Biomimetics, Color and the Arts

Franziska Schenk, Birmingham City University, Birmingham, UK[1]

ABSTRACT

Color as dramatic, dynamic and dazzling as the iridescent hues on the wings of certain butterflies has never been encountered in the art world. Unlike and unmatched by the chemical pigments of the artists' palette, this changeable color is created by transparent, colorless nanostructures that, as with prisms, diffract and reflect light to render spectral color visible. Until now, iridescent colors, by their very nature, have defied artists' best efforts to fully capture these rainbow hues. Now, for the first time, the artist and researcher Franziska Schenk employs latest nature-inspired color-shift technology to actually simulate the iridescence of butterflies and beetles on canvas. Crucially, studying the ingenious ways in which a range of such displays are created by insects has provided the artist with vital clues on how to adapt and adopt these challenging optical nano-materials for painting. And indeed, after years of meticulous and painstaking research both in the lab and studio, the desired effect is achieved. The resulting paintings, like an iridescent insect, do in fact fluctuate in perceived color - depending on the light and viewing angle. In tracing the artist's respective biomimetic approach, the paper not only provides an insight into the new color technology's evolution and innovative artistic possibilities, but also suggests what artists can learn from nature.

Biomimetics, biophotonics, optical devises, special effect pigments, iridescence, color, fine art, painting

1. PIGMENTARY AND STRUCTURAL COLORATION

In pictorial art, pigments have been used since time immemorial. However, natural colors are not only of pigmentary (or chemical) origin, but often have a physical (or structural) basis [1]. The mechanisms causing each type of coloration are fundamentally different. A substance containing pigments, such as paint, is a light-scattering material in which a certain chemical component selectively absorbs in a specific section of the visible wavelength range. [2] The color impression, the remaining part of the light, changes neither hue nor brightness, even when viewed from different angles. Structural color, on the other hand, is caused by light interacting with transparent, colorless nanostructures that selectively reflect light in a certain wavelength range. Here colors are made visible via the optical phenomenon of light interference, resulting in a color that changes with the direction of illumination and viewing angle. Although numerous attempts have been made to capture the visual impression of structurally colored animals in painting: "… colors of this type, by their very nature, defy our best efforts at visual reproduction." [3]

However, thanks to sustained scientific research into nature's iridescence-causing microstructures, the eye-catching optical effects of structural color can now finally be introduced into painting. The development and manufacture of synthetic reflectors, notably the latest multilayer interference flakes, has recently led to a technology that offers artists the potential opportunity to accurately depict nature's iridescence. [4] Interweaving the findings of optical physics, material science and artistic studio practice, Schenk demonstrates here that the study of nature's ingenious color-generating mechanisms can indeed aid artistic innovation and application.

2. BIOMIMETIC NANO-PAINTS

2.1 Evolution of iridescent Nano-paints

For millennia the 'stable' colors, associated with chemical pigments, have been the preoccupations of painters. The rainbow, on the other hand, remained mysterious until the seventeenth century when Newton famously united light and color through

1 franziska.schenk@bcu.ac.uk, www.franziskaschenk.co.uk

his prism experiment, proving that white light consists of all the colors of the spectrum. The changeable hues of bird feathers have kept their secrets much longer. Only in the mid-twentieth century did science verify beyond doubt what the Ancients had intuitively believed, namely that the colors of the rainbow and iridescence (a term evoking Iris, the winged messenger of the Olympic Gods and personification of the rainbow) are inextricably linked. Both phenomena are caused by light interacting with transparent colorless matter. A rainbow is created when the water droplets, like Newton's prism, split white light into its components – the colors of the spectrum. Newton concluded that the angle-dependent colors of birds' feathers must be equally due to light splitters (i.e. thin films), but did not comprehend the precise color producing mechanism [5]. In the1950's electron microscopy, enabling nanoscale observations, finally ascertained that the iridescence, for example, of humming birds is indeed produced by what effectively equates to a stack of thin-films [6]. Here spectral colors are made visible via the optical phenomenon of constructive interference resulting in color that changes with the direction of illumination and viewing angle.

