The Lesser Purple Emperor butterfly, *Apatura ilia*: from mimesis to biomimetics

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Abstract. Until now, hues as dynamic as those adorning the *Apatura* Emperor butterflies have never been encountered in the painting world. Unlike and unmatched by the chemical pigments traditionally found on the painter's palette, the Emperor's wings are studded with strongly reflecting iridescent scales that are structured like those of the iconic morpho butterflies. The scale ridges act as diffractive multilayers, giving rise to narrow-band reflectance spectra. All scales together create a vividly purple iridescent wing colouration that is observed within a narrow angular range only. Recently, synthetic structures analogous to the multilayer reflectors found on butterfly wings have been developed, referred to as effect pigments. Artists can obtain vital clues on how to adapt and adopt these challenging new materials for painting, by tracing the origin of biomimetics back to the ancient concept of mimesis and building on the knowledge accumulated by optical studies. By selecting various effect pigments, and using the Lesser Purple Emperor butterfly, *Apatura ilia*, as exemplar, we have accurately mimicked the butterfly's iridescence in art. The resulting artwork, like the butterfly, fluctuates in perceived colour depending on the direction of illumination and viewing. These nature-inspired-colouration and biomimetic-application methods extend the canon of art.

Keywords: biophotonics – optical art – colour – multilayers - effect pigments
Short title: Biomimetics of the Lesser Purple Emperor

Introduction

Located at the interface of art and science, and drawing on relevant findings from optical physics and material science, this paper argues that the scientific field of biomimetics has the potential to lead to and enable 'smarter' art. In tracing the origin of biomimetics back to the ancient concept of mimesis (defined by Aristotle as 'imitation of nature' both via form and material), we illuminate analogies that exist between the two concepts. In nature as well as art, colour often plays a key role. For centuries, artists, in their attempts to faithfully render natural appearances, forms and colours, have inevitably drawn on the most suitable materials and ‘technologies’ nature provides. As we will see, new synthetic materials modelled on those occurring in nature are continuously being added to the artist’s palette.

Two types of colouration are usually distinguished, namely pigmentary and structural. Whereas pigmented media emit incident light diffusely, structural coloured objects generally reflect light very directionally, with the colours shifting hue dependent on the direction of illumination and viewing. This so-called iridescence thus is intimately connected to structural colouration.

In art, virtually all colours are generated by chemical pigments, and their use is firmly embedded in painting practice and theory. Structural colours are hardly found in art, however. The search to artificially reproduce natural iridescences began at least 3000 years ago when, as proven by an ancient Chinese document, humans already tried to imitate the lustre of precious pearls by mixing different substances [1]. From the mid-20th century, sustained attempts by industry to synthesise various lead, arsenic and bismuth salts for application as pearl lustre pigments finally came to fruition in the mid 1930s. It has since taken industry a further seventy years, and a succession of pearl lustre pigment-generations, i.e., basic lead carbonate in the 1960s, bismuth oxychloride platelets in the 1970’s, followed by mica/metal oxide platelets since the late 1970’s. Eventually, in the late 1990’s, synthetic multilayered pigments capable of mimicking nature’s iridescent hues were realized [2]. Unlike chemical pigments, the new synthetic, so-called effect pigments, consist of alternating layers of transparent, colourless materials with differing refractive indices. They create colour by wavelength-dependent light interference instead by light absorption, similar as the multilayer reflectors found in pearls and butterflies, for example [3].

Although industry has exploited the novel properties of iridescent flakes for nearly two decades, fine art painting has remained slow to assimilate them. Difficulties in sourcing the materials are partly to blame. Although paints based on first-generation mica technology can now be bought from specialist art suppliers, latest multilayer pigments unfortunately often can only be purchased by industry, are prohibitively expensive and unavailable as artist paints. An additional major hindrance is confusion caused by the incompatibility of the material’s properties with the common colour theory as applied in painting [4]. Centuries of extensive experience with light-absorbing pigments have led to firm rules of subtractive colour mixing. As effect pigments are, as a raw material, a whitish powder (no matter what the colour on the label), it immediately becomes apparent that the rules of easel painting no longer hold. In fact, quite in contrast, styling with transparent, interference-effect pigments is additive, a concept alien to most painters. The central tenet of this paper is, however, that the new technology allows mimicking nature's optical technology. And that systematic analysis of the mechanisms causing iridescent colour-mixes in animals can inspire analogous artistic methods.

Gradually introduced since the late 1990's, the principal author of the present paper has since adapted and adopted effect pigments in fine art painting [5]. Building on earlier work on liquid crystals [6,7], Schenk has demonstrated that the considerable challenges posed by the new technology can be overcome by adopting a biomimetic approach [5,8,9]. For instance, the angle-dependent colours of jewel beetles could be faithfully mimicked in large-scale paintings [10].

