

# Characterizing the pigment composition of a variable warning signal of *Parasemia plantaginis* larvae (Arctiidae)

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## Summary

1. Aposematic animals advertise their defences to predators via warning signals that often are bright colours combined with black patterns. Predation is assumed to select for large pattern elements and conspicuousness of warning signals because this enhances avoidance learning of predators. However, conspicuousness of the colour pattern can vary among individuals of aposematic species, suggesting that warning signal expression may be constrained by opposing selection pressures. If effective warning signals are costly to produce, variation in signal expression may be maintained via physiological trade-offs. To understand the costs of signalling that might underlay both physiological and ecological trade-offs, it is crucial to identify the pigments involved in aposematic traits, how they or their precursors are acquired and how their production and/or deposition interact with other physiological processes.

2. We characterized the pigments responsible for the genetically and phenotypically variable orange-black warning signal of the hairy larvae of an Arctiid moth, *Parasemia plantaginis*. We tested orange and black coloured hairs for the presence of six candidate pigment types using high-performance liquid chromatography, spectral and solubility analyses.

3. After excluding the presence of carotenoids, ommochromes, pterins and pheomelanins in orange hairs, our results suggest that tiger moth larvae produce their orange warning signal by depositing both diet-derived flavonoids and trace levels of synthesized eumelanin in their hairs. The nearby black hairs are coloured by eumelanin.

4. In light of previous studies, we conclude that although a large orange patch increases the larvae's antipredator efficacy, variation in the size of orange patches within a population can be driven by scarcity of flavonoids in diet. However, traces of eumelanin found in the orange hairs of the larvae may also play a significant role in the maintenance of the signal pattern on poor quality diets.

5. The goal of the future studies will be to test the condition dependence of pigment deposition in aposematic colour patterns by directly manipulating relevant nutritional parameters such as dietary flavonoid or nitrogen content (i.e. amino acid content).

**Key-words:** melanins, flavonoids, warning colours, insects, aposematism

## Introduction

Aposematic animals often use bright colouration to advertise their secondary defences to predators (Poulton 1890; Ruxton, Sherratt & Speed 2004). Selection by predators

favours these conspicuous warning signals because large and bright patterns are more easily learnt and remembered by predators (Guilford & Dawkins 1991; Forsman & Merilaita 1999; Gamberale-Stille & Tullberg 1999; Lindström *et al.* 1999; Lindstedt, Lindström & Mappes 2008). Therefore, predator psychology and its relationship to the effectiveness of warning signals have gained a lot of

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	F E C	1 6 8 6	B	Dispatch: 15.1.10	Journal: FEC	CE: Balaji Prasad
	Journal Name	Manuscript No.		Author Received:	No. of pages: 8	PE: Ulagammal

attention in studies of warning colour evolution (review in Ruxton, Sherratt & Speed 2004). However, recent work has brought new perspectives to the evolution of aposematism by studying the prey's selective environment as a whole; e.g. it has been shown that environmental constraints (Grill & Moore 1998; Ojala, Lindström & Mappes 2007; Tullberg *et al.* 2008; Lindstedt, Lindström & Mappes 2009a; Lindstedt *et al.* 2009b) and population densities (Sword 1999, 2002) can affect warning signal expression in addition to selective pressures arising from predators.

Many studies considering sexual ornamentation in animals highlight that to be able to study ecological and evolutionary trade-offs between signal expression and other fitness components in detail, it is important to link them with the physiological mechanisms that affect signal expression (e.g. Hill & Montgomerie 1994; Hooper, Tsubaki & Siva-Jothy 1999; Grether, Hudon & Endler 2001). Extending these ideas to the study of warning signals suggests that if the pigments deposited in a warning colour pattern are expensive to acquire or produce, trade-offs between effective warning signal expression and other energetic or resource requirements may occur. To understand possible physiological (and ecological) trade-offs, one first has to know the biochemical composition of aposematic traits. However, the biochemical basis of aposematic colouration has been studied in detail in surprisingly few species (but see Bezzerides *et al.* 2007; Sandre *et al.* 2007). Here, we sought to characterize the pigments responsible for the variable orange-and-black aposematic colouration of larval wood tiger moths (*Parasemia plantaginis*), in the hope that our findings would provide some insight into possible ecological and physiological trade-offs associated with the production of this aposematic colour pattern.

