue and green-shifted
417 rhodopsins (Figs 2,6) similarly to species of *Lycaena* and *Polyommatus* (40, 41). The
418 most striking functional insight in the evolution of blue spectral tuning in *E. atala* comes
419 from chimeric BRh1 variants bearing mutations A116S, G175S and Y177F, which confer
420 a 73-nm bathochromic shift (λ_{max} = 508 nm) that most closely recapitulates the spectral
421 properties of Eat-BRh2 (λ_{max} = 500 nm) compared to other tested variants (Fig. 5G, Fig
422 S4). Intermediate adaptive phenotypes can also be revealed via gradual evolutionary
423 trajectories. Eat-BRh1 variant A116S causes a +5 nm shift alone, but together with
424 I120F, shifts maximal absorbance by an additional +15 nm to λ_{max} = 455 nm. Since these
425 two residue substitutions are conserved across all characterized lycaenid BRh1 loci (Fig.
426 3A), these results show how adjacent sites in helix 3 can contribute to intermediate blue
427 absorbance spectra across lycaenids.

428 The third tuning residue, Tyr177Phe is a key spectral tuning mutation in *E. atala,*
429 since the triple BRh1 variant (A116S/I120F/Y177F) displays a 30 nm bathochromic shift
430 (λ_{max} = 475 nm) compared to its native rhodopsin, and illustrates the multiple ways that
431 gradual spectral tuning can evolve, at least in this species. Two of the reverse tuning
432 substitutions are the same sites responsible for hypsochromic spectral shifts both in a
433 blue-shifted LW rhodopsin of a *Limenitis* butterfly (Y177F, -5 nm) (61) and in a violet-
434 shifted blue rhodopsin of a *Pieris* butterfly (S116A, -13 nm; F177Y -4 nm) (27), stressing
435 the importance of tuning residues lying on the ionone ring portion of the chromophore
436 binding pocket. Spectral tuning modulation in blue-rhodopsin duplicate functions has
437 therefore involved conserved biochemical constraints along independent evolutionary
438 trajectories that selected for partial spectral tuning sites in rhodopsin G-coupled
439 receptors. Reverse mutations are not functionally equivalent in their absolute
440 magnitudes ($\Delta\lambda_{max}$), therefore underscoring the role of epistatic interactions with
441 neighbouring sites resulting in distinct λ_{max} shifts across butterfly lineages.

442 Molecular and phylogenetic studies of opsin evolution in vertebrates have also
443 shown that homologous tyrosine residues in the ionone ring portion of the chromophore-
444 binding pocket (e.g. Y262) in the human blue cone opsin (λ_{max} = 414 nm) are responsible
445 for a 10 nm bathochromic spectral tuning when mutated to Tryptophan (Trp) (74). This
446 illustrates that distant opsin loci meet similar structural and biochemical constraints as
447 those observed in the evolution of vision genes in other vertebrates (11, 14). However,
448 Y177 is unique to *E. atala*, and other BRh1 loci at this position readily possess the F177
449 similarly to Eat-BRh2 (Fig. 3A). Not all BRh2 loci have S175 but instead keep G175 in
450 both blue loci, suggesting an additional yet unknown role for adjacent residues in
451 positions R176K and I178V. The latter residues do not differ highly in hydrophobicity but
452 may still provide the necessary molecular interactions with the ionine ring portion of the
453 chromophore necessary to modulate variable BRh2 spectral phenotypes. Human
454 ancestors also achieved blue sensitivity gradually and almost exclusively via epistasis at
455 seven amino acid residues (55). By studying independent opsin gene duplicates in the
456 butterfly family Lycaenidae, our *in vitro* assays refine our understanding of the molecular
457 basis of convergent colour vision phenotypes and help to identify key determinants of
458 genotype-phenotype relationships across insect blue opsins, although these are only a
459 snapshot of all possible chimeric blue rhodopsin variants along at least three possible

460 evolutionary trajectories. Testing the non-additive interactions at co-evolving BRh2
461 adjacent sites (175-178) in lycaenids lacking red sensitivity will help to fully recapitulate
462 intermediate phenotypes across derived blue-shifted rhodopsin duplicates in addition to
463 those generated by A116S and I120F.

464

465 In theory, a typical tetrachromat can achieve better wavelength discrimination
466 than a typical trichromat (55, 73) because of the interplay between additional gene
467 copies and the coevolution of spectral tuning across rhodopsins decreases the minimal
468 wavelength difference (Δλ) that an insect can discriminate. *Papilio* butterflies, for
469 instance, have some of the most complex retinal mosaics known, with three ommatidial
470 types expressing various combinations of five rhodopsin proteins (UV, B, 3 LW), as well
471 as filtering pigments that produce diverse ommatidial spectral sensitivities (29, 45).
472 Amino acid residues in helix 3 have been shown to mediate an absorbance shift
473 between duplicates LW PxRh1 and PxRh3 in *Papilio (62)*, but lycaenid LW opsins
474 possess a highly conserved helix 3 that does not exhibit any of the spectral substitutions
475 found across Papilionidae, supporting the hypothesis that distinct spectral tuning
476 mechanisms have evolved independently in invertebrate LW opsins. Future work will be
477 able to disentangle the spectral tuning mechanisms of LW opsins *in vitro* using the
478 recombinant purification system described here.

479 In *E. atala*, ommatidial density and expression profiling showed that
480 photoreceptor cells containing BRh2 are less abundant (~25%) compared to those
481 containing UV (~50%) and BRh1 (75%) rhodopsins. In spite of its low density across the
482 eye, the derived green-shifted blue rhodopsin improves signal resolution in the green
483 spectrum and provides direct adaptive benefits for light perception in both males and
484 females. Compared to trichromats, the expanded six-ommatidial types primarily derive
485 from the non-overlapping cellular expression of BRh1 and BRh2 rhodopsin mRNAs in
486 distal rhabdomeric cells. Together, the stochastic rhodopsin mosaic offers remarkable
487 properties that could not be achieved with the limited sensitivity of a single blue opsin
488 gene.

489 In summary, our results support the scenario of a sensory system in which gene
490 duplication generates new opsin paralogs, cis-regulatory changes generate new
491 photoreceptor subtypes via gene-specific expression patterns, and coding mutations
492 tune the spectral sensitivity maxima of two of the four rhodopsins (BRh2, LWRh). All of
493 these changes have contributed to the diversification of visual spectral sensitivities,
494 thereby enhancing colour discrimination.

495

496 ***Co-evolving shifts at blue and red opsins tune intraspecific visual signalling***

497 Additional structural features of the eye can contribute to spectral sensitivity of individual
498 photoreceptors at long wavelengths, including lateral filtering granules found in distal
499 rhabdomeres. However, here the primary mechanism pushing red sensitivity is through
500 functional divergence at the LW rhodopsin locus. This remarkable novelty provides a
501 two-factor interaction (Blue-LW) to modulate green-red sensitivity among closely related
502 taxa.

503 Building on earlier butterfly microspectrophotometry work (19, 40, 41, 53), our
504 study shows that lycaenid species with red-shifted LW opsins have their second
505 maximum sensitivity peak and associated blue rhodopsin shifted to green maximal
506 absorbance with λ_{max} 495-500 nm. By contrast species with a LW ancestral-green opsin
507 with λ_{max} 520-530 nm have their second maximum sensitivity peak at blue wavelengths
508 λ_{max} = 480-490 nm (Fig. 1C, S6A), suggesting modulatory benefits for coevolving
509 spectral shifts at multiple rhodopsins. Within Lycaenidae, reflectance patterns of wing
510 scales have been investigated in the genera *Celastrina* and *Callophrys* (75, 76) and
511 these studies support a scenario of co-evolution of spectral shifts across opsins. The
512 ventral wings visible at rest in Green Hairstreak lycaenids (genus *Callophrys*) typically
513 appear green and consist of yellow and bluish scales with an omnidirectional reflectance
514 peak in the green slightly above 550 nm (76). *Celastrina* species tend to display bright
515 blue coloured wings, which predominantly reflect light in the UV-blue band (75) and can
516 thus be perceived by comparing neuronally the spectral input from light activating retinal
517 photoreceptors expressing both UV/ blue rhodopsins without requiring expanded red
518 sensitivity.

These observations suggest a role for molecular tuning of blue and LW opsin genes in driving the dynamic evolution of green-red spectral sensitivity. Extant human trichromatic colour vision is similarly thought to have evolved via spectral tuning of existing short wavelength-sensitive opsins in concert with molecular variation at duplicated opsin loci leading to middle and long-wavelength sensitivities (55). Ultimately, mechanistic and functional studies of spectral tuning evolution in different orthologs in additional species will enable us to infer the ancestral states and better resolve the evolutionary time scale involved in stages of spectral tuning of blue and red sensitivities across lycaenids.

Colour tuning improves intraspecific signal detection

Two effects of molecular variation in visual pigments in *E. atala* are that its eyes have expanded spectral sensitivity at longer wavelengths as well as increased spectral discrimination in the blue band. In order to investigate the evolutionary consequences of molecular changes in butterfly opsins in the broader context of behaviours requiring colour vision, such as finding oviposition sites, and intraspecific recognition (37, 77-80), we need to analyze the degree of overlap of spectral sensitivities (73) and evaluate this against the spectral composition of the reflected light of the background and other objects, such as that produced by foliage and conspecifics.

The limiting wavelength at which only the human L cone opsin (λ_{max} = 559-563 nm) is sensitive corresponds to approximately 625 nm (81), which is the wavelength at which orange-red can be discriminated from pure red in human colour perception. The human neighboring M cone rhodopsin is at λ_{max} = 530 nm, which at 625 nm, has a sensitivity of 0.05 (81). By extension, for *E. atala*, BRh2 has a sensitivity of 0.05 at 613 nm (Fig. 2, Fig. 6), indicating that R565 would perceive ‘pure red’ wavelengths of light from 613 nm onwards. Alternatively, we can compute the relative sensitivity of the LW rhodopsin at 700nm (3%, Fig. 1, Fig. 3), which is generally accepted as the limit for photopic vision, and then identify the corresponding wavelength at which BRh2 reaches that same sensitivity, which is 619 nm (Fig. 2). Conservatively, we can conclude that the red rhodopsin together with the green-shifted blue rhodopsin BRh2 of *E. atala* contribute

549 to the perception of colours at long-wavelengths up to 613 nm. The LW rhodopsin
550 sensitivity in *A. japonica* is similar to *E. atala*, and the green-red visual spectral
551 sensitivities of *Arhopala* butterflies would capture the dorsal wing secondary reflectance
552 peak between 500-600 nm, which is absent in *Celastrina* or *Callophrys* wings (75).
553 Dorsal *Arhopala* wings also have velvety black edges filled with blue regions that
554 primarily reflect light at 370 nm in males and 400 nm in females (82) and further benefit
555 from the expanded blue sensitivity seen across lycaenid butterflies. Similarly to super-
556 black plumage colouration in birds (83), peacock spiders (84), and recent examples in
557 papilionids and nymphalid butterflies (85), the adjacency and sex-specific regions
558 covered with structural velvety black scales in the lycaenid *E. atala* likely enhance the
559 perceived brightness of nearby colour signals.