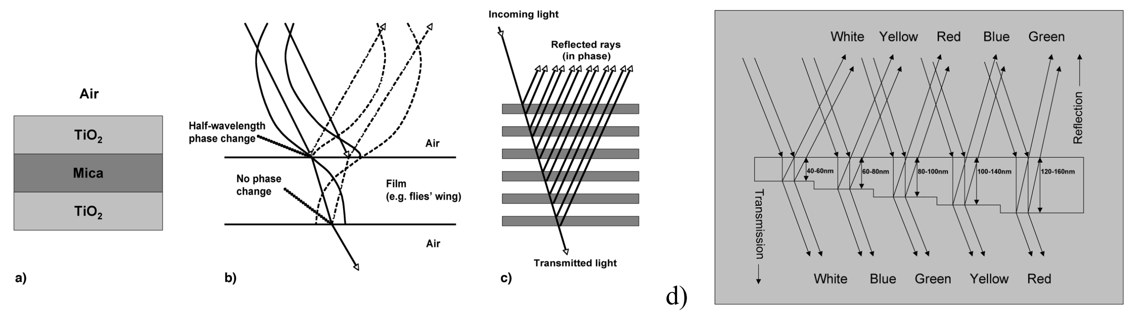

Figure 1. Schematic diagrams of thin-film reflectors: a) TiO2-mica platelet b) single layer reflector c) narroband multilayer reflector d) achieving a range of interference colors: the reflection color is determined by the TiO2-layer's thickness

As can be expected this gem-like color, closely resembling that of precious stones and metals, when finally resolved by science, kindled a 'gold rush' in industry. From the mid-20th century the race was on to develop commercially viable synthetic versions. Sustained attempts by industry to synthesise various lead, arsenic and bismuth salts for application as pearl lustre pigments had finally come to fruition in the mid 1930s. But, while a major advance at the time, 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 (fig.1a,b,d), to eventually arrive at synthetic multi-layered nano-particles capable of mimicking nature's iridescent hues (fig. 1 c). [7] Unlike chemical pigments, the latter do indeed resemble the multilayer reflectors found in, for example, birds and insects. Also consisting of alternating layers of transparent, color-less materials with differing refractive indices, the platelets in question reflect and transmit light instead of absorbing it, creating color by interference. [8] Gradually introduced since the late 1990's, Schenk has since worked on converting these challenging materials for fine art painting.[4] [9]

2.2 Towards a Biomimetic Approach to Painting

Although industry has exploited the novel properties of iridescent flakes for a couple of decades now, fine art painting has been slow to assimilate them. Non-toxic and fade-resistant, the materials outstanding purity, brilliancy and innovative optics have led to a fast rise to prominence in the car, cosmetics and plastics industries. However, so far, the technology appears to have bypassed fine art painting. 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. The major apparent hindrance, however, is the incompatibility with – and the resulting confusion caused by the material's non-adherence to – color theory as applied in painting [10]. Centuries of extensive experience with light-absorbing pigments have led to firm rules of subtractive colorant mixing. When faced with the raw material, a whitish powder (no matter what the color 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 mimics nature's technology. As a result, systematic analysis of the mechanisms that cause iridescent color-mixes in animals can inspire analogous artistic methods. And indeed, building on findings on liquid crystals [11], previous work by Schenk has demonstrated that the considerable challenges posed by the technology can be overcome by adopting a biomimetic approach. [12][2] As will be shown in this paper, due to the unique expertise thus gained it has become for the first time possible to simulate the dynamic, rainbow-like coloration of marine creatures, butterlies and beetles on canvas.