Insects, and Lepidoptera in particular, utilize a variety of pigments (carotenoids, flavonoids, pterins, ommochromes and melanins being most common) to produce oranges and blacks such as those found in the trait in question (Fox 1976; Kayser 1985). These pigments have distinct biochemical properties and linkages to other physiological processes. For example, in previous studies of the chemical basis of warning colouration, bright orange, red and yellow colour elements have been found to be produced by carotenoids (Bezzerides *et al.* 2007; Sandre *et al.* 2007). Animals cannot synthesize carotenoids and must obtain carotenoid pigments directly from their diet (Fox 1976; Hill, Inouye & Montgomerie 2002). Therefore, their scarcity in diet can constrain colour expression (Hill & Montgomerie 1994; Carroll *et al.* 1997; Grill & Moore 1998) and maintain variation in signal production (Grether, Hudon & Millie 1999; Hooper, Tsubaki & Siva-Jothy 1999; Senar, Figuerola & Domenech 2002). Potential linkages to free-radical scavenging and immune support (Burton 1989; Olson 1989; Lozano 1994; Camplani, Saino & Møller 1999; Hörak *et al.* 2001) may also produce competition between colouration and other physiological needs for carotenoid pigments.

Flavonoids and flavins are less well studied from this perspective, but they share a number of ecological and

physiological characteristics with carotenoids. These classes of pigments are employed by many insects in orange, yellow and UV-absorbing colour patterns (Kayser 1985, Burghardt *et al.* 2000, Knüttel & Fiedler 2001), must be derived from dietary plant sources (Knüttel & Fiedler 2001), and may have similar antioxidant and immunological functions (Kayser 1985; McGraw 2005). Arguments paralleling those outlined above, and already extensively propounded elsewhere for carotenoids may also apply to the use of flavonoids and flavins in insect colouration.

While insects do employ diet-derived pigments in their colour patterns, they perhaps more commonly use pigments that they synthesize *de novo*. Pterins, ommochromes and melanins are pigments that can produce orange colouration and must be synthesized from basic precursors (Kayser 1985). Melanin is also by far the most common pigment used in black pigmentation (Fox 1976). Because these pigment types require access to pools of basic precursors, they are likely to compete directly with other physiological processes (Stoehr 2006). For example, melanins are synthesized from tyrosine, an essential amino acid that is required for dopamine and serotonin production (Sugumaran 2002). Ommochromes are derived from tryptophan, another essential amino acid linked to a handful of basic physiological processes (Linzen 1974). Pterins are purine-derivatives, requiring large amounts of guanosine diphosphate for their synthesis. Production of large quantities of any of these pigments is therefore likely to result in physiological trade-offs (Stoehr 2006). It is also worthwhile to note that many insects, including *P. plantaginis*, are herbivorous, feeding on plant material that is predominantly carbohydrate-based, and therefore poor in amino acids and purine-derivatives (reviewed in Mattson 1980; Chown & Nicolson 2004). This suggests that supply of required precursors may be limited by ecological availability (e.g. host-plant quality, Talloen, Van Dyck & Lens 2004; Freitag *et al.* 2005) offering one possible mechanism which may be responsible for producing variation in colour patterns. In addition, colour can be a result of more than just one pigment type. For example, Grether, Hudon & Endler (2001) found that male guppies (*Poecilia reticulata*) use both carotenoids and pteridine pigments in the orange spots that they display to the females, which may have important implications for the signalling utility of these colour patterns. Natural melanins may also often occur in conjunction with the pigment types mentioned above or may contain mixed polymers which produce intermediate colours (Kayser 1985).

Given the variety of potential connections between pigments and other physiological processes, we sought to characterize the pigments responsible for the colouration of the aposematic larvae of the wood tiger moth (*Parasemia plantaginis*). These larvae are polyphagous herbivores which have an aposematic pattern consisting of an orange patch of hair on the dorsal side of their black and hairy body. This pattern is known to exhibit considerable phenotypic variation, influenced by both environmental and genotypic factors (Ojala, Lindström & Mappes 2007; Lindstedt, Lindström & Mappes 2008, 2009a; Lindstedt *et al.* 2009b) (Fig. 1). Thus, even



**Fig. 1.** Variation in the size of the orange patch and black pattern elements in aposematic *Parasemia plantaginis* larvae.

