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The Japanese jewel beetle: a painter's challenge

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Abstract
Colours as dynamic as the metallic-like hues adorning the Japanese jewel beetle have never been captured on canvas before. Unlike, and unmatched by, the chemical pigments of the artist's palette, the effect is generated by layered microstructures that refract and reflect light to make colour visible. Exclusive to nature for millions of years, such jewel-like colouration is only now being introduced to art. Sustained scientific research into nature's iridescent multilayer reflectors has recently led to the development and manufacture of analogous synthetic structures, notably innovative light interference flakes. For the first time this novel technology offers artists the exciting, yet challenging, potential to accurately depict nature's iridescence. Mimicking the Japanese jewel beetle by using paints with embedded flakes, we demonstrate that the resulting painting, just like the model, displays iridescent colours that shift with minute variation of the angle of light and viewing.

S Online supplementary data available from stacks.iop.org/BB/8/045002/mmedia

(Some figures may appear in colour only in the online journal)

1. Pigmentary and structural colouration

In pictorial art, pigments have been used since time immemorial. However, natural colours are not only of pigmentary (or chemical) origin, but often have a physical (or structural) basis (Kinoshita 2008). The mechanisms causing each type of colouration 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[3]. The colour impression, the remaining part of the light, changes neither hue nor brightness, even when viewed from different angles. Structural colour, on the other hand, is caused by light interacting with transparent, colourless nanostructures that selectively reflect light in a certain wavelength range. Here colours are made visible via the optical phenomenon of light interference, resulting in a colour that changes with the direction of illumination and viewing angle. Although numerous attempts (Gould 1804–1881) have been made to capture the visual impression of structurally coloured animals in painting '... colours of this type, by their very nature, defy our best efforts at visual reproduction' (Simon 1971, preface).

However, thanks to sustained scientific research into nature's iridescence-causing microstructures, the eye-catching optical effects of structural colour 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. Interweaving the findings of optical physics, material science and artistic studio practice, we demonstrate here that the study of nature's ingenious colour-generating mechanisms can indeed aid artistic innovation and application.

[3] Many white paints may seem to lack an absorbing pigment, while they do absorb in the UV.

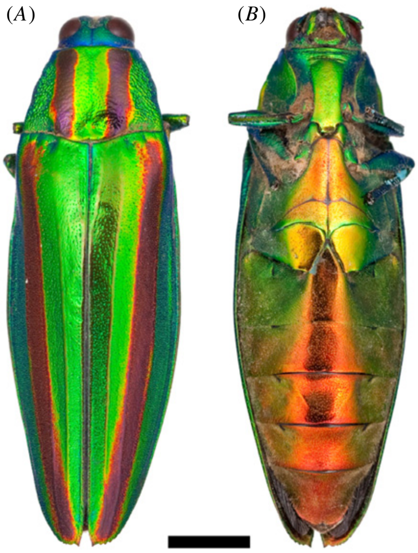

Figure 1. (*A*) female Japanese jewel beetle, *Chrysochroa fulgidissima*. (*A*) Dorsal view. (*B*) Ventral view; bar: 0.5 cm.

2. Jewelled beetles in art: past, present and future

2.1. Jewel beetles in artefacts

As an exemplary case we have chosen the Japanese jewel beetle, *Chrysochroa fulgidissima*, a member of the family Buprestidae, the jewel beetles (figure 1). 'The comparison is, of course, invariably made, for these beetles, small, compact, and frequently solidly iridescent, are the most jewel-like of all insects. [. . .] There can be no doubt, that if the only criterion applied were beauty and the brilliance and intensity of colour, some of the metallic beetles would get the prize if they were exhibited side by side with objects made of gold and precious stones' (Simon 1971, pp 217–8).

Perhaps not surprisingly, the splendour of the Buprestidae, the 'living jewels', was not lost on the natives of those regions where they occur. Many indigenous people have traditionally used their elytra to make ornaments, often for ceremonial robes and regalia. For example, in certain Asian countries, such as India, Thailand and Japan, species of Buprestidae have been utilized in beetle-wing jewellery, decorations, textiles and also precious artefacts. In India, some of the oldest documented uses of beetle wings are found in early Basohli School miniature paintings (1690–1730), where it was customary to utilize pieces of jewel beetle elytra to symbolize the effect of emeralds (Rivers 1994). The Japanese jewel beetle was used as ornament in ancient Japanese times. Indeed, its Japanese name, Tamamushi, derives from archaic Japanese 'Tama', meaning jewels or beautiful things, and 'Mushi', meaning small animals. The famous seventh century Japanese national treasure Tamamushi-no-zushi, the beetle-wing shrine, was decorated with elytra taken from about 2600 specimens (Hariyama *et al* 2005, Vigneron *et al* 2006, Stavenga *et al* 2011).