3. THE BIOMIMETICS OF PAINTING

3.1 Cameleonesque Color: The Color of Change

It was in 1999 that the novel color-technology first came to Schenk's attention - in a chance conversation at the opening of 'Beginnings' (Schenk's group show at Whitworth Gallery, Manchester, UK). At the time the artist was working on a series inspired by the chameleon's subtleties of transformation. A representative from a leading pigment manufacturer suggested latest color-shift flakes might be pertinent. Having been provided with the flakes by the manufacturer it, in fact, subsequently took the artist several years to gain a basic understanding of the optical principles involved and transform the raw material, ironically a grey powder, into a medium suitable for painting [13].

By 2004 Schenk was finally ready to introduce the new technology into her work. While artist in residence at the National Marine Aquarium Plymouth, UK she had, with increasing fascination, observed that unsung hero, the cuttlefish. Perpetually metamorphosing, this 'Chameleon of the Sea' features a continuously changing display of kaleidoscopic color, pattern and texture. In an instant, waves of color can flow across its entire body, changing hue from maybe green to violet and back again - a dynamic flow of oscillating color never seen in painting. Here color has become a complex language [14] supported by a color 'technology' so sophisticated that it equals, if not surpasses, that of our digital age [15]. In loose analogy to a television screen, cuttlefish skin contains individually adjustable 'sub-dots'/cells. These cells are (chemical) primary-color-units that switch on (expand) and switch off (contract), or remain in between, thus (in combination) assuming any color desired via optical mixing. In addition, iridescent 'mirror' cells reflect colors from the surroundings.

But how can one 'represent' such an elusive (or rather illusive) creature in painting? This 'fugitive' in ever-changing disguise perhaps makes most sense in the context of a series, in which each 'individual' image mirrors one of its many appearances. However, with color-variable nano-particles on the artist's palette now, it for the fist time seemed possible to create color-variable paintings. A subtype of multi-layer reflector, the Colorstream® flakes in question, feature layers of varying thickness, each reflecting a different wavelength, thus generating a flow of color that, for example, shifts from green to violet and back again (fig. 2b).

Meticulous and time-consuming research on Schenk's part eventually led to a triptych, 'representing' the cuttlefish in its many guises. The desired 'chameleonesque' effect was achieved. The resulting paintings fluctuate in perceived color, depending both on light variation and the angle of vision[3].

3.2 Butterfly Blue

Captivated by their ephemeral beauty, fragility and capacity for continuous transformation, Schenk turned her attention to butterflies – initially as Artist in Residence at London's Natural History Musuem (2007) and subsquently at the University of

---

[2] Philip Ball has since referred to this work in *Scientific America*, 306:2012, 74 and also the accompanying online feature: *Paintings made with iridescent nanopaints change color on the spot*: http://www.scientificamerican.com/article.cfm?id=schenk-franziska-iridescent-nanopaints

[3] http://franziskaschenk.co.uk/science/mantel-of-many-colours

Birmingham (Physics and Biosciences Depts., 2008-2010) [4]. Crucially in their race for survival, many of these short-lived creatures dazzle with vibrant displays of jewel-like color. The Ancient Greeks borrowed their wings for Psyche, the lovely maiden symbolising the human soul rising towards the 'great beyond'. Many butterflies carry 'heavenly' blue on their wings. However, the exotic Morpho butterfly - its dramatic, dynamic and dazzling metallic blue visible for a quarter of a mile - is perhaps the most spectacular. Klots [16] describes *Morphos* as "jewels" generating flashes of "almost three-dimensional … living" color. What seems poetic licence has recently been proven: some butterfly scales indeed contain optical devices that resemble those of actual jewels [17]: and, like these, do not tarnish. Not surprisingly, such "living" color has never been replicated in the art world, not even in the form of highest-definition photographs or digital prints.

However, now, thanks to latest advances in iridescent technology painters have a truly gem-like, luminous blue at their potential disposal. This subtype of multi-layered reflector features layers of uniform thickness, reflecting the same wavelength repeatedly, each time further amplifying the color's intensity [18]. Just as the *Morpho* butterfly [19] has inspired this man-made technology, it can also teach us how best to employ it. Close microscopic examination of the mechanisms creating the brilliant blue coloration in a range of *Morpho* species has helped Schenk to go some way in reproducing the colors in painting [20][5].