As will be shown in this paper, due to the unique expertise thus gained, it has become possible to simulate the dynamic, metallic-like colouration of butterflies on canvas. Perhaps most notably, *Morpho* butterflies, a subfamily of the Nymphalidae, are famous for their bright blue coloured wings. Their wings are covered by scales, which have an upper lamina consisting of ridges that act as optical multilayer reflectors. Due to interference, the multilayers reflect incident light in a narrow (blue) wavelength range and into a narrow spatial angle [11,12]. The identical optical mechanism causes the iridescent blue colouration displayed by many butterfly species belonging to another nymphalid subfamily, the Apaturinae (the Emperors). These beautiful butterflies combine iridescent, structural colours with pigmentary colouration,

Fig. 1. The Lesser Purple Emperor butterfly, *Apatura ilia* (male). **A** UV image. **B**, **C** RGB images. **A**, **B** About normal illumination. **C** Oblique illumination. Scale bar: 2 cm

Here we put at the centre stage the Lesser Purple Emperor (*Apatura ilia*; Fig. 1), a butterfly species that has featured in several classical paintings. We first present the optical characteristics of this butterfly, and subsequently hone in on particular historical moments during which *A. ilia* has come to short-lived prominence in works of art, such as in late Antiquity, the Baroque and the Contemporary. To introduce how we have attempted to artistically reproduce *A. ilia*'s rich gamut of colours, we analyse a number of effect pigments suitable for our goal. We finally describe the procedures allowing to faithfully apply the novel medium in art.

Optical characteristics of wings and wing scales of *Apatura ilia*

The butterfly species *Apatura ilia* (Denis et Schiffermüller, 1775) is distributed in riparian forests from Europe to the Amur region in Pacific Asia. In the whole range, two phenotypes exist: dark *forma ilia* and light *forma clytie*. The dark phenotype mainly occurs in cooler regions, where the larval development is long, while the light phenotype inhabits warmer habitats, where the caterpillars grow faster [13]. All members of the genus are sexual dimorphic, with only the males displaying iridescent colouration on the dorsal wing side. The structural colour of males is visible in flight when the movements of the wings are noticeable within a certain range of angles, thus forming an excellent contrast to the forest canopy.

The optical phenomena are readily explained by the architecture of the wing scales. Scanning and transmission electron microscopy demonstrated that the iridescence resides in the cover scales. Their scale ridges consist of a stack of chitinous lamellae interspersed with air layers, so creating a multilayer reflector [14]. The multilayered cover scales are found across the entirety of the dorsal forewings and part of the hindwings, as is revealed by UV photography (Fig. 1A). These cover scales are transparent for incident light with wavelengths in the visible range, which hence will reach the underlying ground scales (Fig. 1B). The ground scales contain various amounts of melanin pigment, as is most clearly seen when applying oblique illumination, so that the iridescence is outside the camera's aperture (Fig. 1C). In areas where the pigment density is high, the ground scales function as a strongly absorbing, non-reflecting backing, so that with normal illumination only bright ultraviolet to blue reflections are seen, but in areas with low pigment density, part of the light that passed the cover scales will be reflected by the ground scales and thus will add to the visual signal, leaving light blue to whitish reflections (Fig. 1B).

We also studied the spatial reflection properties of single cover scales by applying imaging scatterometry [10,15]. To this end, the scales were isolated from the wing and glued to a thin glass micropipette (Fig. 2A,B). Illumination of the upper side of a cover scale with a narrow aperture beam of white light yields a purplish reflection, similar as seen at the intact wings (Fig. 2C). The scatterogram appears to be restricted to about a planar spatial distribution (Fig. 2C), closely resembling the scatterograms obtained from *Morpho* cover scales [15]. This is due to the ridges of the scale's upper lamina acting as long and slender multilayers, diffracting light into a plane almost perpendicular to the long axis of the ridges [12]. The scale's lower lamina approximates a thin plate with a bluish reflection (Fig. 2D). Its scatterogram is restricted to about a single spatial direction (Fig. 2E), showing that the lower lamina acts as a blue reflecting thin film, which further enhances the scale's violet-blue-peaking reflectance.

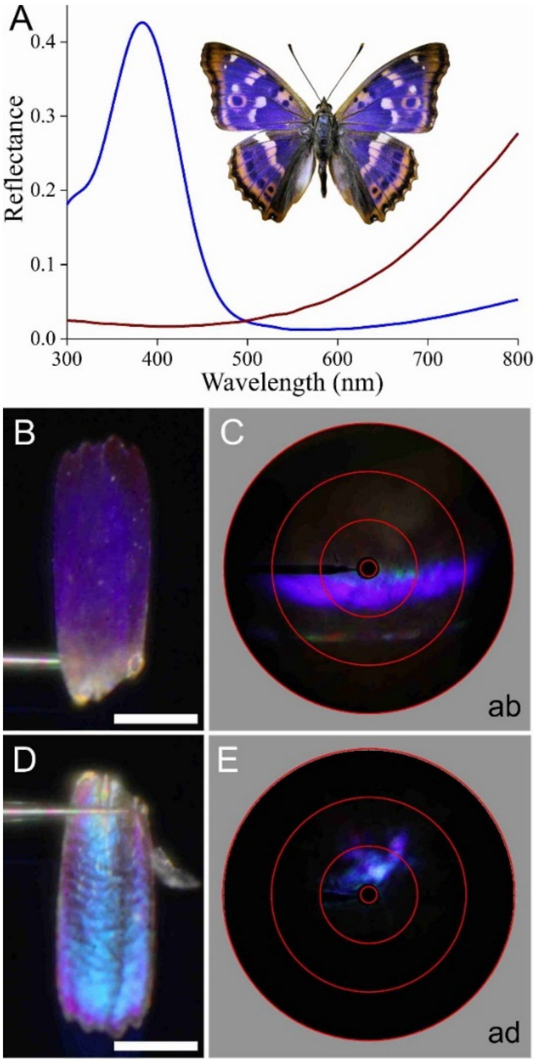

Fig. 2. Spectrophotometry and scatterometry of *A. ilia* wings and scales. **A** Reflectance spectra measured with a bifurcated reflection probe of the dorsal forewing with illumination about normal and obliquely to the scale multilayers (blue and brown curves, respectively). **B** An isolated cover scale photographed at the abwing (upper) side. **C** Scatterogram of the abwing side of the scale of **B**. **D** The scale of **B** seen at the adwing (lower) side. **E** Scatterogram of the adwing side of the scale of **D**.