560 Our wing scale analysis indicates that red colour discrimination is important to
561 see conspecifics due to their striking reflectance above 600 nm (Fig. 7A). Reflectance
562 spectra from the red abdomen and the ventral hindwing are similar and overlap spectral
563 sensitivities of two rhodopsins (LWRh and BRh2), meaning the butterfly can not only
564 detect brightness but can also derive a colour signal from these patterns, and separate
565 these input signals from those of environmental colour cues such as signals produced by
566 foliage (Fig. 7D) (86). Abdominal reflectance in the range 613-619 nm is roughly a third
567 of its maximal reflectance, but there is substantial overlap of the abdomen's spectrum
568 with BRh2 spectral sensitivity, which suggests that the Atala hairstreak's colour
569 perception of the abdominal colour of conspecifics is not pure red, but something more
570 like Orange-Red. All *Eumaeus* species have this orange-red colouration and the red
571 scale reflectance spectra are similar between the sexes, suggesting that it evolved at the
572 base of the *Eumaeus* genera, as an aposematic signal driven by the association with
573 cycads (87). Whereas our results show a clear sex-specific reflectance difference on
574 dorsal wings, it is unclear whether the red warning colouration patterns may have been
575 coopted as a conspecific signal, as in other unpalatable butterflies (79, 88), in which
576 case it could be a by-product of the evolution of a signal used primarily to avoid
577 predation. Hence, the L cones of most birds have red sensitivity from about 550 nm to
578 700 nm (59, 89), and the bright red abdominal/ hindwing reflectance in the near-infrared
579 spectrum would stimulate mostly bird LWS /red (without MWS/ green) to perceive a
580 colour close to "pure red".

Lycaenid butterflies with four rhodopsins can see more colour hues in the blue-green range than mammals that have either di or trichromatic vision (34). Sex-specific scale reflectance spectra on dorsal wings convey colour information that is readily distinguishable by the visual system. Our study, by showing the expanded spectral sensitivity exhibited by lycaenid butterflies through molecular variation and functional changes in their 4-rhodopsin visual system, highlights the importance of peripheral sensory genes in driving the adaptive evolution of multi-modal communication.

588 ## Materials and Methods

589 *Butterflies*

590 Pupae of *Eumaeus atala* were collected from host plants of *Zamia integrifolia* (locally
591 known as "coontie") at the Montgomery Botanical Garden, Miami, FL, USA and reared at
592 22°C in an insectary in the MCZ laboratories under a 12:12 L:D cycle until emergence.
593 *Callophrys sheridanii* and *Celastrina ladon* were collected on Badger Mountain,
594 Wenatchee WA, USA and Wahclella Falls, OR, USA respectively. Eggs and young
595 larvae of *Arhopala narathura japonica* were collected feeding on oak trees (*Quercus*
596 *glauca*) from field sites near Ginoza, Okinawa, Japan and reared in the laboratory in
597 Cambridge, MA, USA until they eclosed as adults.

598

599 *Epi-Microspectrophotometry*

600 Quantitative epi-microspectrophotometry (epi-MSP) was used to determine absorption
601 spectra of butterfly rhodopsins by measuring eyeshine reflectance spectra after
602 photoconversion of the rhodopsin to its metarhodopsin product (54, 90).
603 Compound eyes of most adult butterfly species exhibit eyeshine, a property that
604 allows measuring rhodopsin absorbance spectra as well as spectral sensitivity of
605 photoreceptor pupillary responses in eyes of intact butterflies. When subjected to
606 repeated bright white flashes under incident-light microscope, 1) there is a
607 photochemical effect, i.e. the coloration of eyeshine changes during each flash owing to
608 changes in absorbance spectra that accompany photo-isomerization of rhodopsins to
609 their metarhodopsin photoproducts (90); and 2) there is a pupillary response mediated
610 by intracellular migration of pigment granules within photoreceptor cells, causing the
611 intensity of eyeshine to decrease rapidly with time during each flash (91).
612 Three MSP methods (*in vivo* Photochemistry, Optophysiology, Retinal
613 densitometry) are critical to study rhodopsin properties. The methods are presented
614 here, whereas the rationale upon which the three methods are based and the general
615 procedures for using eyeshine to make photochemical measurements from butterfly
616 eyes are described in detail in SI methods.
617

618 *In vivo* Photochemistry

619 When rhodopsin is photo-isomerized to become metarhodopsin, it undergoes a spectral
620 shift in the absorbance spectrum. For LW rhodopsins, the shift is to shorter wavelengths;
621 the metarhodopsin peak is usually between 490 nm and 500 nm. For both UV-absorbing
622 and blue-absorbing rhodopsins, the shift is to longer wavelengths, typically to 475 nm -
623 490 nm. These photochemical changes are observable in eyeshine reflectance spectra,
624 as increased reflectance caused by loss of rhodopsin, and decreased reflectance
625 caused by the metarhodopsin. The computed absorbance-difference spectrum (DS),
626 therefore, has a positive peak caused by accumulation of metarhodopsin (M), and a
627 negative peak caused by loss of rhodopsin (R) (Fig. 1, 2A).

628 The absorbance difference spectrum relaxes with time in the dark, but changes
629 shape in doing so; the positive peak relaxes to zero much faster than the negative peak.
630 The entire temporal evolution of difference spectra can be reproduced quantitatively by
631 assuming different kinetics for the dark-processes of metarhodopsin decay and
632 rhodopsin recovery. Metarhodopsin decay is well approximated by a single exponential
633 process, but the time constant is a strong function of temperature. Rhodopsin recovery
634 is considerably slower than metarhodopsin decay, making it possible to create a partial
635 bleach using repeated episodes of bright flashes followed by dark periods during which
636 metarhodopsin decays totally from the rhabdom. The difference spectrum for that partial
637 bleach is a direct measurement of the absorbance spectrum of the LW rhodopsin (Fig. 1)
638 (90). Similar experiments with photoconversion of the other spectral types of rhodopsin
639 are more complicated because a bright blue flash designed to efficiently photo-isomerize
640 blue-absorbing rhodopsin will also convert some LW rhodopsins to their
641 metarhodopsins, although with less efficiency. However if the LW rhodopsins are first
642 bleached, then difference spectra for the blue rhodopsin are measurable (Fig. 2A).

643 Photochemical measurements of the *E. atala* blue rhodopsin were done with a
644 male oriented similarly to the female at Elevation 0° and Azimuth 10°. Before
645 photoconversion of the blue rhodopsin, the LW rhodopsins were partially bleached by
646 flashing with 20s exposure to RG645 (20s, 2s/55s). After resting in the dark for 24 min
647 for metarhodopsins to decay, the eye was flashed with 12s RG430 (2s/60s), which
648 converted blue rhodopsin to its metarhodopsin M505. A difference spectrum for R440

649 was computed from reflectance spectra measured before and 9 min after the series of
650 bright blue flashes.

651

652 *Optophysiology*

653 Photoreceptor cells in butterfly eyes contain intracellular pigment granules that move
654 centripetally in response to bright illumination and deplete light from the rhabdom by
655 scattering and absorption. This process creates an effective pupillary response
656 observable as a decrease in eyeshine reflectance (91). This intracellular pigment
657 migration is mediated exclusively by photo-isomerization of the rhodopsin contained
658 within the same cell's rhabdomere and is not influenced by physiological responses of
659 neighboring ommatidia. Thus, the pupillary pigment granules can be used as an optically
660 measured intracellular probe of physiological responses to light from that cell (92).
661 A double-beam Epi-MSP apparatus was used for optophysiological
662 measurements of eyeshine. One beam is deep-red filtered (e.g., 710 nm), that monitors
663 continuously the reflectance of eyeshine but does not itself cause a pupillary response.
664 The second beam delivers a monochromatic flash that evokes a pupillary response,
665 measured by the first beam as a decrease in deep-red eyeshine reflectance. At each
666 stimulating wavelength, the flash intensity is adjusted with computer-controlled neutral-
667 density wheels to produce a criterion decrease in reflectance (usually 3% - 5%).
668 Wavelength sequence is randomized. Both flash duration and inter-stimulus interval are
669 held constant. After completing an experimental series, the butterfly is replaced by a
670 factory calibrated Hamamatsu S1226 photodiode and quantum flux Q measured for
671 every criterion combination of wavelength and wheel setting. Spectral sensitivity is
672 computed as $S(\lambda) = 1 / Q(\lambda)$.

673

674 *Retinal Densitometry*

675 The visual pigment content of rhabdoms can be estimated quantitatively when the
676 tapetal reflectance spectrum is constant (white) for wavelengths shorter than about 600
677 nm (25, 93). A computational model based on an electron micrograph of the tracheolar
678 tapetum shows that this "chirped" set of layers functions as a broadband reflecting

679 interference filter exhibiting a computed reflectance greater than 90% for wavelengths
680 between 320 and 680 nm, thereby justifying the assumption of a white reflectance
681 spectrum in that band. This property of wideband white tapetal reflectance can be
682 exploited to computationally estimate rhodopsin contents. It is most valuable when
683 applied after λ_{max} of UV, blue, and LW rhodopsins have been determined from *in vivo*
684 photochemistry (Fig. 1; Fig. 2A) and optophysiology (Fig. 2B). R360, R440, and R565
685 have been determined in *E. atala* (Fig. 2C-D).

686 The procedure is sequential. First, a reflectance spectrum was measured after all
687 metarhodopsins had decayed from the rhabdoms, e.g., after overnight dark-adaptation
688 (black filled circles). Next, the dark spectrum was stripped of round-trip optical density
689 (OD) 1.50 (*male, m)* or 1.00 (fe*male, f*) of R565 rhodopsin so that the residual spectra
690 (red lines) were flat from 570 nm out to the 690 nm roll-off of tapetal reflectance. Next,
691 those residual spectra were stripped of OD 0.36 (*m*) and 0.22 (*f*) of R440 (cyan lines),
692 leaving large dips in the blue-green around 500 nm that were poorly fit by a single blue
693 opsin. However, stripping of OD 0.72 (*m)* and 0.55 (*f)* λ_{max} 395 (Retinal Binding Protein,
694 RBP) left UV residues (magenta lines) well fit by density of 0.55 (*m*) and 0.55 (*f*) of R360.
695 The remaining residuals (blue lines) were subjected to least-squares fitting to the
696 rhodopsin template (Fig. 2E), which produced excellent R495 fits of 0.39 (*f*) and 0.70
697 (*m*), supporting the presence of the fourth rhodopsin, R495.

698 The spectral sensitivities of *Arholopa, Celastrina and Callophrys* rhodopsins were
699 investigated using the same techniques as described in SI methods.