3.2.1 Adjusting Tonal Value

Notably, among various species of the *Morpho* family the entire range of blue color tones, ranging from a pale moonbeam-blue to a deep, intense violet-blue is represented. Some of these colors glitter with a metallic lustre; others resemble silky satin; and still others display a subdued pearly sheen. But how can this diversity be explained when different *Morpho* species share virtually identical mechanisms for color generation? Answering this question provided Schenk with the solution to a major problem: intermixing interference flakes with opaque white or black absorption pigment (a method commonly adopted by painters to adjust tonality) inevitably compromises iridescence. Alternative artistic strategies for controlling tonality, purity and lustre were established by comparing the color mechanisms of three *Morpho* butterflies, namely *M. sulkowskyi*, *M. didius* and *M. rhetenor*.

Morpho sulkowskyi and *M. didius* share virtually identical light reflecting structures. Yet, *M. sulkowskyi* displays a pale pearly blue that shifts from blue-green to violet and comes and goes. At oblique angles, when the blue all but disappears, a faint yellow background color and brown markings become visible. *Morpo didius,* on the other hand, features a deeper, less angle-depended version of the same blue. Scientific studies have established that this marked difference can be attributed mainly to the varying amounts of black absorption pigment (melanin) present/absent in the two species. Melanin is distributed in the scales of *M. didius* (beneath the blue reflectors), while only a negligible amount is present in *M. sulkowskyi* [21].

And indeed the crucial role base pigment plays in adjusting color tone is confirmed when working with interference flakes. If a blue interference color is coated on white, the resulting effect is analogous to what can be observed in *M. sulkowskyi:* the angle-dependent blue reflection switches on and off to reveal a muted yellow. If, however, the blue is applied on black all transmitted light is absorbed and only blue light-waves survive – a pure, intense blue results. Again, this is consistent with what scientists have discovered in *M. didius*. Importantly, depending on the background's tonal value, the same narrowband structure can produce vivid metallic-like effects, and subtle two-color opalescence [22].

3.2.1 Matching Intensity, Purity and Lustre

---

[4] http://www.birmingham.ac.uk/schools/biosciences/research/artists-in-residence/interact/index.aspx

[5] http://franziskaschenk.co.uk/science/interact-iridescence-in-butterflies-and-paints

Initial experimentation with early-generation mica-based technology (Figure 2a), proved that the natural mica-based platelets covered in a very thin layer of titanium dioxide (TiO_2,) [23] (which still remain the most requested special effect pigments today), were not suitable to fully replicate the luminostiy and color travel of Morpho blue. In fact, the pearlescent ‘pigments’ most suitable for replicating the intensity of *M. didius* and *M. sulkowsyki’s* hues are based on borosilicate glass (Figure 2c), such as Miraval® Blue and Firemist® Colormotion Topaz. They combine unique color purity with high transparency, intensive light reflection and noticeable narrowband color travel. To re-create both versions of *Morpho* blue, Schenk overlaid the same blue-reflecting glass flake on backgrounds differing in tonal value. To our knowledge, no pearlescent ‘pigment’ matching the purity and intensity of *M. rhetenor* exists to date. Despite 50 years of research, the latest pearlescent generation cannot rival nature’s iridescent ‘genius’.