though the frequency of intermediate orange signal sizes (proportion of orange approx. 40–50%) appears to be high, the proportion of the orange in larval colouration can vary approximately from 20% to 80% (Ojala, Lindström & Mappes 2007; Lindstedt, Lindström & Mappes 2009a). Predators learn to avoid larvae with large orange patches (proportion of orange > 60%) faster, suggesting selection toward larger signal sizes (Lindstedt, Lindström & Mappes 2008). Larvae are also chemically defended by sequestered iridoid glycosides (Lindstedt *et al.* 2009b). Despite possible directional selection by predators, existing variation in the size of the orange patch indicates that opposing selection pressures may constrain effective warning signal expression (Ojala, Lindström & Mappes 2007; Friman *et al.* 2009; Lindstedt, Lindström & Mappes 2009a). Moreover, if the pigments deposited in the colour signal pattern are expensive to acquire or produce, physiological constraints may restrict optimal signal expression, thus maintaining the observed variation. In an earlier study Ojala, Lindström & Mappes (2007) found that larvae reared on an artificial diet poor in flavonoids and carotenoids (Ojala *et al.* 2005) expressed smaller orange patches compared to larvae reared on a high quality diet that was rich in flavonoids and carotenoids. This indicates that pigment deposition to the warning signal is susceptible to variation in environmental conditions and therefore effective signal expression may be constrained by environmental factors. To gain insight into the physiological mechanisms underlying warning signal variation in *P. plantaginis*, we sought to identify the orange and black pigments composing the signal using high-performance liquid chromatography (HPLC), solubility and fluorescence analyses, as well as characterization of the pigments *in vivo* and *in vitro* via spectrometry. More specific information regarding the biochemical composition of this warning signal should allow for future work to study the physiological aspects of warning signal expression in detail and address questions such as: How expensive are the pigments responsible for the warning signal to produce or acquire? Are the pigments known to be linked to any immu-

COLOR

nological or physiological functions? And what kind of resources (e.g. in diet) could limit their production?

## Materials and methods

### BIOLOGICAL MATERIAL

Larvae for the pigment samples were fed with a mixture of *Taraxacum* spp. leaves and lettuce to ensure high survival rate of the larvae during rearing. Because the colour pattern of *P. plantaginis* larvae is based on the colour of hairs, orange and black hairs from the larvae were collected with forceps and stored in Kimax-tubes from frozen late instar larvae. Hairs were stored at  $-20^{\circ}\text{C}$  and sample amounts used for the analyses were 20 mg per analysis. We tested the orange and black hairs for presence of six candidate pigment groups (carotenoids, melanins, flavonoids and flavins, pteridines and purine derivatives, ommochromes, and papiliochromes).

### FLUORESCENCE AND SOLUBILITY TESTS

Fluorescence and solubility of the hair pigments were tested first to shorten the list of possible pigment types. Pterins and purine derivatives, papiliochromes, flavonoids and flavins are fluorescent when stimulated with ultraviolet (UV) light, whereas melanins, ommochromes and carotenoids do not fluoresce (Fox 1976; Kayser 1985; Umehachi 1985). We subjected orange and black hair samples to short- and long-wave UV light (254 and 366 nm) using a Mineralight lamp (model UVGL-58; UVP Inc., San Gabriel, CA, USA), and noted any fluorescence visible to the naked eye. In addition, extracted pigments in solution were evaluated for fluorescence.

Pterins and purine derivatives, papiliochromes and flavonoids are all soluble in strong acids and bases (Fox 1976; Kayser 1985; Umehachi 1985). Therefore, to test for the presence of these pigments, we micronized hair samples using a ball-mill, and placed the ground samples in 0.1 M NaOH overnight. Flavonoids and papiliochromes are also soluble in aqueous and organic (alcohol) solvents (Kayser 1985; Umehachi 1985; Burghardt, Proksch & Fiedler 2001). We therefore micronized an additional set of samples and placed them in 90% methanol overnight. The following day, both sets of samples were microcentrifuged for 20 min at 12 000 rpm, and the resulting supernatant measured for the presence of extracted pigmentary material using an absorbance spectrophotometer across a wavelength range from 190 to 900 nm (DU 520; Beckman Coulter, Fullerton, CA, USA). Resulting spectra were compared to published spectral profiles of each pigment class. Similar protocols were also followed using acidified methanol to screen for ommochromes (see below).