Still, rather than being a mere preoccupation of the past, the apparent human fascination with jewel beetles still endures, as evidenced by the recent return to the spotlight of a magnificent stage costume made in 1888 for famed Shakespearean actress Ellen Terry. Incorporating 1000 jewel beetle wings, the dress was originally created for Terry's portrayal of Lady Macbeth and a year later immortalized by American painter John Singer Sargent in a portrait now in London's Tate Gallery. Finally, after two years of restoration work, amounting to 1300 h of labour, Ellen's famous costume is back where it belongs—taking centre stage in a new contemporary display at Smallhythe Place, in Kent, where modern audiences continue to be wowed by its beauty.[4]

Jan Fabre's work provides further compelling evidence of the enduring appeal of jewel beetle iridescence. In 2009, the contemporary artist decorated the ceiling of the Royal Palace in Brussels, which had remained unfinished since 1909, with 1.6 million shimmering green iridescent jewel beetles. Fabre and 30 other diligent artists, armed with a truck-full of beetles and glue, transformed the empty ceiling into one bejewelled with a sea of swirling and twinkling green. As one gazes up at the masterpiece from the floor, the whole mass of wing cases appears to move as the light reflects from different angles.[5]

All this demonstrates that, throughout the ages, iridescent jewel beetle specimens have been widely used in artefacts across the world. Yet, using real organisms for decoration and art may not necessarily be advisable from the naturalist's point of view. This considered, artificial materials are certainly a welcome alternative. The Japanese craftsman Shun Koiwa (artist name: Komei) may have been taken this into consideration when he developed, in 1932, the Tamamushi-nuri lacquer coat, a hard surface treatment of wood requiring the application of up to 50 layers of special lacquer by hand, separated by thin films of metal dust. As the technique's name indicates, this beautiful finish is claimed to resemble the iridescent Tamamushi (i.e. Japanese jewel beetle), and, in particular, the purple stripe on its back (Vigneron *et al* 2006).

Around the same time, similar breakthroughs were made in North America and Europe, which would eventually lead to synthetic colours even truer to those of the Japanese jewel beetle. Sustained attempts by industry to synthesize various lead, arsenic and bismuth salts for application as pearl lustre pigments finally came to fruition. This time continuing a search that began at least 3000 years ago when, as proven by an ancient Chinese document, humans already sought to imitate the lustre of precious pearls by mixing different substances (Krüger 1919). While a major advance at the time, it has since taken industry a further 70 years, and a succession of pearl lustre pigment-generations (i.e. basic lead carbonate in the 1960s, bismuth oxychloride platelets in the 1970s, followed by mica/metal oxide platelets since the late 1970s), to eventually arrive at synthetic multilayered pigments capable of mimicking nature's iridescent hues (Maile *et al* 2005). Unlike chemical pigments, the latter do indeed resemble the multilayer reflectors found in, for example, pearls and beetles. Also consisting of alternating layers of transparent, colourless materials with differing refractive indices, the platelets in question reflect and transmit light instead of absorbing it, creating colour by interference (Pfaff 2008). Gradually introduced since the late 1990s, the principal author

[4] www.nationaltrust.org.uk/smallhythe-place/things-to-see-and-do.

[5] www.instructables.com/community/Ceiling-art-made-from-beetle-shells.