700

701 *De novo* E. atala *eye transcriptome*

702 The heads of 10 adult males (1 day old) were dissected under ambient light with their
703 antennae and palpi removed prior to flash freezing in liquid nitrogen. Total RNA was
704 extracted using the Direct-zol RNA extraction kit (Zymoresearch, CA, USA). Illumina
705 paired-end libraries were constructed using the Ultra II RNA Directional kit (New England
706 Biolabs, USA) and sequenced with an Illumina HiSeq v4. Adaptors were removed using
707 Trimgalore (94) and low quality reads were filtered out prior to generating a *de novo*
708 assembly reference transcriptome for all libraries in the Trinity sequence assembly and

709 analysis pipeline (95). This assembly resulted in 301656 transcripts with a contig N50 of
710 2519 bp, and average contig lengths of 1029 bp. Small fragments were filtered out
711 based on expression values using Kallisto (96). Opsin sequences from two other
712 lycaenids (41) were used as queries to identify all opsin mRNAs across tissues in the
713 final assembly using BLAST (97). To confirm their identity, the candidate opsin
714 sequences were blasted back to the NCBI non-redundant database.

715 *Lycaenid LW opsin cDNA characterization*

716 RNA was extracted from eye tissue preserved in RNA shield reagent (Zymo Research)
717 for *A. japonica, Ce. ladon and Ca. sheridanii*. Samples were first removed from the
718 storage solution with sterile forceps, briefly blot dried on a sterile Kimwipes paper, flash
719 frozen in a mortar containing liquid nitrogen and finely ground using a cold pestle.
720 Following RNA purification, we quantified RNA using a Quant-iT RNA kit and a Qubit
721 fluorometer (Invitrogen). From purified RNA, we synthesized cDNA using the The
722 GoScript™ Reverse Transcription System (Promega) and amplified a central region of
723 the long-wavelength opsin using degenerated oligonucleotide primers 5'-
724 TTGAAGCTTCARTTYCCNCCNATGAAYCC-3' (forward) and 5'-CGAATTCGTCAT
725 RTTNCCYTCIGGNACRTA-3' (reverse) (48). Single bands of expected sizes were
726 obtained, and the PCR products were purified with Exo-SAP, following Sanger
727 sequencing. We thereafter used the SMARTer RACE cDNA Amplification kit (Clontech)
728 to prepare 5'- and 3'- RACE cDNA for each species. We carried out RACE PCRs, and to
729 increase the specificity of RACE reactions, we performed nested PCRs for each cDNA
730 and obtained single-band PCR products, which were gel-purified using a Qiaquick Gel
731 Extraction Kit (Qiagen), ligated into PCR2.1 Vector kit (Invitrogen) and transformed into
732 competent TOPO10 cells (Invitrogen). Single bacterial clones were purified, and plasmid
733 DNAs were sequenced using M13F and M13R primers at the Harvard DF/HCC DNA
734 Resource Core. In total we obtained sequences from 5 to 10 opsin clones for each
735 RACE cDNA. Based on the 5'- and 3'-UTR information, gene-specific primers were
736 designed and used in combination with respective eye cDNAs to confirm the integrity of
737 each full-length LW opsin coding frame sequence. Opsin subfamily phylogenetic
738 placements were confirmed by aligning selected lepidopteran opsin genes extracted

739 from Genbank using the MAFFT package as implemented in Geneious (98), and a
740 Neighbor-Joining (NJ) tree of the aligned dataset was constructed using RAxML (99).

741

742 *Cloning and protein expression*

743 The coding region of each opsin transcript was amplified from eye cDNA and subcloned
744 in a modified pFRT-TO expression vector cassette derived from pcDNA5 and containing
745 the human cytomegalovirus (CMV) immediate early promoter (Invitrogen, USA). The
746 expression plasmid was modified to include a C-terminal tag by the monoclonal antibody
747 FLAG epitope sequence (DYKDDDDK), followed by a Ser-Gly-Ser linker peptide, a T2A
748 peptide sequence (EGRGSLLTCGDVEENPG) and the fluorescent marker protein
749 mRuby2. Plasmid DNAs were verified by Sanger sequencing and purified with the endo-
750 free ZymoPURE™ II Plasmid Midiprep Kit (Zymo Research, USA). Two micrograms of
751 plasmid DNAs were used to transfect small-scale HEKT293 cultures and optimize
752 expression conditions both via mRuby2 visualization and western blot analysis. Cells
753 were plated at a density of $0.6x10^6$ cells in a 6-well culture dish containing DMEM
754 medium (Gibco), and transient transfection was achieved after 48h when reaching 80%
755 confluency in a 1:3 ratio DNA (µg): PEI (µL) (Polysciences, USA) at 1mg/mL in
756 molecular grade water, filter-sterilized at 0.22 µm. The transfected cells were harvested
757 in cold D-PBS (Sigma-Aldrich) after 2 days, centrifuged at 4°C for 5 min at 4000 rpm,
758 and resuspended in 50 µL Ripa lysis buffer (Invitrogen) supplemented with 1% n-
759 Dodecyl β-D-maltoside (Sigma-Aldrich). Cell membranes were lysed for 1h at 4°C with
760 gentle rotation on a sample homogenizer, and cell debris collected by centrifugation at
761 4°C for 15 min at 13,000 rpm. The crude protein lysate concentration was quantified by
762 BSA (Sigma-Aldrich) and 25 µg crude extract was loaded on NuPAGE™ 3-8% Tris-
763 Acetate gels (ThermoFisher) and transferred to a polyvinylidene difluoride membrane on
764 a TurboBlotTransfer system (Biorad Laboratories). The membranes were blocked with
765 1% milk (Biorad) in phosphate-buffered saline containing 0.1% Tween 20 (PBS-T,
766 Biorad) and incubated overnight with primary antibodies (aFLAG 1:2,500, aHSP90
767 1:50,000, GE Healthcare) containing 0.01% Sodium azide (Sigma Aldrich) on a gently
768 rocking platform at 4°C. After washing with TPBS the membranes incubated with aFLAG
769 and aHSP90 were respectively incubated with HRP Conjugated ECL anti-mouse and

770 ECL anti-rabbit (Amersham, USA), revealed using the SuperSignal West Femto (Thermo
771 Scientific) and imaged on a ChemiDoc system (Biorad Laboratories).

772

773 *Transient expression, purification of expressed rhodopsins and spectroscopy*

774 High-expressing clones from GPCR opsin cDNAs were transiently expressed in
775 HEKT293 cells prior to *in vitro* purification. For each construct, cells were seeded at a
776 density of $1.0x10^6$ cells on day 0 in fifteen tissue culture dishes (10 cm diameter, ref
777 25382-166, VWR) in DMEM High Glucose, GlutaMAX (Life Technologies) supplemented
778 with 10% FBS (Seradigm Premium, VWR, USA). Lipid complexes containing 24 µg
779 DNA: 72 µL PEI (1mg/mL) diluted in Opti-MEM I Reduced Serum (Life Technologies)
780 were added 48h later to cells reaching 75-85% confluency. Six-hours post-transfection,
781 the culture medium was exchanged with new medium containing 5 $\mu.mol^{-1}$ 11-*cis*-retinal
782 (2mg/mL stock in 95% Ethanol) and under dim red illumination. The *cis*-retinal
783 absorption peak at 380 nm was confirmed using a NanoDrop™ 2000/2000c UV-VIS
784 Spectrophotometer (Thermo Fisher) prior to each experiment using a 1:100 dilution in
785 ethanol. Culture plates supplemented with cis-retinal were wrapped in aluminium foil and
786 cells were incubated in the dark. Forty-eight hours post-transfection, the medium was
787 decanted under dim red light illumination. Cells were scraped from the plates in cold
788 filter-sterilized HEPES wash buffer (3mM $MgCl_2$, 140mM NaCl, 50mM HEPES pH6.6-8.5
789 depending on protein isoelectric point) containing complete EDTA-free protein inhibitors
790 (Sigma-Aldrich), centrifuged for 10 min at 1,620 rcf at 4°C, and resuspended in 10 mL
791 wash buffer for two consecutive washes. After the second wash, cell pellets were gently
792 resuspended in 10mL cold wash buffer containing 40 µM 11-*cis*-retinal. Cells expressing
793 opsin-membrane proteins were incubated in the dark during 1h at 4°C on a nutating
794 mixer (VWR) to increase active rhodopsin complexes, and cells were then collected by
795 centrifugation at 21,500 rpm for 25 min at 4°C on a Sorvall WX Ultra 80 Series equipped
796 with an AH-629 Swinging Bucket Rotor (Thermo Scientific).

797 Transmembrane proteins were gently extracted by pipetting in 10 mL ice-cold extraction
798 buffer (3mM $MgCl_2$, 140mM NaCl, 50mM HEPES, 20% Glycerol v/v, 1% n-dodecyl β-D-
799 maltoside, complete EDTA-free protein inhibitors) and incubated for 1h at 4°C prior to

800 centrifugation at 21,500 rpm for 25 min at 4°C. The 10mL crude extract supernatant
801 containing solubilized rhodopsin complexes was added to 1mL Pierce™ Anti-
802 DYKDDDDK Affinity Resin (Thermo Scientific, USA) and incubated overnight at 4°C in a
803 15mL falcon on a nutating mixer. Samples were loaded on Pierce™ Centrifuge Columns
804 (ref 89897, Thermo Scientific, USA) and after 3 washes of the resin-bound FLAG-
805 epitope rhodopsin complexes with 3-column reservoir volumes of elution buffer (3mM
806 $MgCl_2$, 140mM NaCl, 50mM HEPES, 20% Glycerol v/v, 0.1% n-dodecyl β-D-maltoside),
807 the rhodopsin was eluted in 2mL elution buffer containing 1.25 mg (265 μM) Pierce™ 3x
808 DYKDDDDK Peptide (Thermo Scientific, USA). The eluate was concentrated using an
809 Amicon Ultra-2 Centrifugal Filter Unit with Ultracel-10 membrane (Millipore, USA), for 35
810 min at 4°C and 3,500rpm. The concentrated eluate (~350μL) was aliquoted in Amber
811 light-sensitive tubes (VWR, USA) and kept on ice in the dark. Ultraviolet-visible
812 absorption spectra (200-800nm) of dark-adapted purified proteins were measured in the
813 dark from 1.5 uL aliquots using a NanoDrop™ 2000/2000c UV-VIS spectrophotometer
814 (Thermo Fisher). Opsin purification yields were estimated following BSA analysis (Table
815 S23, SI methods). Spectroscopic analysis was performed from the mean value of 4-6
816 independent spectral measurements. Raw absorbance data were fitted to a visual
817 template (100) and polynomial functions analyses performed in R (V.0.99.486) (101)to
818 determine the opsin maximal absorption peaks.