### CHARACTERIZATION BY REFLECTANCE SPECTROMETRY

We evaluated the spectral properties of the pigments *in vivo* by taking spectral reflectance measurements from samples of *P. plantaginis* hairs mounted on black cardstock following methods outlined in Rutowski *et al.* (2005). Samples were illuminated using an pulsed-xenon light source (Model PX-2; Ocean Optics, Dunedin, FL, USA) positioned at the zenith above the sample and oriented normal to the sample's surface. Spectra were collected from the illuminated area using an optical fibre positioned at  $45^{\circ}$  below the zenith and connected to a spectrophotometer (USB2000; Ocean Optics). All spectra were normalized in relation to a magnesium oxide white standard. These spec-

tral measures gave us the opportunity to compare the reflectance spectra of both orange and black hairs to known spectra of different pigments. In particular, this allowed us to compare carotenoids and melanins, which are both non-fluorescent under short-wavelengths, but have distinctive spectral signatures. Carotenoids have their strongest absorbance peaks in the mid-wavelength ranges (450–550 nm), but absorb little if any UV light (300–400 nm), resulting in characteristic UV reflectance off of carotenoid-containing integumentary structures (e.g. Andersson & Prager 2006). Melanins, on the other hand, absorb strongly at all visible and UV wavelengths, producing reflectance spectra that increase slowly and monotonically from UV to long wavelengths (Sarna & Sealy 1984).

#### HPLC-ANALYSIS

##### Carotenoid analysis

Carotenoid analysis was carried out as in McGraw *et al.* (2004, 2005) with modifications. About 5 mg of hair sample was placed into a screw-capped tube and 2 mL acidified pyridine (three drops of 12 N HCl in 50 mL of pyridine) was added. Tubes were filled with argon gas and then closed tightly. Sample tubes were placed in an oven where they were kept for 3 h at 95 °C. After cooling to room temperature, 2 mL of water and 1 mL of hexane: tert-butyl methyl ether (TBME) (1:1) was added into the tubes. Tubes were shaken for 5 min and centrifuged at 3000 rpm for 5 min. Non-polar organic phase (upper layer) was removed and placed into HPLC tubes and the hexane: TBME solution was evaporated with nitrogen gas. Dried samples were redissolved in 250 µL of HPLC mobile phase (acetonitrile:methanol, 1:1, v/v). The bottom layer consisting of water and pyridine was evaporated to dryness with nitrogen gas and analysed for pheomelanin (see below).

The HPLC system (Waters, Milford, MA, USA) consisted of a Waters 510 HPLC pump with a flow rate set to 0.5 mL min<sup>-1</sup>. A sample of 50 µL was injected with Waters 717 plus autosampler. Samples were run through a Gemini reversed phase C18 column of 150 mm length × 3 mm i.d. particle size 5 µm (Phenomenex, Torrance, CA, USA) analytical column, maintained at 32 °C. Data were acquired between 250 and 600 nm with Waters 996 Photodiode Array Detector. Processing of the data was done with Millennium32 software.

##### Ommochrome analysis

Several synthetic ommochromes were obtained in the laboratory by the method of Butenandt (Butenandt & Schaefer 1962) and identified by HPLC coupled with mass spectrometry. These ommochromes were then used as standards in the following analysis. The hair samples were crushed in 2 mL acidified methanol using a glass tissue grinder. Each sample was transferred to a 2 mL Eppendorf tube and incubated overnight at room temperature. The method of separation of the different compounds was based on a technique of ion-pairing described previously (Arnault *et al.* 2003). Separations studies were carried out using a second Waters HPLC system, consisting of a 600E quaternary gradient pump, a 996 diode array detector and a 717 autoinjector. The UV absorbance spectral data were collected from 200 to 500 nm. Compounds were separated on a Hypurite Elite reversed phase C18 column of 150 mm length × 3 mm i.d. particle size 3 µm (Thermo Hypersil; Keystone, Bellafonte, PA, USA). The gradient was based upon a binary solvent system. Solvent A consisted of 20 mM sodium phosphate monobasic and 10 mM heptanesulphonate, pH 2.1 (adjusted with orthophosphoric acid 85%) and solvent B consisted of 50% acetonitrile/50% solvent A (v/v), pH 2.1.

The data were acquired and processed using Millennium 3.1 software (peak identification based on retention time combined with a spectral library).

##### Pheomelanin analysis

Pheomelanin analysis was performed according to Kolb *et al.* (1997) and Borges *et al.* (2001) with slight modifications. To identify peaks in the pheomelanin analysis we used 3-amino-4-hydroxyphenylalanine (AT; Aeros Organics) as a standard. Hypophosphorous acid (50%) (H<sub>3</sub>PO<sub>2</sub>; Sigma) and hydriodic acid (HI, Fluka) were used to hydrolyse the samples. As an ion-pair we used 1-octanesulphonic acid (Sigma). We used AT, red human hair samples (received from a female colleague) and feather samples [4–8 mg, originating from the head of a male domestic chicken (*Gallus domesticus*)] to calibrate the method. They were placed into screw-capped tubes to which 20 µL 50% H<sub>3</sub>PO<sub>2</sub>, 500 µL 57% HI and 100 µL UHQ-water was added. Tubes were tightly closed and samples were hydrolysed in oven at 130 °C for 16 h. After that we dried samples in the oven at 60 °C for 3–6 h under stream of nitrogen. Dried samples were redissolved in 1 mL of 0.05 M Li-phosphate buffer (pH 4.0) similar to Borges *et al.* (2001).