Historic attempts to mimic *Apatura ilia* and iridescence in art

Apatura ilia acquired its scientific name only in the 18th century. Fabricius, the Danish entomologist who christened the species, apparently made up *Apatura* based on the Greek apatao, meaning to deceive, so possibly attempting a learned joke by inventing pseudo-Greek nomenclature to hint at, and employ, deception (Ref. 16, pp. 140-141). The male Lesser Purple Emperor’s mantle is somber brown one minute and the next an electric brilliant purple, indeed a matter of ‘now you see it, now you don’t’. Arguably, it may precisely be this dual quality of alternately concealing and revealing the underlying darkness that has made, and continues to make, the Emperors a symbol most apt for inclusion in a particular genre of art, namely the *momento mori*, the Latin phrase for “remember you will die”, that originated in ancient Rome.

Fig 3. *Momento Mori*, Pompeii (House cum workshop I, 5, 2, triclinium), 30 BCE-14CE, Inv. No. 109982, Napels National Archaeological Museum. **A** The complete mosaic. **B** Detail. (from https://pompeiitourguide.me/2013/07/30/memento-mori-at-pompeii/)

An emblem most striking for the clarity of its allegorical representation was excavated from the ruins of Pompeii beneath the volcanic ash in 79 AD (Fig. 3A). Sandwiched between a skull and wheel is a butterfly with what appear to be iridescent purple wings. Although Marren (Ref. 16, p. 159) identified the butterfly as the Lesser Purple Emperor, *Apatura ilia*, and particularly the phenotype *Apatura ilia f. clytie*, the actual specimen differs distinctly in the number of eyespots (Fig. 1, 3). Clearly some artistic licence has been taken here, possibly to create the illusion of the eyes following round the viewer.

Most likely it was the gem-like purple colouration that singled out *Apatura* for inclusion in Ancient art, adorned as they are with a colouration resembling that of the amethyst. For according to Pliny, it is the amethyst that displays the best purple of all [17][1]. Apparently, the Ancients, in their search for the best purple dyestuff, were looking for a gem-like lustre 'the colour of clotted blood, dark by reflected, and brilliant by transmitted light [18][2]. However, not even purple of Tyre, the most precious of Ancient dye, which is based on chemical dyes, equals the iridescent lustre displayed by the Lesser Purple Emperor. Only amethyst comes close, owing to its violet colour created by impurities of iron suspended in an otherwise transparent quartz crystal nanostructure [19].

In the Pompeiian floor mosaic, *Apatura*'s gem-like quality was captured not via brushstrokes of purple dye, but via the use of small cubes, some of which made of coloured glass; the latter were beginning to be manufactured at the time in order to mimic precious stone and iridescence alike [20]. To suggest the wings' iridescent colour-play, tesserae, small tiles usually formed in the shape of a cube, were selected that gradually transitioned from a light orange to a deep ruby and dark purple. Although, to our knowledge, no material analysis has been conducted on this particular mosaic, archeometric investigations conducted on comparable Pompeiian mosaics suggest that the opaque oranges and reds might perhaps be due to cuprite (copper) aggregates dispersed in a lead-rich matrix and that the presence of manganese in a soda-lime-silica glass matrix creates the more translucent deep purples [21]. At the time, glass manufacture underwent rapid innovation and growth, enabling and triggering a new emphasis on clear and translucent coloured varieties, the latter affording a much higher degree of gem-like depth and lustre [22].

[1] Following Classical precedence, Bede characterizes the purple amethyst as emblematic of Heaven. This heavenly connotation of purple passed during the Middle Ages increasingly to blue, especially in its precious form of lapis lazuli, although the purple cast of this latter was prized as late as the fourteenth century; see Ref. 16, p. 73.

[2] Pliny, Natural History, IX, xxxvi, 126, in Ref. 9, p. 222.

These early developments in glass making in turn kick-started a century-long quest by the Romans to imitate the jewel-like quality of iridescence, as is evidenced by the famous Lycurgus Cup of the 4th Century AD. Arguably the pinnacle of Roman glass-technology, the cup is dichroic. In direct light it resembles jade, but in transmitted light it turns to a translucent blood-red ruby colour. Actually, unbeknown to the Romans themselves, they were nanotechnology pioneers, because colloidal silver-gold alloy nano-particles were generated via heat-treating a suspension of minute amounts of gold and silver in a soda-lime-silica glass matrix coloured with manganese [23].

Butterflies have been mostly absent from high art during the Middle Ages, but made a temporary return to prominence in the 17th century in the context of the Vanitas still-life genre, a thoroughly Baroque take o n the Roman *momento mori*. In 1618, Marchello Provenzalle (1575-1639) used small glass stones in an attempt to mimic iridescence [24]. Resembling green bottled glass, these particular stones emitted green 'flames' owing to an additional distinguishing feature: they were facetted like diamonds. In these 'structurally coloured' tesserae, it is the stone's structure that causes a beam-like reflection, with pigments playing a filtering role.