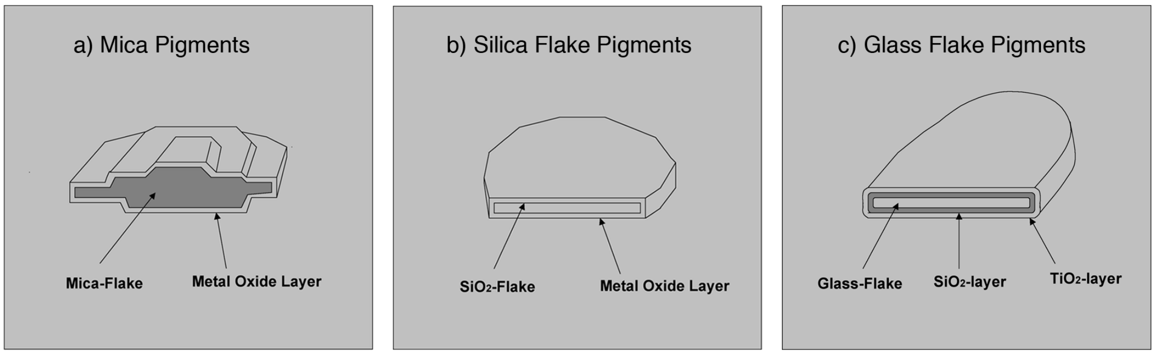

Figure 2. Generic perlescent ‘pigments’.

3.3 The Rainbow Hues of Jewelled Beetles

More recently Schenk has turned her attention to the rainbow colors of beetles and how to match the noticeable color travel displayed by certain species. With the Japanese Jewel Beetle as exemplar, to arrive at vital clues on how to best reproduce the beetle’s shifting coloration, ample scientific data was drawn on [25], [26]. The optical mechanisms involved have been clarified in detail [27]. The elytra, modified hardened forewings, covering the flexible, transparent hind wings when the beetle is at rest, reflect maximally in the green region, with longitudinal, dark-purple stripes interrupting the pattern; at the borders in between the green and purple areas, the cuticle is red/orange. The underside of the beetle is highly curved and colored orange.

3.3.1 Matching shifting jewel-like color

Adopting a biomimetic approach, the scientific data assembled on the Japanese Jewel Beetle’s coloration to date was deployed to established vital clues on how to best reproduce the specimen in painting. Comparative optical measurements performed on the beetle and on paint samples (incorporating interference flakes), confirm that the beetle’s iridescent coloration can indeed be matched. Not only the appearance with normal illumination but also the color impression at various angles of incidence could be satisfactorily mimicked. Upon an increasing angle of light incidence, the color of the reflected light is shifted towards the shorter wavelengths. The iridescence, that is the angle-dependency of the coloration of beetle and paint, was further studied by imaging scatterometry.

The Japanese Jewel Beetle’s elytra, modified hardened forewings covering the flexible, transparent hind wings when the beetle is at rest, reflect maximally in the green region, with longitudinal, dark-purple stripes interrupting the pattern; at the borders in between the green and purple areas, the cuticle is red/orange. The underside of the beetle is highly curved and colored orange. In an attempt to faithfully reproduce the coloration, Schenk et al [28] focused their search for suitable materials on the pearlescent multilayer pigment families launched over the last decade. Building on previous research, Schenk initially narrowed down the choice to two different systems of effect pigments: 1) LCP Helicone® colesteric effect pigments and 2) various classical thin-film multilayer reflectors, such as Variocrom™, Colorstream® and Firemist® Colormotion. The latter being synthetic goniochromatic, multi-quadrant, non-quarter wave multilayer pigments that (by a suitable choice of differing layer thicknesses create noticeable color travel). All systems under investigation achieve a particularly marked variation of color in dependence of viewing angle.