819

820 *Preparation of RNA probes and RNA* in situ *hybridization*

821 We created *in vitro* transcription templates from UVRh, BRh1, BRh2, LWRh opsin
822 complementary DNA cloned in approximately 700-base-pair (bp) segments to pCRII-
823 TOPO (Invitrogen). Antisense cRNA probes were synthesized using T7 or Sp6
824 polymerases using either digoxigenin (DIG) or fluorescein (FITC) labelling mix (Sigma-
825 Aldrich) from gel-purified PCR templates. The synthesized cRNA probes were ethanol-
826 precipitated with NH_4OAc 7.5M and 1 μL glycogen, spun down at 4°C for 30 min, re-
827 dissolved in pure water and stored at -80°C. These RNA probes were first used to test
828 mRNA expression for each opsin receptor gene. We then tested the probes by dual
829 colour *in situ* hybridization using combinations of DIG and FITC probes to map opsin
830 receptor expression patterns.

831 For *in situ* hybridization, *E. atala* compound eyes were dissected and immersed in 1.5mL
832 eppendorf tubes containing freshly-made 4% formaldehyde (FisherScientific)/1x PBS for
833 2h at room temperature for fixation, then immersed successively in increasing sucrose
834 gradient solutions (10%, 20%, 30% in PBS) for 1h each, stored in 30% sucrose solution
835 overnight at 4°C, briefly transferred in OCT:sucrose 1:1, embedded in OCT (Tissue-Tek)
836 and frozen in dry ice. Tangential and longitudinal eye sections (12 µm) were obtained
837 using a cryostat (Leica), mounted on VWR Superfrost Plus Micro slides and used for
838 RNA *in situ* hybridization following a procedure described in details previously (102).
839 Double fluorescence *in situ* hybridization was performed using 100 µl hybridization
840 solution (pre-hybridization buffer supplemented with 4% Dextran sulfate (Sigma)
841 containing a combination of two opsin cRNA probes, one labeled with DIG and one
842 labeled with FITC (at 1ng.µl^{-1} for UVRh and BRh2, and 0.5ng.µl^{-1} for BRh1 and LWRh).

843 *Eye anatomy*

844 Each *E. atala* eye was immersed for prefixation in 2.5% Glutaraldehyde/2%
845 paraformaldehyde in 0.1M Sodium Cacodylate buffer (pH 7.4) (Electron Microscopy
846 Sciences, PA, USA) for 2h at room temperature, then stored at 4°C for 12-14h prior to
847 fixation, embedding, ultrathin sectioning and mounting on copper grids for TEM analysis
848 as described in SI methods.

849

850 *Homology modeling and targeted mutagenesis*

851 To investigate the molecular basis of spectral tuning differences between the duplicated
852 blue visual opsins, we carried out site-directed mutagenesis of amino acid substitutions
853 that could contribute to possible changes in the maximal absorption spectra of dark-
854 adapted rhodopsins. First, the Eat-B1 (λ_{max} = 435nm) and Eat-B2 (λ_{max} = 500nm) opsin
855 amino acid sequences were uploaded to the SWISS-MODEL protein recognition engine
856 (103) to generate templates aligned against the invertebrate squid rhodopsin crystal
857 structure (PDB2Z73) (72). The predicted homology model for each blue opsin was
858 analyzed in Pymol (104) to identify homologous binding sites in the *cis*-retinal binding
859 pocket within a range of 5Å from any carbon in the retinal polyene chain. Of the 101
860 amino acid substitutions that differ between the duplicate opsins, 21 residues were

861 predicted to interact with the *cis*-retinal chromophore, with 6 variant sites between both
862 opsin sequences.

863 Amino acid sequences from blue opsins were retrieved from Genbank and aligned using
864 the MAFFT package followed by NJ tree inference and support analysis derived from
865 1,500 bootstrap replicates in Geneious (97) prior to visualization in EvolView (98) with
866 squid rhodopsin as the outgroup. The phylogeny was used to identify functionally
867 convergent amino acid replacements repeatedly associated with similar shifts in
868 absorption spectra between blue opsin duplicates. We identified amino acid positions
869 that were likely to reside within the chromophore binding pocket of the opsin protein, and
870 that also had diverging biochemical properties (charge and/or polarity).. A BRh1 plasmid
871 DNA construct was modified to incorporate variant positions found in BRh2, namely
872 A116S (S1), I120F (S2), G175S (S3), Y177F (S4), I206C (S5), and F207C (S6).

873 Chimeric BRh1 rhodopsin constructs bearing single variant sites located on helix 3 (S1,
874 S2) and the β-strand located between helices 3 and 4 (S3, S4) were purified and
875 analyzed by spectroscopy in the native dark state. Since only S1 and S4 had tuning
876 effects in the range of interest, we combined coevolving adjacent site variants S1/S2,
877 and S3/S4 and followed two distinct routes by successively adding variant sites creating
878 triple mutants. Starting from a green-shifted BRh1 variant carrying S5 and S6, a third
879 trajectory was studied where variant sites S1, S2, S4 were also successively added.

880

881 *Wing reflectance*

882 Reflectance spectra were measured from leaves of *Zamia integrifolia* leaves (Zamiacae)
883 collected at the Montgomery Botanical Garden (Miami, FL, USA), and from *E. atala*
884 discrete wing, thorax, and abdominal patches of coloured-scales from both males and
885 females ($N_{individuals}$=3-5, 2 to 4 measurements per scale type, SI datafile 2), and in a Leitz
886 Ortholux-Pol microscope equipped with a Leitz MPV-1 photometer with epi-illumination
887 block, fitted with a Leitz 5.6X/0.15P objective. The illuminator filled the back focal plane
888 of the objective with axial incident light. The photometer measured reflected light from
889 the full aperture of the objective from a spot in the front focal plane that was 210 μm in
890 diameter. Reflectance data were corrected for stray light by subtracting data measured

from the MSP objective viewing a light-dump comprised of substantially out-of-focus black velvet cloth. Corrected reflectance data were normalized against the same normalization constant of 0.179 to preserve relative brightnesses among all measured body patches. Normalized reflectance data were analyzed in R (V.0.99.486) (101).

Data accessibility

Our sequencing data have been deposited in the GenBank database under accession numbers MN831881-MN831887 and under SRA Bioproject XXXXX. Data for photochemistry and optophysiological measurements, opsin absorbance spectra, reflectance spectra and transcriptomics expression are available as supplementary files.

Competing interests

We declare no competing interests

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Figures and Tables

Figure 1. Long-wavelength photochemical difference spectra from lycaenid butterflies. Difference spectra (DS) were obtained following partial bleaches of long wavelength rhodopsins from dorsal retina of intact butterflies. Datapoints represent absorbance differences between amounts of Rhodopsin (R, green or red) and its Metarhodopsin photoproduct (M, blue) product after a dark-period that followed photoconversion. Each black curve represents a computed difference spectrum for least square fits estimates at *(A)* R570 of *Arhopala japonica*, *(B)* R562 of *Eumaeus atala* and *(C)* R518 of *Callophrys sheridanii*. In *E. atala* the difference spectrum was acquired upon complete degradation of the M photoproduct and with small contributions from R440 and RBP395. In *Celastrina ladon*, λ_{max} of M and λ_{max} of R are very close, which pushed the DS negative peak to the right. Photographs represent respective butterflies (left) and butterfly eyeshine (right) in the dorsal retina (see also Fig. S1).

Figure 2. *In vivo* evidence for four rhodopsins in the Atala hairstreak butterfly. *(A)* Photochemical analysis of a butterfly male eyeshine using an epi-microspectrophotometer. Log-reflectance difference absorbance spectra (DS, Difference Spectrum, filled circles) and fitted curves (solid line) measured from dark-adapted eyes via partial-bleaching experiments of R440. *(B)* Optophysiological analyses designed to measure pupillary sensitivity in the UV. The least squares fit analysis provides confident estimates for a UV rhodopsin with λ_{max} at 360nm. Comparison to sensitivities in the blue, driven by R440 and in the red, driven by LW R565 rhodopsins, show that those two opsins make no contributions in the UV. *(C-D)* Densitometric analysis of an epi-microspectrophotometric reflectance spectrum of a male *(C)* and female *(D).* Completely dark-adapted *E. atala* eyeshine is used to confirm the contribution of each estimated visual pigment in the eye. The black dots plot the log-reflectance spectrum. The red curve is the spectrum after having computationally stripped optical density (OD) 1.50 of rhodopsin with λ_{max} 565 nm so that the residual spectrum is flat from 565 nm to 660 nm; cyan curve, the log-reflectance spectrum after having stripped OD 0.36 of R440 to produce a residual flat from 450 nm. The black curve is the log-reflectance spectrum after stripping OD 0.72 for R395 and 0.55 R360, leaving a residual spectrum fit by a fourth-rhodopsin R495. The densitometric analysis of female eyes *(D)* is qualitatively identical, with stripping densities of 1.55 R565, 0.40 R440, 0.80 RBP395 and 0.55 R350, leaving a residual indicative of a fourth pigment contribution, fit by rhodopsin R495. Stripping the R495 residual leaves the curve plotted in open squares that is the putative average log-reflectance spectrum of the tapetum, that is flat from the UV out to 660 nm. *(E)* Computational analysis of male residual reflectance spectra supports the contribution of a fourth opsin pigment with λ_{max} peaking around 495 nm. The residual fit for females is shown in the

954 inset. *(F)* Sensitivity data from an optophysiological threshold experiment measured at
955 wavelengths close to λ_{max} values (360 nm, 440 nm, 495 nm, 562 nm) of the four rhodopsins. This
956 shows that sensitivities at 440 nm and 495 nm cannot possibly be driven by R565.
957
958 **Figure 3. Functional characterization of red-shifted long wavelength lycaenid butterfly**
959 **opsins.** *(A)* Schematic of modified pCDNA expression vector cassette and workflow for functional
960 characterization of rhodopsin complexes with cis-retinal chromophore. All steps following addition
961 of cis-retinal are performed under dim red-light illumination. *(B)* Neighbour-Joining (NJ) tree of
962 butterfly long wavelength opsins. Bootstrap node support is as follows: 50-74%, white circle; 75-
963 94%, grey circle; ≥ 95%, black circle. Previously published λ_{max} physiological data are indicated in
964 parentheses when known (20, 27, 40, 41, 45). Corresponding family names are labeled on the
965 right. L, T and P correspond to lycaenid subfamilies Lycaeninae, Theclinae and Polyommatinae,
966 respectively. *(C-F)* Dark spectra of long wavelength rhodopsin (LWRh) expressed using an
967 HEKT293 transient cell culture system and purified via FLAG-epitope. LWRh rhodopsin
968 absorbance spectra are indicated with black dots (Table S7, Dataset S1), and a rhodopsin
969 template data (100) was computed to obtain the best estimates of λ_{max} fitting the data. (C)
970 *Arhopala japonica* purified LW opsin with λ_{max} = 570 nm, (D) *Eumaeus atala* purified LW opsin
971 with λ_{max} = 567 nm, *(E) Callophrys sheridanii* purified LW opsin with λ_{max} = 525 nm, (F) *Celastrina*
972 *ladon* purified LW opsin with λ_{max} = 525 nm.
973
974 **Figure 4**. **Anatomical overview of a typical ommatidium in *Eumaeus atala*.** *(A)* Diagram
975 illustrating a typical ommatidium and the relative contribution of nine photoreceptor cells R1-R9 at
976 different depths along the rhabdom (480 µm long). Photoreceptors R1 and R2 are proximal cells
977 in region *a* (126 µm) that contribute microvillar structures containing UVRh, BRh1 and BRh2
978 rhodopsins. Photoreceptors R3-R4 are proximal receptors containing LWRh and Brh1
979 rhodopsins. Photoreceptors R5-R8 are distal cells exclusively expressing the LWRh rhodopsin
980 (see also Fig 4, Fig S2). The basal cell, R9 is restricted to the region immediately proximal to the
981 basement membrane (460 µm, h). The expressed mRNA opsin type was not investigated in this
982 cell. *(B)* Scanning electron micrographs from a male dorsal eye region at 30° elevation across the
983 rhabdom. Scale bars, 2 µm. *(C)* Distal microvilli in regions *a- b* are exclusively oriented parallel to
984 the R1-R2 axis (left panel). As R3-R4 cells expand and contribute the majority of microvilli from
985 regions *c* to *e*, together with novel contributions from proximal receptors R5 to R8, three
986 ommatidia subtypes are formed that exhibit microvillar contributions parallel to (left panel) but
987 also intertwisted (middle panel) and perpendicular to the R1-R2 axis (right panel). Scale bars, 500