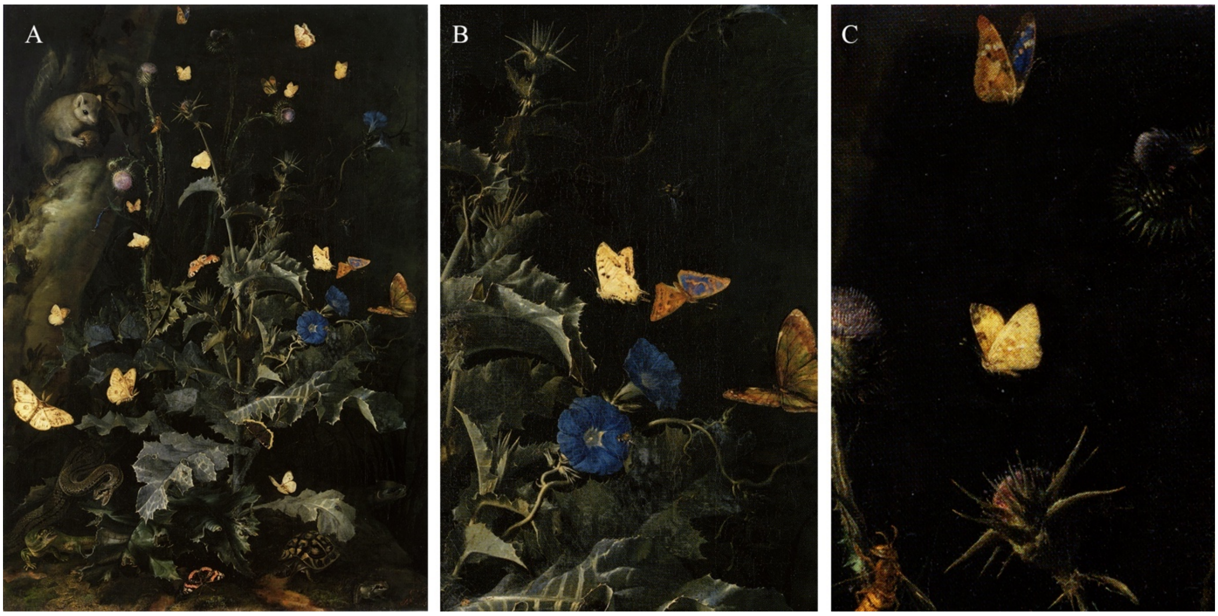

Fig. 4. Painting featuring *A. ilia*. Otto Marseus van Schrieck, 'The Large Thistle', c.1670, canvas, 132.6 x 93.5cm , Munich, Alte Pinakothek, Inv.no. 1966 **A** The complete canvas. **B** Detail one. **C** Detail two.

The Amsterdam painter Otto Marseus van Schrieck (c. 1620-1678) included *Apatura ilia* and many other butterflies in his 'forest floor' still-lifes (Fig. 4). In particular the arrival of the microscope, a novel tool used by Marseus van Schrieck to conduct animal and plant studies in preparation for his paintings, does echo the era's newfound fascination with the infinitesimal [25]. In fact, when depicting butterflies, he pressed butterfly wings into the wet paint, embedding their scales into the canvas so that the insect's natural iridescence became part of the work (Carroll, 2017; https://www.nybooks.com/daily/2017/11/15/marseus-in-the-land-of-snakes/). In the absence of suitable paints, butterfly iridescence was reproduced by using actual iridescent butterfly wings.

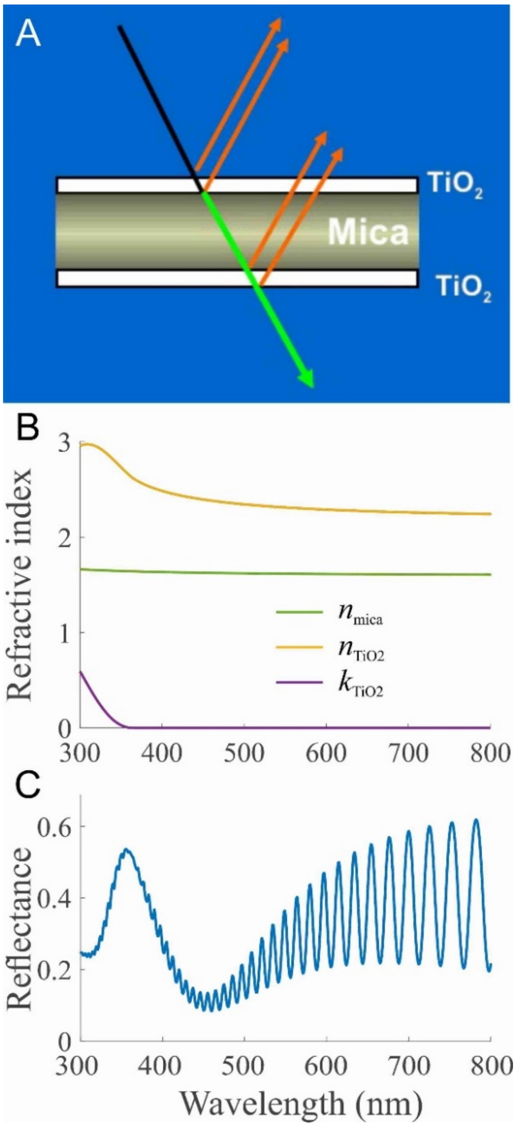

Fig. 5. Modelling the reflectance of a mica-flake. **A** Schematic flake of mica with on both sides a TiO_2 thin film. **B** Real parts of the refractive indices, *n*, of mica and TiO_2, and the imaginary part, *k*, of TiO_2 as a function of wavelength (from https://www.filmetrics.com/refractive-index-database/TiO2+-+Amorphous/Titanium-Dioxide). **C** Reflectance spectrum of a mica flake with variable thickness between 5.9 and 6.0 µm, with on both sides 95 nm thick TiO_2 thin films in air.