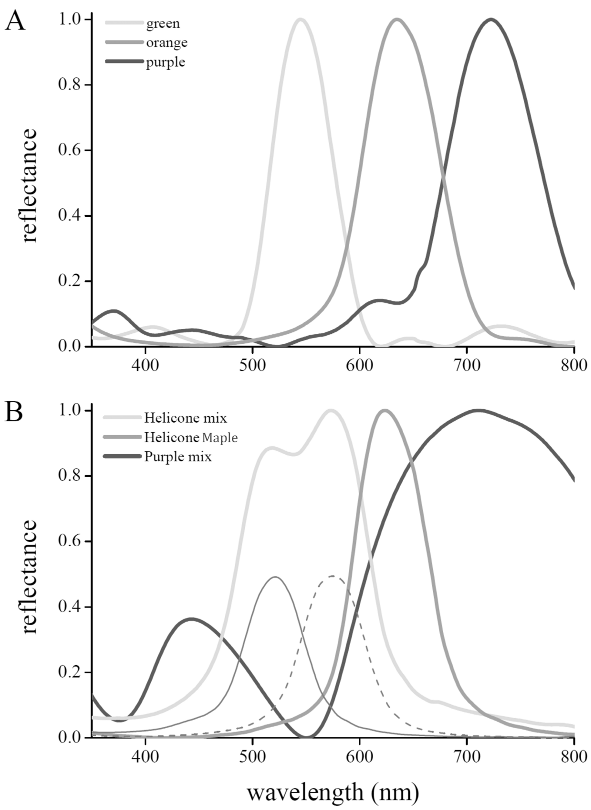

Figure 3. Normalized reflectance spectra with perpendicular illumination of the Japanese Jewel Beetle and effect paint. **A** The reflectance spectra of the green part of the elytra, the orange underside and the purple stripes of the elytra of the Jewel Beetle. **B** The spectra of the effect paints used in mimicking the beetle colors. The grey curves represent the reflectance spectra of the two components that together make up the green Helicone® mix spectrum.

Subsequent optical measurements conducted, analysed and viusalised by G. Stavenga's lab (Groningen University) confirm that to achieve a near-perfectly match to the deep-purple coloration of the beetle's stripes (which reflects dark-purple/red into angles up to about 30°, changing into red/orange at angles around 60°, and into yellow and broad-band white above an angle of incidence and reflection of 60°) color-mixing proved essential. To this end Variocrom™ Magic Purple, a non-quarter wave multi-layer pigment was intermixed with Iriodin® Lava Red (a quarter-wave pigment) in order to extend and adjust the hue and range of color travel. The resulting color mix indeed closely mimics the purple of the beetle's stripe – as confirmed by subsequent imaging scatterometry. Spectrometry shows a strong difference in the reflectance spectra, especially in the short wavelength range. This difference, however, is negligible for human observers.

To match the elytral green (visible at angles up to about 45°, which at larger angles changes into blue and violet, and at angles above 70° becomes a broad-band white) [29] again mixing proved necessary. This time a mix of LCP Helicone® Jade and LCP Helicone® Scarabeus achieved the desired color travel. No mixing was necessary to match the 'orange' underside: orange is displayed at angles up to about 45°; at larger angles the color changes first to yellow than green and green-blue to finally, at angles above 70°, turns into a broad-band white. LCP Helicone® Maple proved the perfect match.

A subtle point to be emphasised here is that the optical properties of Helicone® flakes differ, in an important aspect, fundamentally from the Jewel Beetle's cuticle. 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. Instead the helicoidal orientation of a single type of a birefringent unit provides the change in refractive index necessary for reflectivity [30] In other words, while cholesteric pigments also take the form of a transparent, colorless layered platelet, here all layers are composed of the same material, namely a highly cross-linked, liquid crystalline organic polymer with a helical superstructure. Each layer, consisting of an array of aligned elongated liquid crystal molecules, has a different orientation with respect to the neighbouring layers. One turn of the helix, the pitch, represents a rotation of 360° and determines the color of the resulting flake (Figure 4). However, notably, the difference between thin-film and helicoidal systems is somewhat irrelevant to the human observer, because of the incapacity of the human eye to distinguish between the interference effects generated.