988 nm. *bm,* basement membrane*; rh,* rhabdom*; nc,* nucleus*; tp,* tapetum*; vc*, vacuole; 1-9,
989 photoreceptor cells R1 to R9.

990 **Figure 5. Adjacent photoreceptor localization between duplicate blue opsin mRNAs drives**
991 **retinal mosaic expansion.** Double fluorescent *in situ* hybridization shows six ommatidial types in
992 *E. atala* compared to ancestral butterfly eyes. *(A-F)* Exclusive one-cell one-mRNA expression
993 pattern in distal photoreceptors R1 and R2, showing for *(A*) UVRh (inset in *(D*)**,** *(B)* BRh1 mRNA
994 (inset in *(E*)) and *(C*) BRh2 mRNA (inset in *(F*)). Circles highlight the four distinct opsin expression
995 patterns in R1 and R2. *(G-I)* UVRh, BRh1 and BRh2 mRNAs do not coexpress in R1-R2 cells.
996 Photoreceptor cells R3-R8 express the LWRh opsin (red). Males and females show dorso-ventral
997 dimorphism (Fig. S4). *(J)* Schematic representation of opsin-based photoreceptor classes in
998 males and females of the six ommatidial types as follows (R1-R2-R3/R8): UV-UV-LW, UV-B1-
999 LW, UV-B2-LW, B1-B1-LW, B1-B2-LW, B2-B2-LW.

1000 **Figure 6. Residues responsible for spectral tuning shifts in blue rhodopsins.** *(A)* NJ tree of
1001 selected lepidopteran blue opsin amino acid sequences. The squid rhodopsin, *Todarodes*
1002 *pacificus* (acc. nr. CAA49906) is used as outgroup. Bootstrap node support is as follows: 50-74%,
1003 white circle; 75-94%, grey circle; ≥ 95%, black circle. Dots above the partial multiple sequence
1004 alignment shows the 21 amino acid residues residing within 5 Å of any carbon atom in the retinal
1005 polyene chain. *Blue* dots identify the six positions where amino acid residues differ between *E.*
1006 *atala* BRh1 and BRh2, blue rectangles highlight variants at these positions in lycaenids. Residue
1007 numbering is based on residue position in the squid rhodopsin. Residues are coloured according
1008 to their physicochemical properties in Jalview v2 (105). Grey arrows indicate β-strands forming
1009 the binding pocket. *(B)* Blue opsin absorbance spectra (dots) fitted to the visual template (cyan
1010 and blue line functions), respectively. *(C)* Predicted structure for Eat-BRh1 based on homology
1011 modeling with the squid rhodopsin with variant sites Ala116, Iso120, GLy175, Phe177, Iso206.
1012 *(D)* Native Brh1 rhodopsin bearing S1 (A116), S2 (I120) and S4 (Y177). *(E)* Substituting residues
1013 116, 120 and 177 leads to a 30-nm partial blue-shift in rhodopsin absorbance λ_{max} in the triple
1014 mutant (see also Figure S2). This tuning shift may be mediated by several possible mechanisms
1015 including additive effects caused by novel hydrogen bond formation at the coevolving adjacent
1016 sites 116 and 120 *(F)* and with nearby conserved residues G115 and G121. *(G)* An alternative
1017 evolutionary route involves substituting G175S (S3) which partially compensates the green tuning
1018 shift of double mutant A116S/Y177F (Fig. S6, Table S8) and tunes the absorbance spectrum
1019 near 500nm. These alternative trajectories highlight additive and epistatic interactions between
1020 four residues at sites 1-4 *(F, H)* in the acquisition of the blue-shifted function.

1021

1022 **Figure 7. Wing and body spectral reflectance in *Eumaeus atala*.** *(A)* Female (F) and male (M)
1023 dorsal forewing (DFW), ventral hindwing (VHW), thorax and abdominal scales. The photographs
1024 below each wing are magnified views of representative coloured wing scales in patches
1025 measured by epi-microspectrophotometry (MSP). The field of view for each photograph is 210 μm
1026 in diameter. Photographs were acquired using an Olympus TG-1 camera set at zoom 2.8. *(B-C)*
1027 Graphs of mean reflectance spectra ± standard errors of the mean of wing scale patches *(B)* and
1028 body scales *(C)* (N=3-5 individuals per sex). *(D)* Leaf reflectance spectra (4-5 measurements per
1029 leaf surface) (SI Datafile 2). *(E) E. atala* rhodopsin absorbance spectra. Male and female wing
1030 reflectance spectra are not exclusive, and spectral shapes are highly consistent indicating that
1031 male and female spectra are similar in the visible. In females, hindwing cyan spots show a
1032 reflectance peak at 540 nm *(B)*. Blue scales on the thorax and dorsal forewings have a
1033 reflectance peak at 490-500 nm. Hindwing *(B)* and abdominal red patches *(C)* have identical high
1034 reflectance spectra at long wavelengths in both sexes. MSP analyses from black areas of ventral
1035 hindwings *(B)* showed that black scales are only 1 % as reflective as adjacent cyan scales in the
1036 blue/green band. Brightness in black regions decreases 100-fold compared to adjacent cyan
1037 scales in both sexes. All reflectance curves overlap at contributing wavelengths for at least two
1038 rhodopsins, thereby efficiently distinguishing foliage and sex-specific wing colour patterns.