Mimicking *Apatura ilia*'s iridescence

Adopting a biomimetic approach, the scientific data on *A. ilia*'s colour mechanisms presented above was drawn on to arrive at vital clues on how to best reproduce the butterfly in painting. The various attempts and procedures leading to this result are described below. To faithfully reproduce the colour of *A. ilia*, the most suitable multilayer pigments currently available were investigated. We hereby considered that nature's metallic-looking reflectors are non-metallic, i.e. they consist of dielectric materials that are often colour-less and transparent. Hence, while special effect pigments do exist that are based on metal (i.e. metallic effect pigments), we instead focused our search for suitable materials on pearlescent technology and the respective pigment lines. The multilayer reflectors present in butterfly wing scales consist of alternating thin plates of chitin and air, which have refractive indices of about 1.6 and 1.0, respectively [26]. To achieve a high reflectance of a wing scale then requires several layers. The cover scales of *A. ilia* therefore have 5-6 overlapping lamellae, meaning 10-12 layers [27] (some morphos have even scales with up to >10 stacked lamellae [12]).

In effect pigments, however, materials with a very high refractive index are selected. For instance, the (real part of the) refractive index of TiO_2 is 2.3-2.5 in the visible wavelength range, which makes it a highly powerful candidate for strongly reflecting materials, because a high reflectance can already be realized with a few layers (Fig. 5). As an example, a mica-flake (refractive index ~1.6) with thickness varying between 5.9 and 6.0 µm and on both sides a 95 nm thick TiO_2 thin film creates a high reflectance peaking at ~400 nm; the high frequency modulation is due to the total thickness of the flake of ~6 µm (Fig. 5).

To mimic the violet colouration of *A. ilia*, we investigated a number of violet interference 'pigments', each based on a different substrate, and each belonging to a different effect pigment family. Firstly, Pyrisma® Color Space Violet is an effect pigment based on a natural mica flake coated with a specially developed layer of titanium dioxide, together with a narrow particle size distribution (5-35 µm). Xirallic® Amethyst Dream, on the other hand, belongs to a transparent 'High Chroma Crystal Effect Pigment' family based on aluminum oxide flakes (alumina flakes), produced using a crystal growth process. The extraordinary colour purity and transparency of the resulting pigments obtained by coating Al_2O_3-flakes with high-refractive metal oxides (in this instance with titanium dioxide) can be attributed to the synthesis procedure yielding single-crystalline thin flakes. The pigment, possessing a narrow particle size distribution of about 5 to 30 µm as well as a high aspect ratio, displays an intensive glitter effect - the so-called crystal effect or sparkle. Previously, the resulting sparkle effect could not be achieved with small-sized effect pigments. In contrast, Firemist® Violet, while also a sparkle pigment, relies on a smooth surface and larger particle-size distribution (5-300 μm) to create a brilliant, star-like glitter. Based on TiO_2-coated borosilicate glass-flakes, Firemist® Violet combines both unique colour purity with high transparency, intensive light reflection and noticeable narrowband colour travel.