Extraction of the compounds was done with an aromatic sulphonic acid solid-phase extraction (SPE) column (Strata SCX, 100 mg mL<sup>-1</sup>, Phenomenex, Torrance, CA, USA).

The SPE columns were first washed two times with 1 mL of methanol. Columns were then washed three times with 1 mL of Li-phosphate buffer before addition of the samples. After washing twice with 1 mL of water, AT and AHP were eluted with 2 mL of 0.3 M KCl, pH 8.5.

For the HPLC analysis we used a GS50 gradient pump, LC25 chromatographic oven and ED50 electrochemical detector (all units Dionex, Sunnyvale, CA, USA). The detector was set to 350 mV. Separation was done by a Gemini 5-µm C18, 150 × 3.0 mm i.d. analytical column (Phenomenex). The column was used at room temperature with an injection volume of 25 µL of SPE treated sample solution.

The data were acquired and processed with Chromeleon 6.50 SP6 Build 1032 software.

The mobile phase consisted of a mixture of 1:99 (v/v) methanol:potassium phosphate buffer (0.01 M, pH 5.7), 1-octanesulphonic acid sodium salt (1 mM) as an ion-pair reagent and disodium EDTA (0.1 mM). The flow rate was 0.5 mL min<sup>-1</sup>.

##### Eumelanin analysis

Eumelanin analysis was done according to Borges *et al.* (2001) with modifications. Samples (7–9 mg) were placed in a screw-capped tube to which 820 µL 0.5 M NaOH, 80 µL 3% H<sub>2</sub>O<sub>2</sub> and an internal standard (48 nmol phthalic acid) were added. Samples were then heated in boiling water for 20 min. After cooling 20 µL 10% Na<sub>2</sub>SO<sub>3</sub> and 250 µL 6 M HCl was added. Samples were then extracted twice with 7 mL ethyl acetate. Ethyl acetate was dried at 45 °C under a stream of air. The residue was dissolved into 1 mL of starting HPLC mobile phase.

HPLC analysis was carried out with an HPLC, equipped with a GS50 gradient pump, AS50 autosampler and UVD 170U UV/Vis detector (Dionex). 50 µL of sample was injected into a Spherisorb S5 C8, 250 × 4.6 mm i.d. analytical column (Waters, Milford, MA, USA). The column was set to 40 °C. Analytes were detected at wavelength 280 nm and the data was collected with Chromeleon 6.50 SP6 Build 1032 software. HPLC mobile phase consisted of 0.01 M potassium phosphate buffer (pH 2.1) and methanol. Flow rate was 1.0 mL

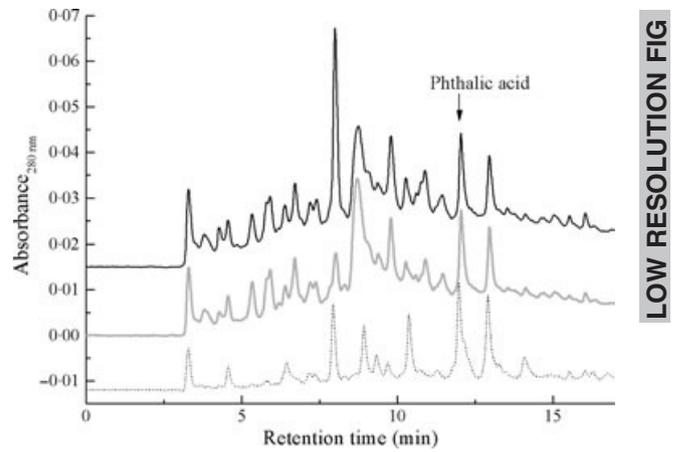
1 min<sup>-1</sup> and the used gradient was as follows: 99:1 buffer:MeOH (v:v)  
 2 ramped evenly from time 0 to 15 min to 40:60 buffer:MeOH (v:v),  
 3 held at 40:60 for 6 min and ramped evenly back to initial eluent composition  
 4 over 5 min. We compared chromatograms obtained from  
 5 *P. plantaginis* to chromatograms obtained from black human hair.