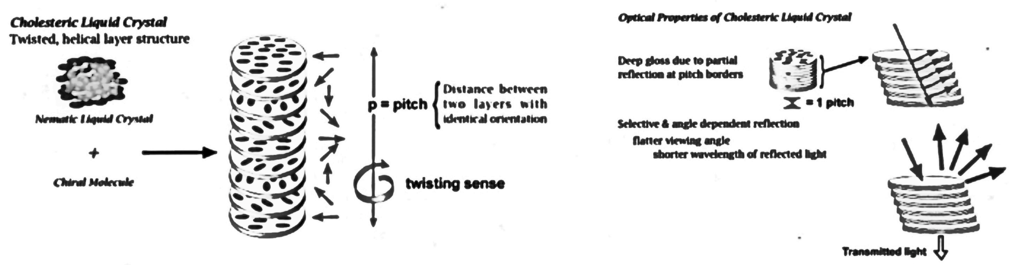

Figure 4. Optical principles of cholesteric liquid crystal pigments. Courtesy of Kobo Products, Inc. (2008)

To arrive at the final artwork, drawing on the above findings, biomimetic strategies were employed - pinpointing "old-masterly" techniques as the most appropriate. 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 the jewel beetle's cuticle - where the overall color effect is due to black melanin overlaid with structural color. Notably, as additive color mixing is at work here, a black pigmentary base is crucial if the purest, most vivid iridescent hues are to be achieved.

With this in mind, as a first step, detailed tonal drawings of both the beetle's ventral and dorsal side were created, which subsequently were developed into black monochrome "under-paintings" - the latter not only constituting an inversed version of the original drawing, but also featuring a textured surface. Subsequently, utilising our optical measurements, these were overlaid with iridescent paints based on the effect pigment selected to fully mimic the Japanese Jewel Beetle's coloration. And indeed the desired effect is achieved – the final paintings, just like the model, change with every minute variation of the angle of light and viewing. This introduces an element of ephemeral change, movement and transience into painting, traditionally a stationary medium [31].

4. CONCLUSIONS

In conclusion, whereas artists have been able to reproduce pigmentary colors in paintings since humans' earliest memory, until now this has not been the case for structural colors. The examples discussed here demonstrate, however, that with the help of latest iridescent color technology, biological structural colors can, at last, be simulated in painting. Effect pigments, and the resulting paints based on light interference, are beginning to open up a completely new area 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[6].

---

[6] http://nautil.us/blog/the-quest-to-understandand-mimicnatures-trickiest-colors

It is hoped that this review 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 color-variable flakes continue to present to the contemporary painter. For, given time and continued research, iridescent color technology has the potential to revolutionise fine art painting.

Acknowledgements

This research was funded by the Arts and Humanities Research Council (AHRC), the Wellcome Trust and the Arts Council of England. Thanks also go to Andrew Parker (Natural History Museum, London) and Doekele G. Stavenga (Computational Physics, Groningen University) for their input, advice and support. And Bodo D. Wilts (Physics, Cambridge University) for providing optical measurements related to the Japanese Jewel Beetle.