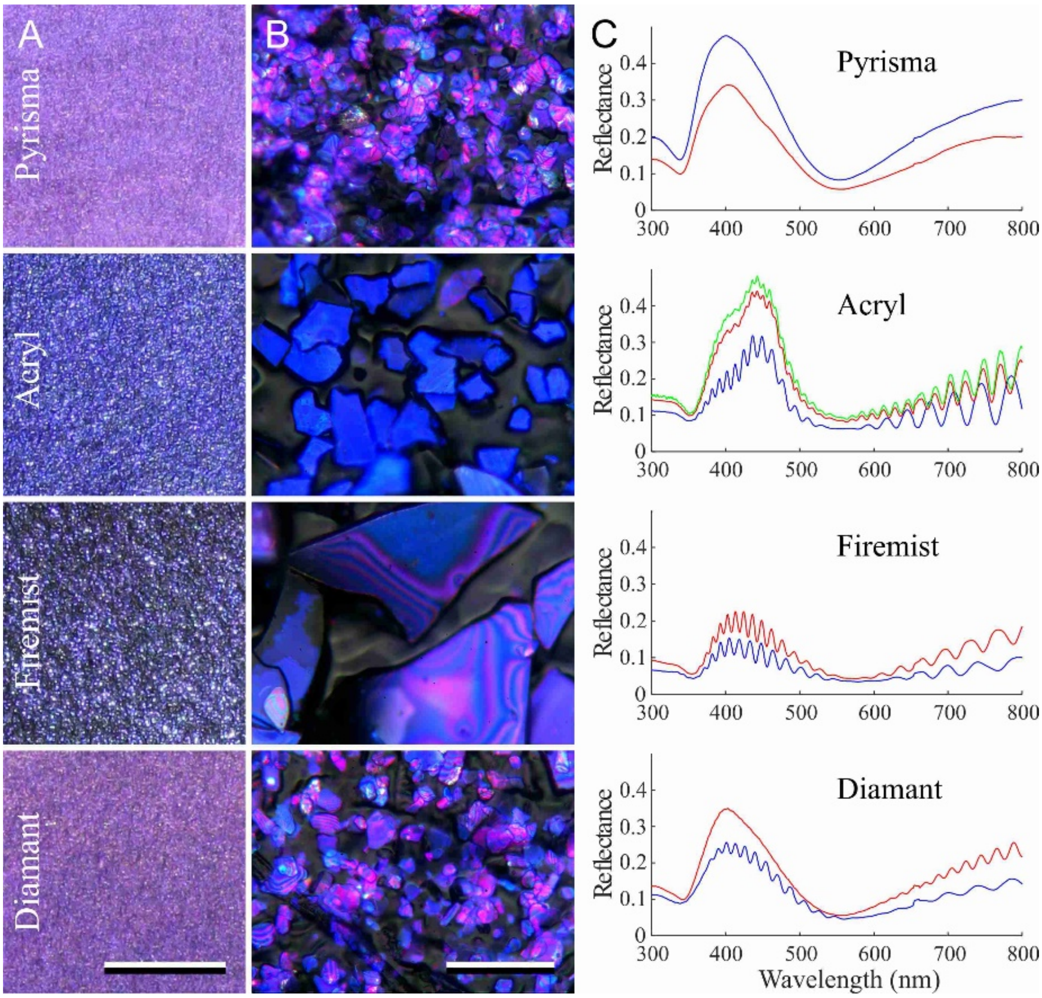

Fig. 6. Photographs and reflectance spectra of four effect pigments, i.e. Pyrisma (Color Space Violet), Acryl (Helicone Sapphire), Firemist (Violet), and Diamant (Xirallic Amethyst Dream). **A** The pigments on black paper. **B** Micrographs showing the flaky composition of the effect paints. **C** Reflectance spectra measured with a bifurcated reflection probe from various areas of **A**. Scale bars: **A** 10 mm, **B** 0.1 mm.

In addition, we investigated another type of interference Acryl-glass pigment, LCP Helicone® Sapphire, which incidentally belongs to the first ever effect pigment family (introduced in the mid 1990's) to generate distinct angle-dependent colour effects. A subtle point to be emphasised here is that the Helicone® effect pigments are not classical thin-film multilayer reflectors, but a subtype based on liquid-crystal polymers (LCP), known as cholesteric effect pigments. Unlike thin-film multilayers, LCP's do not consist of alternating layers of two or more isotropic materials, but instead the helicoidal orientation of a single type of a birefringent unit provides the change in refractive index necessary for reflectivity [3]. In other words, while cholesteric pigments also take the form of a transparent, colourless layered platelet, here all layers are composed of the same material, namely a highly cross-linked, liquid crystalline organic polymer with a helical superstructure, the pitch of which determines the reflected colour.

We selected four effect pigments that produced colourations resembling that of our butterfly, Pyrisma (Color Space Violet), Acryl (Helicone Sapphire), Firemist (Violet), and Diamant (Xirallic Amethyst Dream), and prepared paint samples on black paper (Fig. 6A). Micrographs show that the flake size considerably varies between the different materials (Fig. 6B). The reflectance spectra measured from the different samples compared with those from the butterflies confirm that the iridescent colouration of *A. ilia* can indeed be matched (Fig. 6C).

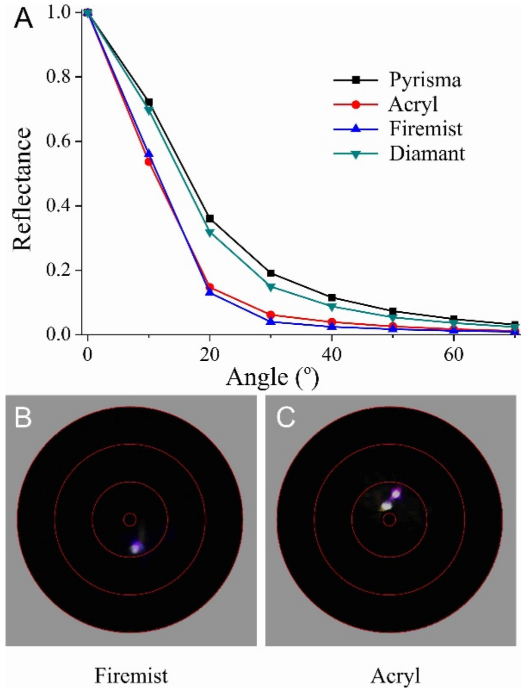

Fig. 7. Angle dependence of the reflectance of the effect pigments and imaging scatterometry. **A** Reflectance as a function of angle of reflection of normally illuminated paint samples. **B** Scatterograms of Firemist- and Acryl/Helicone-samples created by local illumination with a narrow aperture white light beam.

To quantify the spatial properties of the effect pigments, we applied angle-dependent reflectance measurements. Normal illumination with a narrow-aperture light beam and then measuring the reflectance at the sample's peak wavelength as a function of the angle of reflection yielded reflected light distributions with full width at half maximum between 20º and 30º, demonstrating that the reflections are very directionally indeed (Fig. 7A). Actually, imaging scatterometry showed that very local illuminations with a narrow-aperture beam create almost perfect specular reflections (Fig. 7B). However, the directions appeared to depend on the location, clearly being the consequence of the variability in the planar orientation of the flakes (Fig. 6B), as is also illustrated by Fig. 7C, where two flakes were hit by the light beam. The not fully specular reflections of the pigment samples are clearly the result of the not fully planar orientation of the flakes in the samples.