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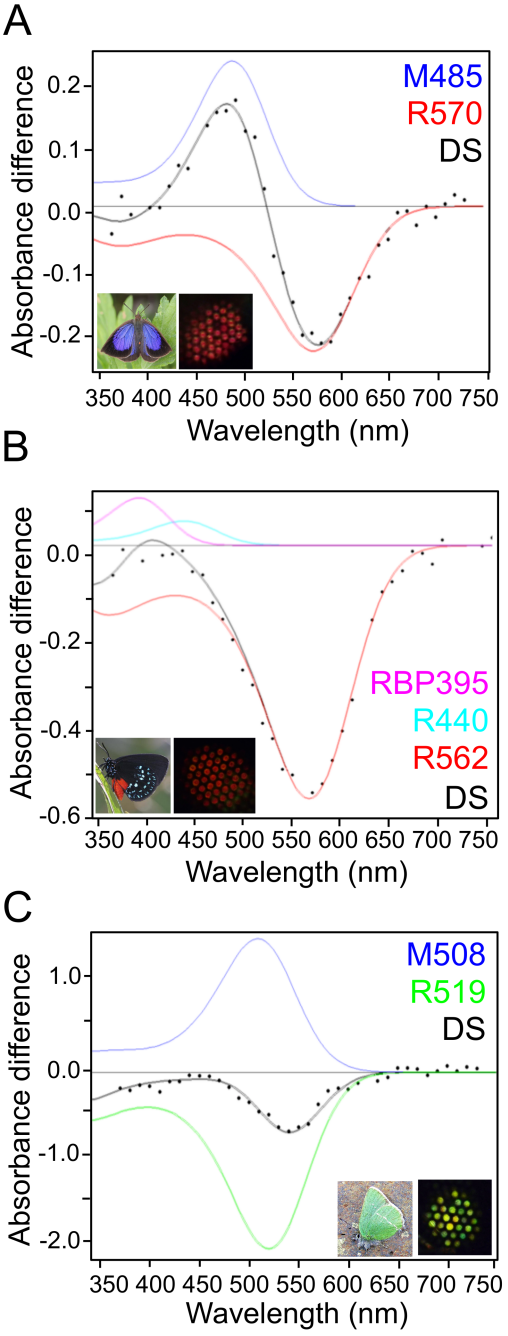
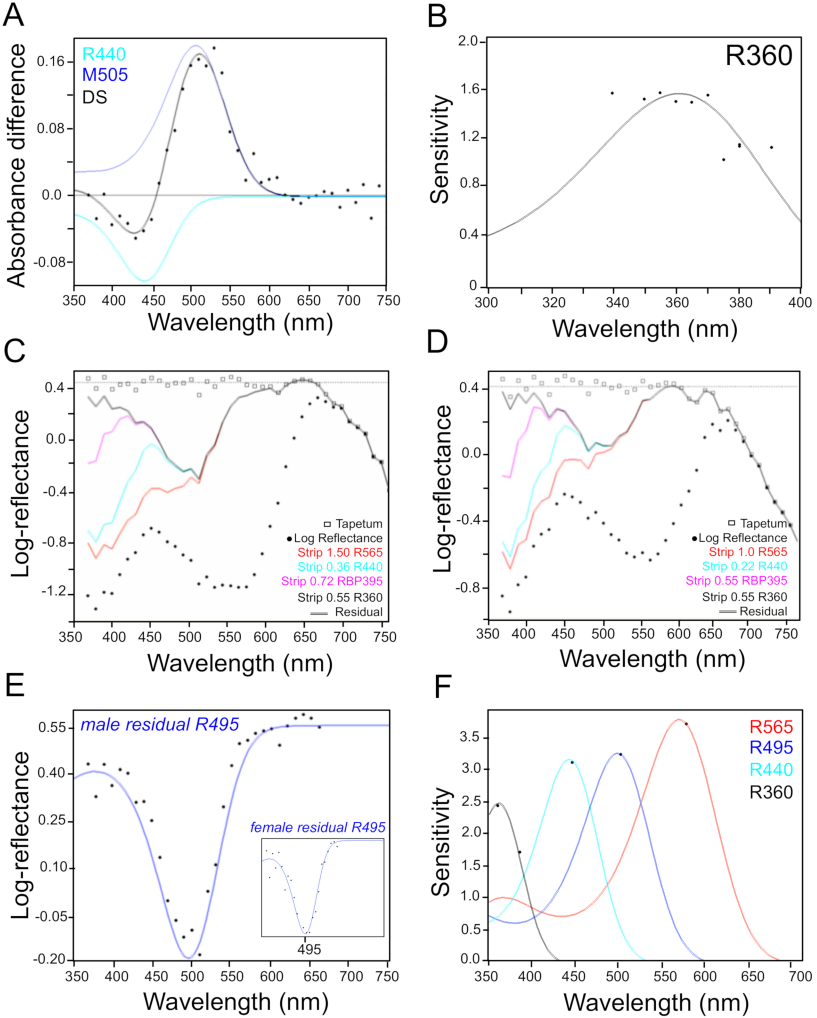
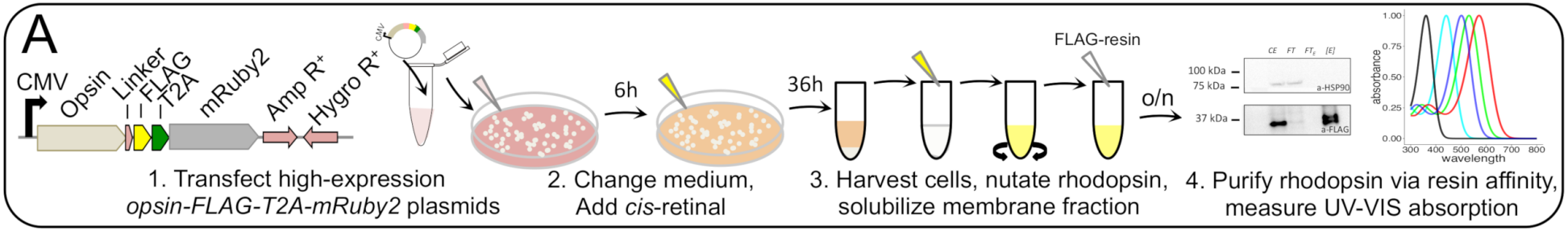
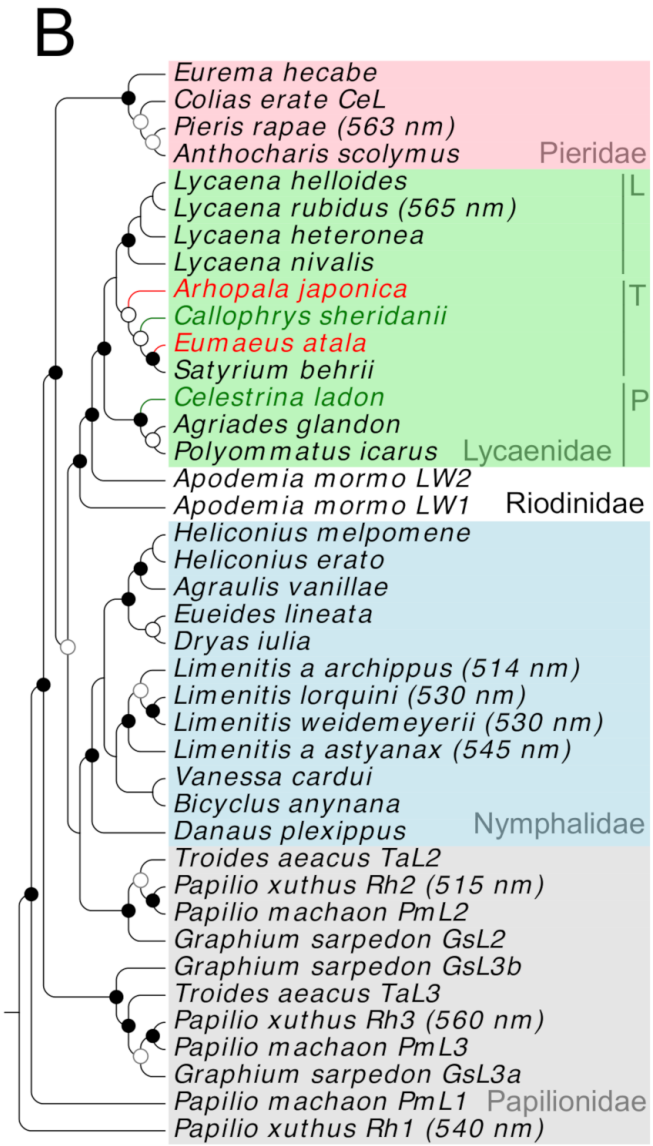
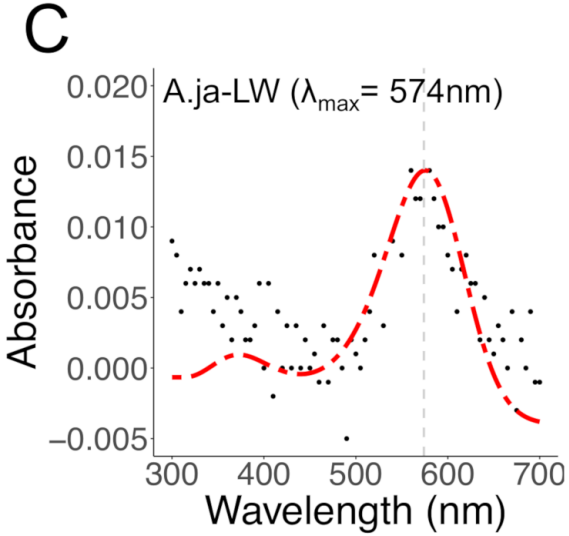
1270

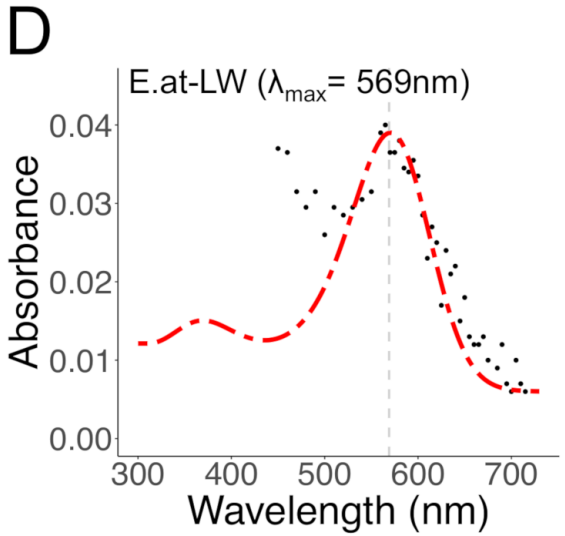

A
M485
R570
DS
Absorbance difference
0.2
0.1
0.0
-0.1
-0.2
350 400 450 500 550 600 650 700 750
Wavelength (nm)
B
RBP395
R440
R562
DS
Absorbance difference
0.0
-0.2
-0.4
-0.6
350 400 450 500 550 600 650 700 750
Wavelength (nm)
C
M508
R519
DS
Absorbance difference
1.0
0.0
-1.0
-2.0
350 400 450 500 550 600 650 700 750
Wavelength (nm)

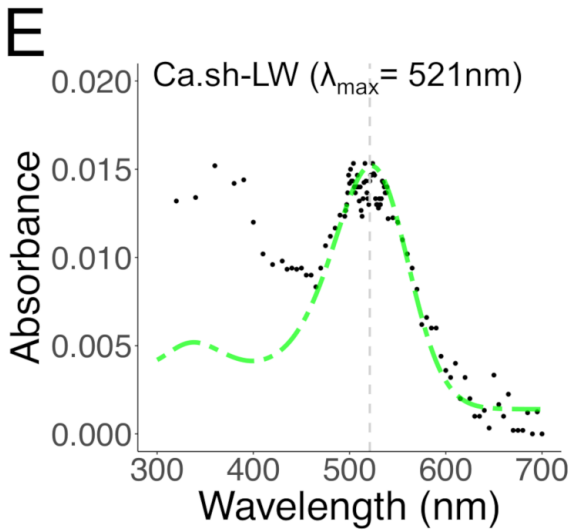

A
R440
M505
DS
Absorbance difference
Wavelength (nm)
B
R360
Sensitivity
Wavelength (nm)
C
Tapetum
Log Reflectance
Strip 1.50 R565
Strip 0.36 R440
Strip 0.72 RBP395
Strip 0.55 R360
Residual
Log-reflectance
Wavelength (nm)
D
Tapetum
Log Reflectance
Strip 1.0 R565
Strip 0.22 R440
Strip 0.55 RBP395
Strip 0.55 R360
Residual
Log-reflectance
Wavelength (nm)
E
male residual R495
female residual R495
495
Log-reflectance
Wavelength (nm)
F
R565
R495
R440
R360
Sensitivity
Wavelength (nm)

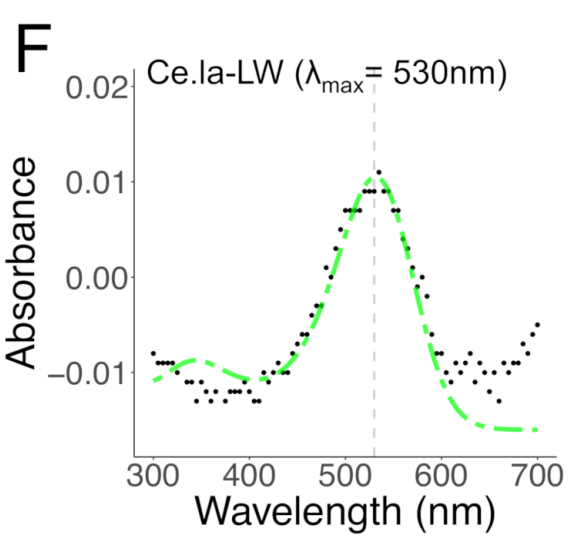

A
CMV
Opsin
Linker
FLAG
T2A
mRuby2
Amp R+
Hygro R+
6h
36h
FLAG-resin
o/n
100 kDa
75 kDa
37 kDa
a-HSP90
a-FLAG
absorbance
wavelength
1. Transfect high-expression opsin-FLAG-T2A-mRuby2 plasmids
2. Change medium, Add cis-retinal
3. Harvest cells, nutate rhodopsin, solubilize membrane fraction
4. Purify rhodopsin via resin affinity, measure UV-VIS absorption