## 7 Results

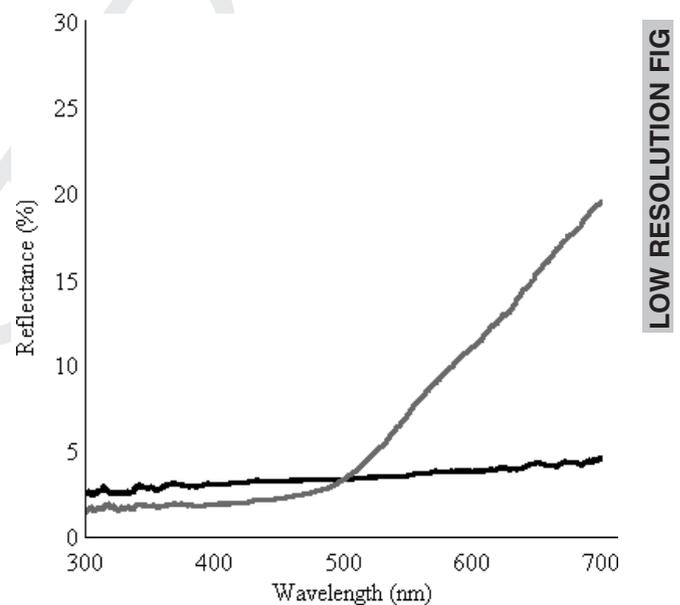
### 9 ORANGE HAIRS

10 The orange pigments found in the hairs were not fluorescent  
 11 *in vivo*, but were soluble in 0.1 M NaOH and methanol solutions,  
 12 and fluoresced faint yellow in solution. Absorbance spectra of the extracted  
 13 material most closely resembled the general properties of flavonoids, with  
 14 absorbance strongest in the far-UV (in methanol:  $\lambda_{\max}$  = 281 nm, shoulders at  
 15 234 nm, 311 nm). In addition to the strong match between solubility,  
 16 fluorescence and absorbance properties of the extracted pigment and known  
 17 properties of flavonoids, several lines of evidence help to exclude carotenoids,  
 18 pterins and ommochromes. Carotenoids can easily be excluded due to the  
 19 fluorescent and UV-absorbing properties of the extracted pigment. Results  
 20 from our HPLC analyses also confirm the absence of carotenoids in the orange  
 21 hairs. Ommochromes and pterins can also be ruled out, as they are not  
 22 expected to be soluble in methanol. This is also supported by our HPLC  
 23 analyses as we did not find any matched peaks with the ommochrome  
 24 standards tested. In addition, ommochromes have characteristically strong  
 25 absorbance peaks in the near-UV, violet, blue or green, whereas the  
 26 pigment(s) isolated from the orange hairs absorbs most strongly in the  
 27 far-UV.

28 The HPLC analyses revealed that orange or black hairs did  
 29 not contain pheomelanins. This is in accordance with the scientific literature,  
 30 where pheomelanins have only been described from vertebrates (Fox 1976;  
 31 Kayser 1985). As such, pheomelanins were excluded from further analyses.  
 32 However, we found eumelanin in the HPLC analyses of orange hairs, as  
 33 the peaks in HPLC chromatograms of human black hair matched with the  
 34 peaks of *P. plantaginis* (Fig. 2). This was also supported by the  
 35 reflectance measurements. Eumelanin itself is not equally light absorbing  
 36 across all visible wavelengths as one might suppose from its often very  
 37 black hue in animal tissues. Instead, melanin is strongly absorbent across  
 38 all light wavelengths, but is more strongly absorbent in the short  
 39 wavelengths (Sarna & Sealy 1984). Therefore, tissues that contain small  
 40 amounts of eumelanin should gradually increase in light reflectance when  
 41 moving towards longer wavelengths. This feature is rarely seen in melanin  
 42 patterns, as eumelanin has such a high extinction coefficient across visible  
 43 wavelengths (Fox 1976; Kayser 1985). However, at trace amounts one can  
 44 begin to see this difference between long and short wavelengths. The spectra  
 45 shown in Fig. 3 may therefore also be consistent with what would be  
 46 expected from very small amounts of melanin deposited in these hairs.  
 47 Such a contribution of trace amounts of melanin to the orange-colouration  
 48 of these hairs would also be consistent with our fluorescence results, where  
 49 melanin may be



21 Fig. 2. HPLC chromatograms of the *Parasemia plantaginis* black hairs (black line), orange hairs (grey line) and human black hair (dotted black line) in eumelanin analysis.