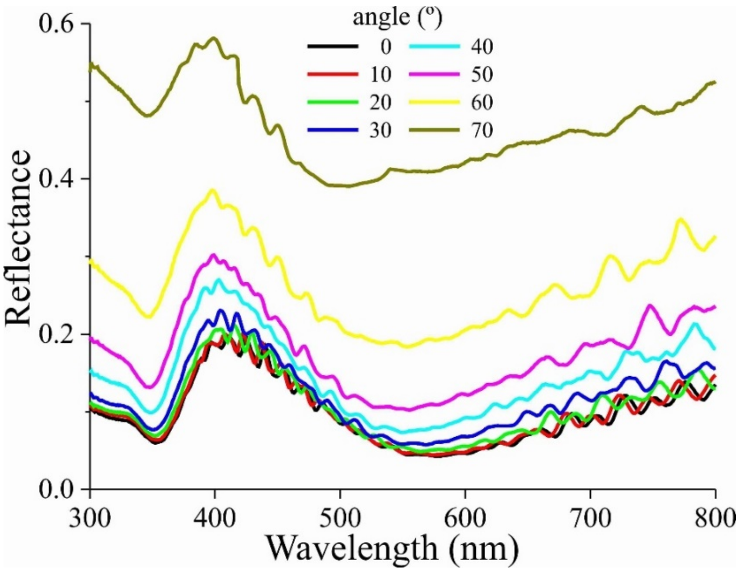

Fig. 8. Angle-dependent reflectance of Firemist at black paper measured with two fibers positioned mirror-wise, i.e. one fiber delivered the light and the other fiber was in the mirror position.

Figure 8 presents reflectance spectra as a function of angle of light incidence for the Firemist sample. We measured the reflectance in the mirror angle for both TE-(transverse electric) and TM-(transverse magnetic) polarised light, which showed the classical behaviour that the reflectance of TE-polarised light steadily increases with the angle of incidence, while the reflectance of TM-polarised light stays low over a large spatial angle. As the human eye is incapable of polarisation vision, we averaged the TE- and TM-spectra (Fig. 8). As expected from classical multilayer theory, the spectra shift to the shorter wavelengths with increasing angle of light incidence. Because the diameter of the detection area was ~0.5 cm, the signal was also the average of numerous flakes. The spectra nevertheless feature a clear ripple, indicating that the dimensions and orientations of the flakes are still rather uniform.

The role of reflecting structures and absorbing pigments in *A. ilia*

An important point to reiterate here is that in many butterflies both structures and pigments contribute to the visual signal. This is the case in the male *A. ilia*, as mentioned above. The scale coat on the butterfly's dorsal forewings consists of pigmentary ground scales overlayered with structurally-coloured cover scales. All cover scales strongly reflect UV-blue light, and the ground scales will partly reflect and backscatter the incident light, depending on their melanin concentration (Fig. 1). The light flux reflected by the wing hence is the sum of the reflections of the cover and ground scales. In the eye spots, where the ground scales are strongly pigmented (and therefore black), normal illumination causes a deep-blue colour due to only the cover scale reflections. However, in the wing areas that are distinctly white with oblique illumination, the ground scales are unpigmented, so that the reflection with normal illumination consists of reflected light emerging from both the cover and ground scales, resulting in a very faint blue-white. With intermediate pigmentation of the ground scales, the reflections are blue-orange or blue-brown, overall resulting in a distinctly-patterned wing-display (Fig. 1).

Similar cases have been studied in other butterflies. Most morphos feature more or less homogeneous blue-reflecting wings, due to a backing of melanin below the strongly reflecting scale ridges, but *Morpho cypris* features a striped wing pattern, due to selective areas with strongly pigmented vs unpigmented scales [28]. In the blue wing areas of nymphaline butterflies, the lower lamina of the cover scales acts as a blue-reflecting thin film and the ground scales are black due to a high melanin content. Yet, the same cover scales when backed by unpigmented ground scales result in whitish wing areas [29].

The final artwork

In order to accurately replicate *A. ilia* in painting, we need to realise that the pigmentary colouration of a material always exists due to the medium's inhomogeneities that reflect and scatter the incident light, which is in turn selectively absorbed by the embedded pigment, so that only the non-absorbed, backscattered light is observed. Structural colouration, however, exists only when the material contains inhomogeneities with nanoscale dimensions, which then reflect light in a specific wavelength range due to interference. Hence for our replication two types of materials had to be combined: 1) paints based on chemical pigments, and 2) structurally-coloured materials.

To fully mimic *A. ilia*’s dynamic on-off colour display, firstly, a detailed underpainting was created. Traditional pigment-based paints were used to replicate in meticulous detail the entire wing pattern, which, for example, includes eyespots and white bands. Subsequently this pigmentary base was then overpainted with various layers of UV-blue reflecting interference paint. Both LCP Helicone® Sapphire and Firemist® Violet flakes were incorporated into the final paint that was specially formulated for this particular purpose. In the process, areas of differing pigmentary background colour (ranging from white to orange and brown to black) were overlaid with the same blue-violet interference flake mix.