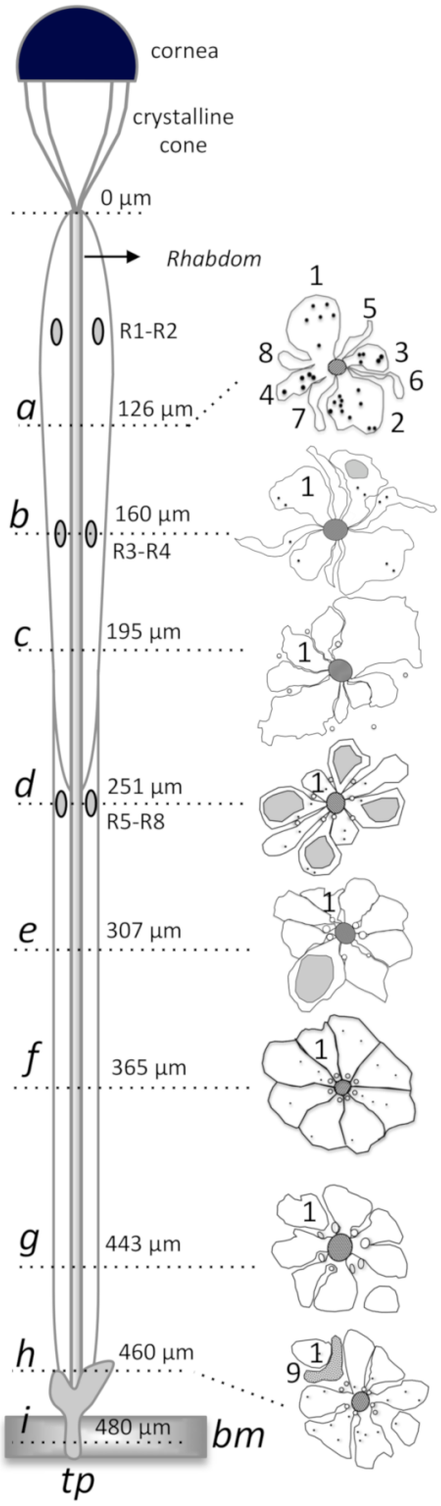

B
Eurema hecabe
Colias erate CeL
Pieris rapae (563 nm)
Anthocharis scolymus
Pieridae
Lycaena helloides
Lycaena rubidus (565 nm)
Lycaena heteronea
Lycaena nivalis
Arhopala japonica
Callophrys sheridanii
Eumaeus atala
Satyrium behrii
Celestrina ladon
Agriades glandon
Polyommatus icarus
Lycaenidae
L
T
P
Apodemia mormo LW2
Apodemia mormo LW1
Riodinidae
Heliconius melpomene
Heliconius erato
Agraulis vanillae
Eueides lineata
Dryas iulia
Limenitis a archippus (514 nm)
Limenitis lorquini (530 nm)
Limenitis weidemeyerii (530 nm)
Limenitis a astyanax (545 nm)
Vanessa cardui
Bicyclus anynana
Danaus plexippus
Nymphalidae
Troides aeacus TaL2
Papilio xuthus Rh2 (515 nm)
Papilio machaon PmL2
Graphium sarpedon GsL2
Graphium sarpedon GsL3b
Troides aeacus TaL3
Papilio xuthus Rh3 (560 nm)
Papilio machaon PmL3
Graphium sarpedon GsL3a
Papilio machaon PmL1
Papilionidae
Papilio xuthus Rh1 (540 nm)

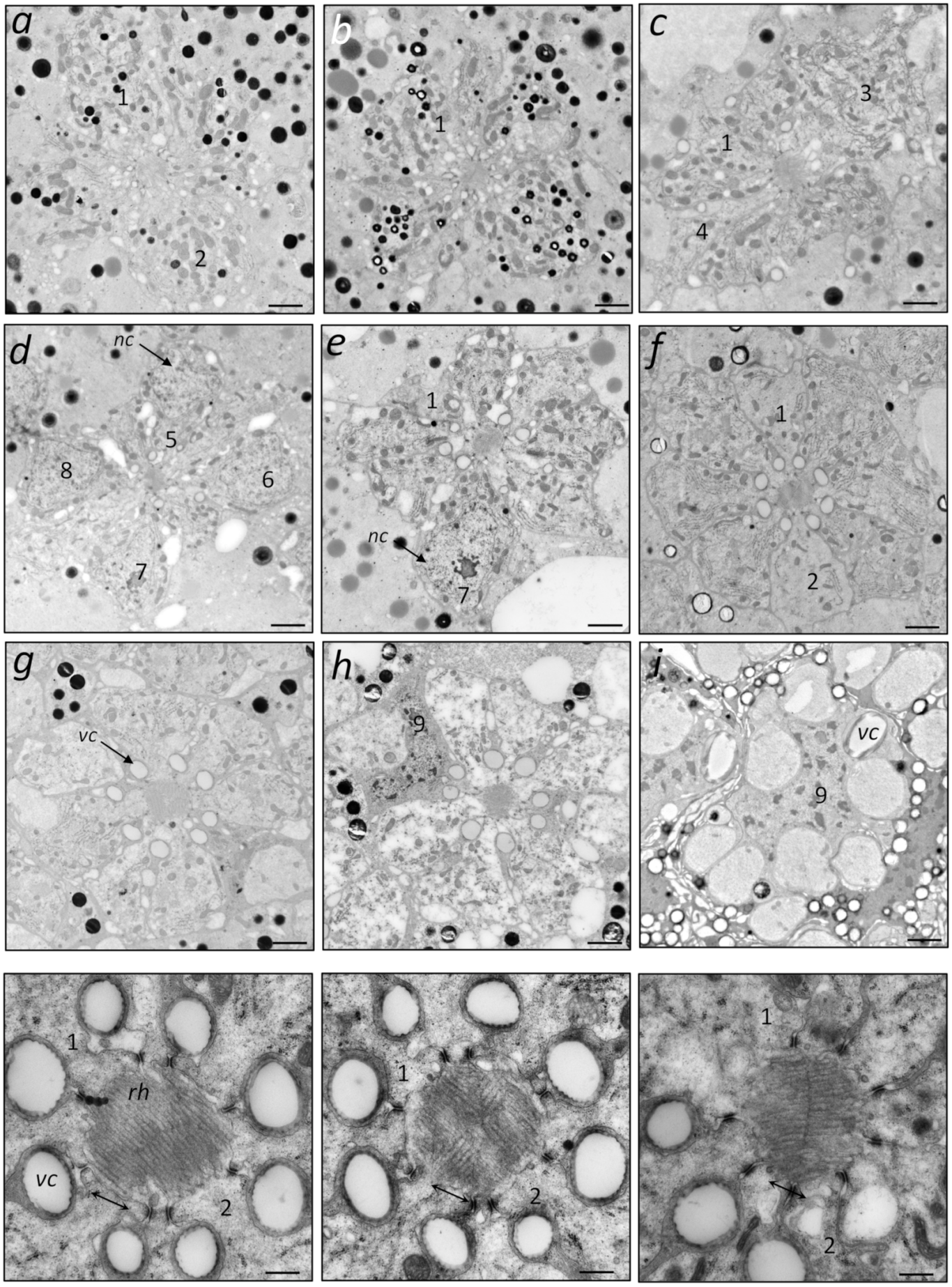

C
A.ja-LW (λmax= 574nm)
Absorbance
Wavelength (nm)

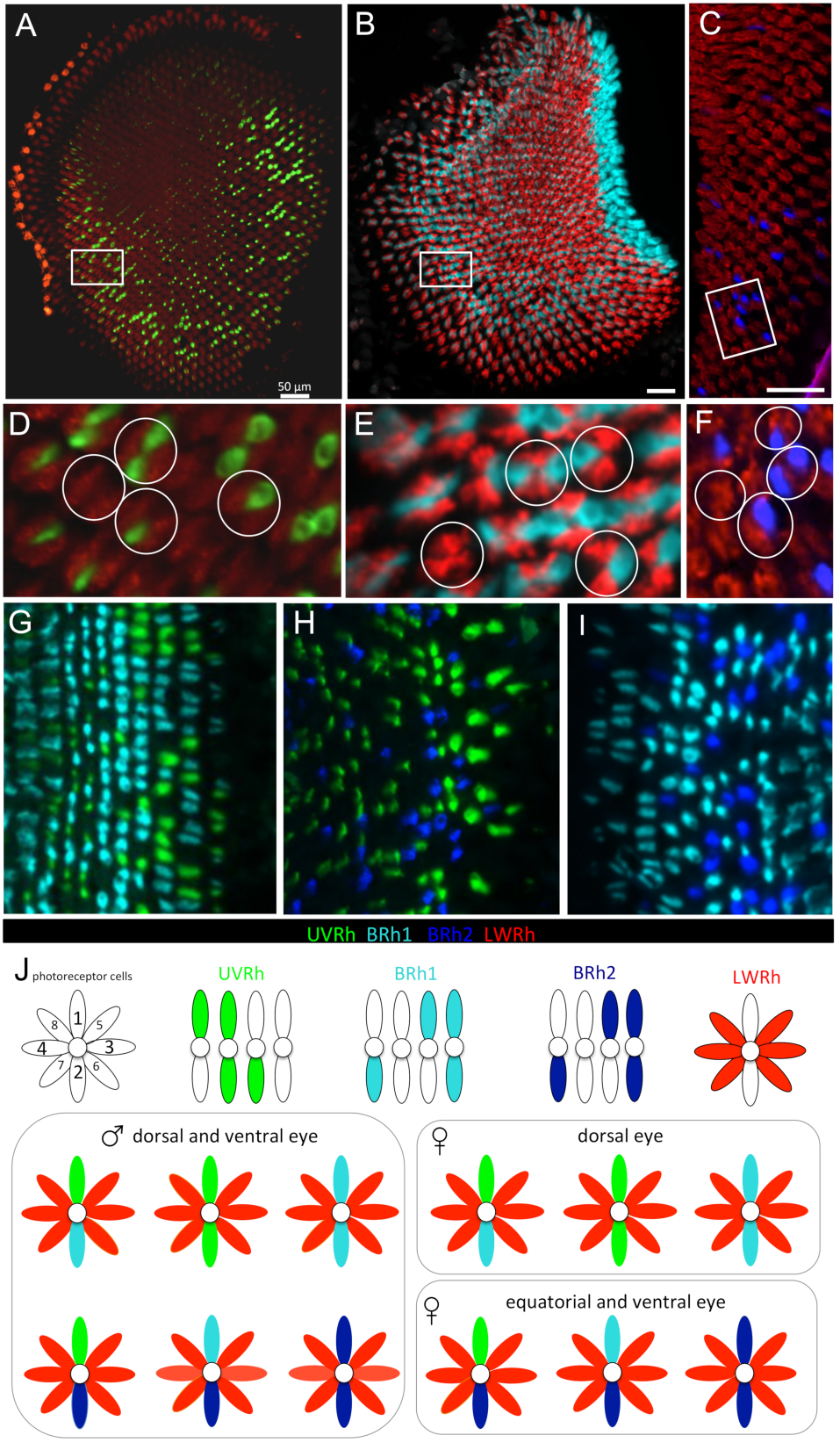

D
E.at-LW (λmax= 569nm)
Absorbance
Wavelength (nm)