22 Fig. 3. Lines show mean spectra of orange hairs (grey line) and black hairs (black line) of *Parasemia plantaginis* larvae. All values are percents scaled relative to complete dark and a magnesium dioxide white standard.

quenching the fluorescence of flavonoids *in vitro* which is visible in solution. Taken together, we conclude that the orange hair colour is based on flavonoids and traces of eumelanin pigments.

### BLACK HAIRS

Pigments in the black hairs were not soluble in any solvents tested and did not fluoresce, excluding all alternatives except melanins (Fig 3). HPLC analyses revealed that the black hairs of *P. plantaginis* contained eumelanins. The HPLC chromatograms of black and orange hairs of *P. plantaginis* were almost identical with the exception of the peak at 8 min repre-

1 sending in all likelihood PTCA. The ratio of this peak between  
 2 black and orange hairs was 4:1, which is similar to the ratio of  
 3 PTCA in human black and red hair analysed by comparable  
 4  $H_2O_2/HO$ -oxidation (Liu *et al.* 2005). However, the relative  
 5 peak size of likely PTCA peak in black hairs of *P. plantagin*  
 6 was triple to that of human black hair. On the other hand the  
 7 chromatograms of *P. plantagin* seemed to be more complex  
 8 compared to chromatograms of human black hair indicating  
 9 a more heterogeneous structure of the eumelanin present.

## 11 Discussion

13 Much of the empirical efforts to understand the costs of  
 14 bright colouration have focused on carotenoid-based colour-  
 15 ation in vertebrates (e.g. Endler 1980; Hill & Montgomerie  
 16 1994; Grether, Hudon & Millie 1999; McGraw & Hill 2000,  
 17 Hill, Inouye & Montgomerie 2002). However, there is accu-  
 18 mulating evidence that other pigment groups such as mel-  
 19 anins, flavonoids and pterins may impose significant  
 20 acquisition and/or production costs resulting in physiological  
 21 trade-offs (Saffranek & Riddiford 1975, Windig 1999; True  
 22 2003; Talloen, Van Dyck & Lens 2004, McGraw 2005; Grif-  
 23 fith, Parker & Olson 2006). In this study our results suggest  
 24 that aposematic *P. plantagin* larvae produce the colour of  
 25 their orange warning signal by depositing flavonoids and  
 26 trace elements of eumelanin into the hairs. The black pattern  
 27 elements are formed of hairs containing high levels of eumela-  
 28 nin.

29 The results of our pigment analyses are consistent with  
 30 the study of Ojala, Lindström & Mappes (2007). According  
 31 to the results of that study, the *P. plantagin* larvae reared  
 32 on a diet high in flavonoids (*Rumex* sp., Ojala *et al.* 2005)  
 33 expressed larger signal sizes than larvae reared on artificial  
 34 diet that included only traces of flavonoids (Ojala *et al.*  
 35 2005). Although large signal size is beneficial against preda-  
 36 tors (Lindstedt, Lindström & Mappes 2008), our findings  
 37 combined with the results of Ojala, Lindström & Mappes  
 38 (2007) offer indirect evidence that flavonoid concentration  
 39 of the diet could constrain the size of the orange warning  
 40 signal. However, even on an artificial diet which had only  
 41 trace amounts of flavonoids (Ojala *et al.* 2005) *P. plantagi*-  
 42 *nis* larvae were able to express rather large signals. This  
 43 suggests that the warning signal sizes of *P. plantagin* larvae  
 44 are not purely dependent on the flavonoids in diet. That is,  
 45 larvae may be able to compensate for the variation in diet  
 46 quality and its consequences on warning signal expression  
 47 by using two kinds of pigments to produce their warning  
 48 signal pattern (see also Grether, Hudon & Endler 2001).  
 49 This indicates that traces of eumelanin found in the orange  
 50 hairs of the larvae may also play a significant role in the  
 51 maintenance of the signal pattern on poor quality diets.  
 52 More work to understand how the pigment composition of  
 53 orange hairs may respond to changes in diet is clearly  
 54 needed.