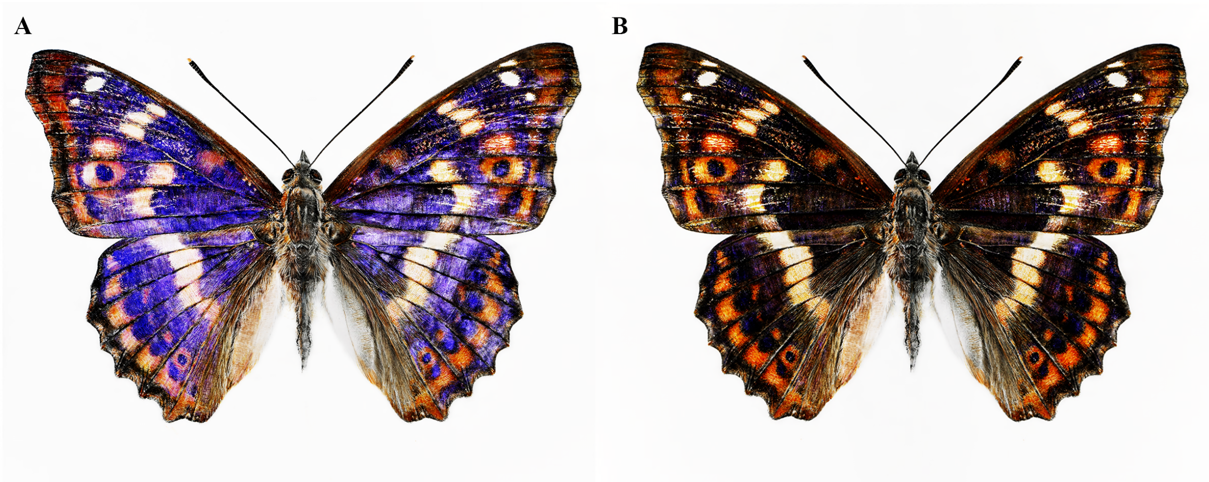

Fig. 9. The final painting (160 x 185 cm), © F. Schenk. **A** About normal illumination. **B** Oblique illumination.

The resulting optical effects indeed perfectly matched what can be observed in the actual *A. ilia* specimen (Fig. 9). For example, depending on the viewing angle, the centre of an eyespot appears either intensely blue (Fig. 9A) or turns into a pure black ‘pupil’ (Fig. 9B), due to the blue-reflection generated by the effect pigment flakes switching on and off to conceal/reveal the strongly absorbing black background below. In other areas with a brown pigmented ground, the reflection colour shifts further towards violet; and on orange further towards pink-red.

If one observes in the painting the white bands adorning *A. ilia’s* dorsal wings, the resulting effect is that the angle-dependent blue-violet reflection switches on and off to reveal a muted yellow-green underneath (Fig. 9A, B). The interference flakes’ layered structure effectively reflects light in the blue-violet wavelength range, but light with longer wavelengths is transmitted and then reaches the white ground, which thus yields a yellow-green back scattering. Thus, both light components become visible. At face angle we see a blue-violet reflection and at oblique angle its complementary transmission colour – the yellow-green. Evidently, the ultimate colour effect does much depend on what lies below the reflector. Depending on the background's hue and tonal value, the same narrowband structure can produce vivid pure metallic-like effects, and subtle two-colour opalescence.

Conclusion

To arrive at the final artwork, in the absence of ready-made paints and rules of application, the flakes selected had to initially be turned into paint suitable for fine art application. Only once an appropriate binder and formula had been found was it possible to consider potential artistic strategies, eventually pinpointing "old-masterly" techniques as a possible way forward. Incidentally, so-called "traditional" methods (e.g. involving a tonal "under-painting" overlaid with semi-transparent glazes) are most in keeping with the complex layering present in *A. ilia*, where the overall colour pattern displayed is due to differing hues and tones of melanin overlaid with the same structural colour. Notably, as colour mixing is at work here, the pigmentary base is crucial in determining the overall colour effect.

With this in mind, as a first step, a detailed pigmented "under-painting" of the butterfly's dorsal side was created, also featuring a textured surface. Finally, drawing on our optical measurements, this was overlaid with iridescent paint based on the most suitable effect pigment mix selected to fully mimic *A. ilia*'s colouration. Satisfactorily, the final painting (Fig. 9), just like the model (Fig. 1), changes with every minute variation of the angle of light incidence and viewing. This introduces a fully novel element of change, movement and transience into the medium of painting, which traditionally is inert and static.

In conclusion, whereas artists have been able to reproduce pigmentary colours in paintings since human's earliest memory, until now this has not been the case for structural colours. The example of *A. ilia* demonstrates that, with the help of latest iridescent colour technology, biological structural colours can finally be simulated in painting. Effect pigments, based on light interference, when used as paint are beginning to open up a completely new era of artistic activity. Thus, for the first time, an important segment of natural reflection can be recreated in art, potentially leading to novel artistic expressions and experiences.

It is hoped that this overview of pearlescent effect pigments, together with the associated optical principles introduced, will provide artists with the intimate specialist knowledge essential to take full advantage of the manifold creative opportunities the technology has to offer, encouraging them to extend both their palette and repertoire. By harking back to the exemplar of the Renaissance painter as chemist, material scientist and, in this case, physicist, future generations of painters will inevitably develop diverse and imaginative ways in which to creatively employ this emerging technology. Basic ground rules for artistic application derived from biomimetics will, no doubt, further aid this process, thus helping to overcome the major challenges interference flakes continue to present to the contemporary painter. For, given time and continued research, iridescent colour technology has the potential to revolutionise fine art painting.

Acknowledgements

This study was financially supported by AFOSR/EOARD grant FA9550-15-1-0068 (to DGS).

Conflicts of interest

There are no conflicts to declare.

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