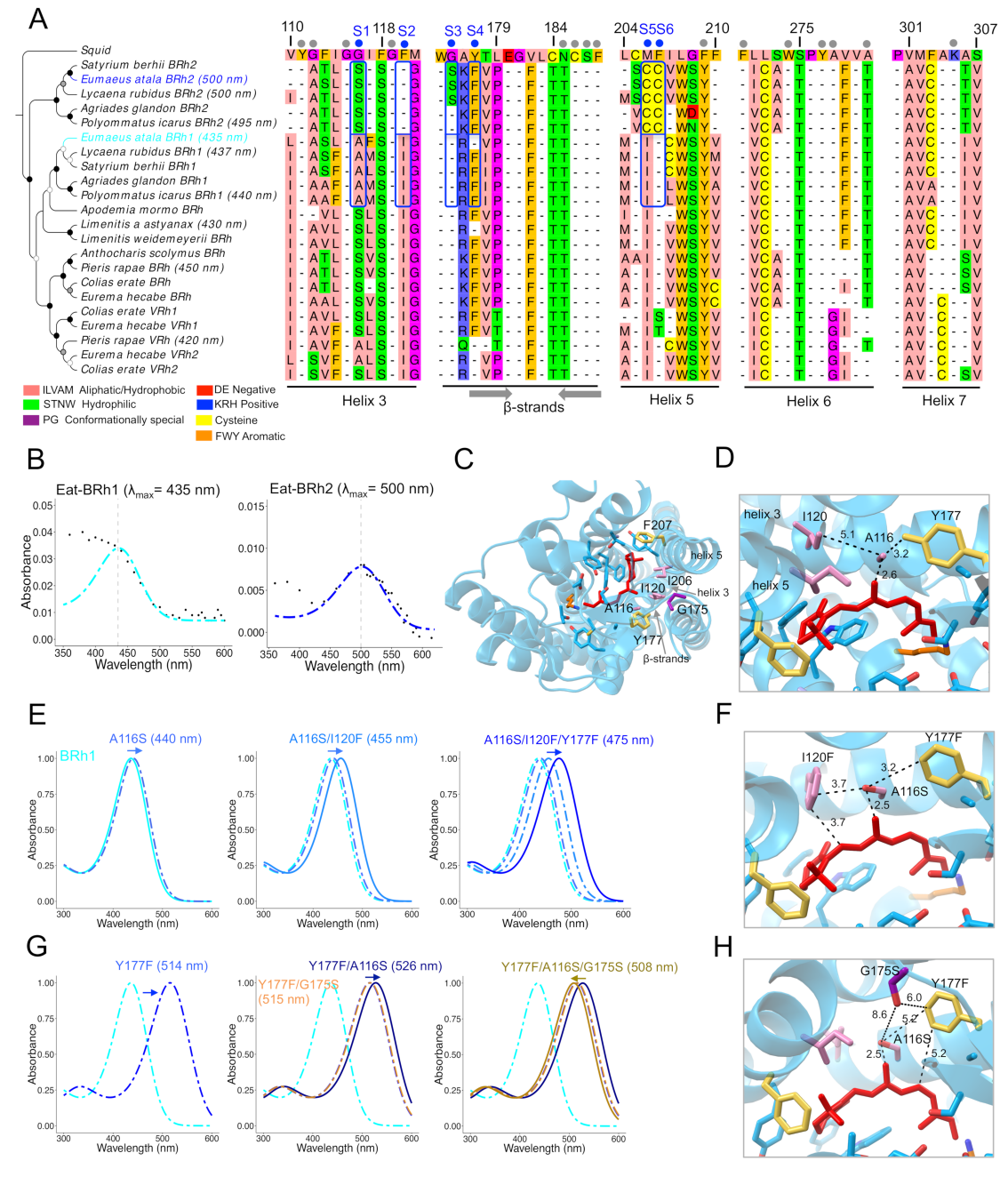

E
Ca.sh-LW (λmax= 521nm)
Absorbance
Wavelength (nm)

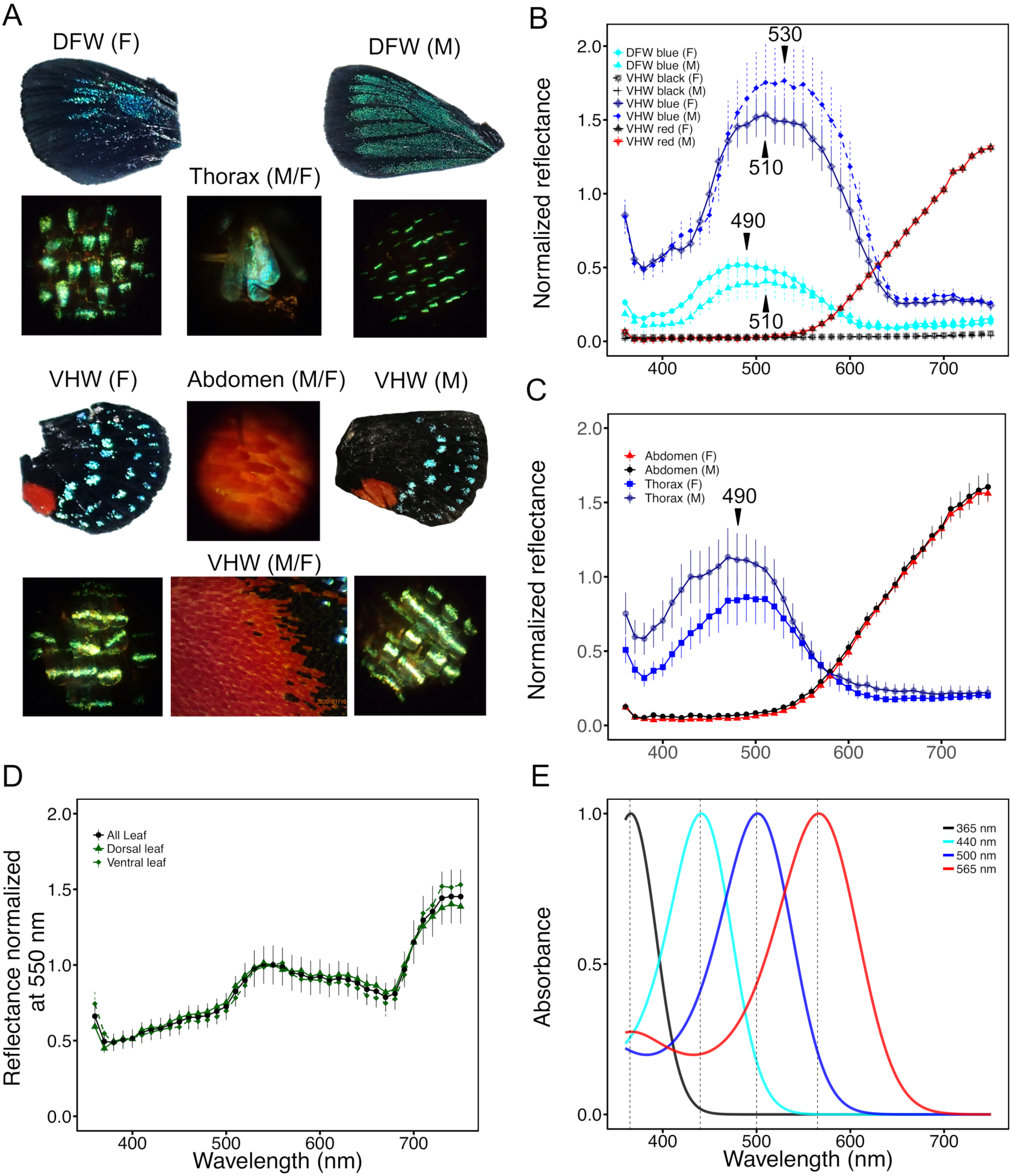

F
Ce.la-LW (λmax= 530nm)
Absorbance
Wavelength (nm)


A
cornea
crystalline cone
0 µm
Rhabdom
R1-R2
a
126 µm
b
160 µm
R3-R4
c
195 µm
d
251 µm
R5-R8
e
307 µm
f
365 µm
g
443 µm
h
460 µm
i
480 µm
bm
tp


B
a
b
c
d
nc
e
nc
f
g
vc
h
i
vc
C
rh
vc


A
B
C
50 µm
D
E
F
G
H
I
UVRh BRh1 BRh2 LWRh
J photoreceptor cells
1
2
3
4
5
6
7
8
UVRh
BRh1
BRh2
LWRh
♂ dorsal and ventral eye
♀ dorsal eye
♀ equatorial and ventral eye


A
Squid
Satyrium berhii BRh2
Eumaeus atala BRh2 (500 nm)
Lycaena rubidus BRh2 (500 nm)
Agriades glandon BRh2
Polyommatus icarus BRh2 (495 nm)
Eumaeus atala BRh1 (435 nm)
Lycaena rubidus BRh1 (437 nm)
Satyrium berhii BRh1
Agriades glandon BRh1
Polyommatus icarus BRh1 (440 nm)
Apodemia mormo BRh
Limenitis a astyanax (430 nm)
Limenitis weidemeyerii BRh
Anthocharis scolymus BRh
Pieris rapae BRh (450 nm)
Colias erate BRh
Eurema hecabe BRh
Colias erate VRh1
Eurema hecabe VRh1
Pieris rapae VRh (420 nm)
Eurema hecabe VRh2
Colias erate VRh2
ILVAM Aliphatic/Hydrophobic
STNW Hydrophilic
PG Conformationally special
DE Negative
KRH Positive
Cysteine
FWY Aromatic
Helix 3
β-strands
Helix 5
Helix 6
Helix 7
B
Eat-BRh1 (λmax= 435 nm)
Eat-BRh2 (λmax= 500 nm)
Absorbance
Wavelength (nm)
C
F207
helix 5
I206
I120
helix 3
A116
G175
Y177
β-strands
D
helix 3
I120
Y177
A116
helix 5
5.1
3.2
2.6
E
A116S (440 nm)
BRh1
A116S/I120F (455 nm)
A116S/I120F/Y177F (475 nm)
Absorbance
Wavelength (nm)
F
Y177F
I120F
A116S
3.2
3.7
2.5
3.7
G
Y177F (514 nm)
Y177F/A116S (526 nm)
Y177F/G175S (515 nm)
Y177F/A116S/G175S (508 nm)
Absorbance
Wavelength (nm)
H
G175S
Y177F
A116S
6.0
8.6
5.2
2.5
5.2


A
DFW (F)
DFW (M)
Thorax (M/F)
VHW (F)
Abdomen (M/F)
VHW (M)
VHW (M/F)
B
530
510
490
510
DFW blue (F)
DFW blue (M)
VHW black (F)
VHW black (M)
VHW blue (F)
VHW blue (M)
VHW red (F)
VHW red (M)
Normalized reflectance
C
490
Abdomen (F)
Abdomen (M)
Thorax (F)
Thorax (M)
Normalized reflectance
D
All Leaf
Dorsal leaf
Ventral leaf
Reflectance normalized at 550 nm
Wavelength (nm)
E
365 nm
440 nm
500 nm
565 nm
Absorbance
Wavelength (nm)