55 Interestingly, results from the study by Ojala, Lindström &  
 56 Mappes (2007) also suggest that investment in the melanic  
 components of the aposematic signal may be costly. Darker

*P. plantagin* larvae with higher amounts of melanin in their  
 hairs had lower survival and lower growth rates compared to  
 larvae with larger orange patterns irrespective of diet quality.  
 This offers indirect evidence for the 'costly melanin' hypothe-  
 sis (i.e. the investment in black hairs on the body could incur  
 costs). Trade-offs between melanization and life history traits  
 have also been shown in other insect studies between adult  
 melanization and development time (Talloen, Van Dyck &  
 Lens 2004) or adult size (Saffranek & Riddiford 1975) or both  
 (Windig 1999; Ma *et al.* 2008) further supporting the idea that  
 melanin-based black colour patterns can be expensive to pro-  
 duce.

Why then does the warning signal pattern of *P. plantagi*-  
*nis* vary if production of smaller orange patches and larger  
 black patterns are associated with higher production (mela-  
 nin) and predation costs (smaller orange patterns, Lind-  
 stedt, Lindström & Mappes 2008)? Our suggestion is (see  
 also Ojala, Lindström & Mappes 2007, Friman *et al.* 2009;  
 Lindstedt, Lindström & Mappes 2009a) that opposing selec-  
 tion pressures on signal size could in certain situations make  
 production of more extensive black pigmentation advanta-  
 geous. Even though larger orange warning signals are more  
 effective against predators (Lindstedt, Lindström & Mappes  
 2008), this benefit in *P. plantagin* larvae may trade off  
 against benefits arising from larger black pattern elements,  
 such as thermoregulatory benefits (Lindstedt, Lindström &  
 Mappes 2009a) and better immunity against pathogens (Fri-  
 man *et al.* 2009). In general, darker colouration can also  
 protect individuals from UV-radiation (Hessen 1996; but  
 see Gunn 1998). However, even if larger melanic pattern ele-  
 ments are favoured in a particular selective regime, variation  
 in the size of black pattern elements may be maintained if  
 important dietary precursors are scarce (e.g. Morris, Yu &  
 Rogers 2002). Thus, a more robust understanding of the  
 extant variation in this aposematic colour pattern will need  
 to incorporate information regarding the selective benefits  
 and dietary limitations simultaneously acting on both the  
 orange (flavonoid- and eumelanin-based) and black (eumel-  
 anin-based) components and their relative sizes. Since black  
 melanin based pattern elements are part of the protective  
 colour pattern in many herbivorous insects, costs involved  
 with melanin production are a likely if little studied factor  
 in insect colour production.

In addition to Ojala, Lindström & Mappes (2007), few  
 studies have addressed condition dependence of warning sig-  
 nal expression so far (e.g. Grill & Moore 1998; Sword 1999;  
 Sandre *et al.* 2007). Based on the few studies that have probed  
 this interesting question, it seems that pigment deposition and  
 its susceptibility to environmental conditions may vary  
 among aposematic species depending on ecological specifics,  
 such as diet characteristics and importance of other selection  
 pressures. For example, Sandre *et al.* (2007) found that pro-  
 duction of carotenoid based yellow colouration was not influ-  
 enced by diet manipulations in the polyphenic *Orqyia antiq*  
*ua* larvae. This is not very surprising because carotenoids are  
 often plentiful in the diet of herbivores (e.g. Ojala *et al.* 2005).  
 However, variation in the carotenoid or flavonoid content of

diet could be more important for non-herbivorous species whose diet contains smaller quantities of these compounds. For instance, in aposematic ladybirds (Marples, Van Veelen & Brakefield 1994) the intensity of carotenoid based orange-to-red colour in their elytra is increased with increasing amount of aphids containing carotenoids in their diet (Britton *et al.* 1977; Grill & Moore 1998; Bezzerides *et al.* 2007). Therefore, in the future, more studies are needed where the condition dependence of pigment deposition and possible physiological trade-offs are directly tested by manipulating relevant dietary constituents such as carotenoid, flavonoid or nitrogen content (i.e. amino acid content) of a diet. Before these more targeted empirical tests are possible, more information about the chemical composition of the pigments used by aposematic species is needed. As shown in the *P. plantaginis* case, chemical analysis of aposematic colouration can propose new lines of research into the complex interactions involved in expression of warning signals.

## Acknowledgements

We thank Kevin McGraw and Riitta Julkunen-Tiitto for the valuable advices to pigment analyses and Eira Ihalainen, Sami Merilaita, John Endler, Candy Rowe, Christer Wiklund and anonymous reviewer who commented the text. Hannah Rowland kindly donated her red hairs used for the calibration in pheomelanin analysis. This study was funded by the Academy of Finland under the Finnish Centres of Excellence in Evolutionary Ecology and Evolutionary Research.

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Received 30 November 2009; accepted 21 December 2009

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