References

[1] Kinoshita, S., [Structural Colors in the Realm of Nature], World Scientific, Singapore (2008).
[2] Many white paints may seem to lack an absorbing pigment, while they do absorb in the UV.
[3] As quoted in Simon, H., "Preface" in [The Splendour of Iridescence: Structural Colors in the Animal World], Dodd, Mead, New York, USA (1971).
[4] Schenk, F and Parker, A.R. "Iridescent colour: from nature to the painter's palette", Leonardo (MIT) 44(2), 108-115 (2011).
[5] Newton, I. [Opticks] (1730*)*, reprint, Dover Publications Inc., New York (1952).
[6] Greenewalt, C.H., Brandt, W., Friel, D.D., "The Iridescent Colors of Hummingbird Feathers," Proceedings of the American Philosophical Society*,* 104(3), 249-253 (June 1960).
[7] Maile, F.J., Pfaff, G. and Reynders, P., "Effect pigments—past, present and future," Progress in Organic Coatings*,* 54, 150–163 (2005).
[8] G. Pfaff, G., [Special Effect Pigments*:* Technical Basis and Applications], Vincentz Network, Hannover, Germany, (2008).
[9] Schenk, F., "Nature's fluctuating colour captured on canvas?," International Journal of Design & Nature and Ecodynamics, 4(3), 274-284 (2009).
[10] Kueppers, H., [Color: Origin, Systems, Uses],Van Nostrand Reinhold Ltd, London, UK (1972). For color synthesis and basic color theory, see also: http://cs.nyu.edu/courses/fall02/V22.0380-001/color_theory.htm.
[11] For early work on liquid crystals see: Charnay, Y., "A new medium for expression: painting with liquid crystals," Leonardo (MIT), 15, 219-221 (1982) and Lembert, R., "Liquid crystals: a new material for artists", Leonardo (MIT), 2, 45-50 (1969).
[12] Schenk [9] and Schenk et al [4], Ball, P. has also referred to this work in "Nature's colour tricks", Scientific American, 306, 74 (2012) and the accompanying online feature: "Paintings made with iridescent nanopaints change color on the spot" http://www.scientificamerican.com/article.cfm?id=schenk-franziska-iridescent-nanopaints
[13] Schenk [9].
[14] Hanlon, T.R., Messenger, J.H., [Cephalopod Behaviour], Cambridge University Press, Cambridge,120-131(1996).
[15] Parker, A., [In the blink of an eye: how vision kick-started the big band of evolution], Free Press, London, 91(""2003).
[16] Klots, A.B., quoted by Simon [3], 198.
[17] Vukusic, P., "Structural colour effects in Lepidoptera", [Structural Color in Biological Systems], eds. S. Kinoshita, S. & Yoshioka, S., Osaka University Press, Osaka, 107 (2005).
[18] Pfaff, G., "Optical principles, manufacture, properties and types of special effect pigments" (Chapter 2), [Special Effect Pigments], ed. G. Pfaff, 2nd ed., Vincentz, Hannover, 72 – 83 (2008).

[19] Berthier, S., [Iridescences: The Physical Colors of Insects], Springer, London, 88 (2007).
[20] Schenk [9] and Schenk et al [4].
[21] Kinoshita, S. and Yoshioka, S.,"Photophysical Approach to blue Coloring in the *Morpho* Butterflies," in Kinoshita, S. and Yoshioka, S. (eds.), [Structural Colors in Biological Systems: Principles and Applications], Osaka University Press, Osaka, 138-139 (2005).
22. Vukusic, P., "Structural Colour Effects in Lepidoptera," in Kinoshita and Yoshioka [21], 95-112.
23. Pfaff, G. and P. Reynders, P., "Angle-Dependent Optical Effects deriving from Submicron Structures of Films and Pigments," Chemical Review 99(7), 14-34 (1999).
24. Pfaff, G., "Optical Principles, manufacture, properties and types of special effect pigments," in Pfaff, G. (ed.), [Special Effect Pigments], Vincentz Network, Hannover, 16-91 (2008).
25. Schenk, F., Wilts, B. and Stavenga, D.G., "The Japanese Jewel Beetle: a Painter's Challenge", Bioinspiration & Biomimetics, IOP Publishing Ltd, 8(4) doi:10.1088/1748-3182/8/4/045002 (2013), http://iopscience.iop.org/1748-3190/8/4/045002 Ref: BB/468615/SPE.
26. Stavenga D. G., Wilts B. D., Leertouwer H. L. and Hariyama T., "Polarized iridescence of the multilayered elytra of the Japanese jewel beetle, Chrysochroa fulgidissima", Phil. Trans. R. Soc. B 366 709–23 (2011).
27. Vigneron J. P., Rassart M., Vandenbem C., Lousse V., Deparis O., Biro L. P., Dedouaire D., Cornet A. and Defrance P., "Spectral filtering of visible light by the cuticle of metallic woodboring beetles and microfabrication of a matching bioinspired material", Phys. Rev. **E** 73 041905 10 (2006).
28. Schenk et al. [25].
29. Stavenga et al [26].
30. Pfaff, G. (ed.), [Special Effect Pigments], Vincentz Network, Hannover (2008).
31. Schenk et al. [25].