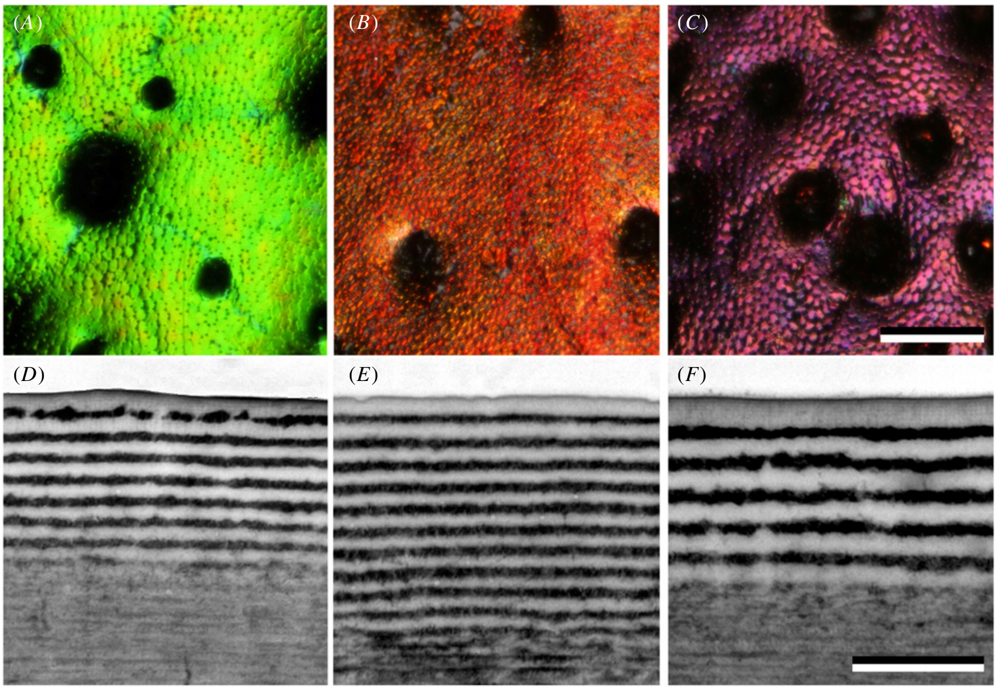

Figure 2. Photographs and transmission electron microscopy (TEM) images of the cuticular surface of the Japanese jewel beetle, *Chrysochroa fulgidissima*. (*A*) Green part of the elytron. (*B*) Orange ventral area. (*C*) Purple stripe of the elytron; bar: 100 μm. (*D*)–(*F*) Transversal TEM sections of the cuticle of the three cases of (*A*)–(*C*), showing the multilayered structure; bar: 1 μm.

of the present paper has since worked on converting these challenging materials for fine art painting (Schenk 2009).

2.2. Biomimetic art: the future

Although industry has exploited the novel properties of iridescent flakes for over a decade, fine art painting has been 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. The major apparent hindrance, however, is the incompatibility with—and the resulting confusion caused by the material's non-adherence to—colour theory as applied in painting (Kueppers 1972).[6] 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 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 mimics nature's technology. As a result, systematic analysis of the mechanisms that cause iridescent colour-mixes in animals can inspire analogous artistic methods. And indeed, previous work (Schenk 2009, Schenk and Parker 2011, Ball 2012) has demonstrated that the considerable challenges posed by the technology can be overcome by adopting a biomimetic approach (also see Charnay 1982, Lemberg 1969). 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, metallic-like colouration of the Japanese jewel beetle on canvas.

[6] http://cs.nyu.edu/courses/fall02/V22.0380-001/color_theory.htm.

3. Iridescence-generating mechanisms of the Japanese jewel beetle and effect pigments

To arrive at vital clues on how to best reproduce the Japanese jewel beetle ample scientific data was drawn on. The optical mechanisms involved in the jewel beetle's body colouration have been clarified in detail (Stavenga *et al* 2011). The elytra, modified hardened forewings, covering the flexible, transparent hindwings 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 coloured orange (figure 1).

In line with the above, we have categorized the jewel beetle colours into three cases, the main green of the elytra, the orange of the underside, and the purple stripes of the elytra (figures 2(*A*)–(*C*)). Transmission electron microscopy conducted on samples of cuticle taken from each of these areas demonstrates that the colours are due to interference reflectors, consisting of differently spaced, alternating layers of chitin and melanin (figures 2(*D*)–(*F*)). In all cases, an about 1.3 μm thick distal sheet, forming the epicuticle, features several layers with alternating high and low electron density, about 16 in the green, 22 in the orange area, and 12 in the purple area. Multilayer reflection is without question the most common and the best understood iridescence mechanism causing structural colouration. Optical multilayers consist of a stack of layers alternating in material properties, specifically in the refractive index (figure 3). The refractive index values together with the

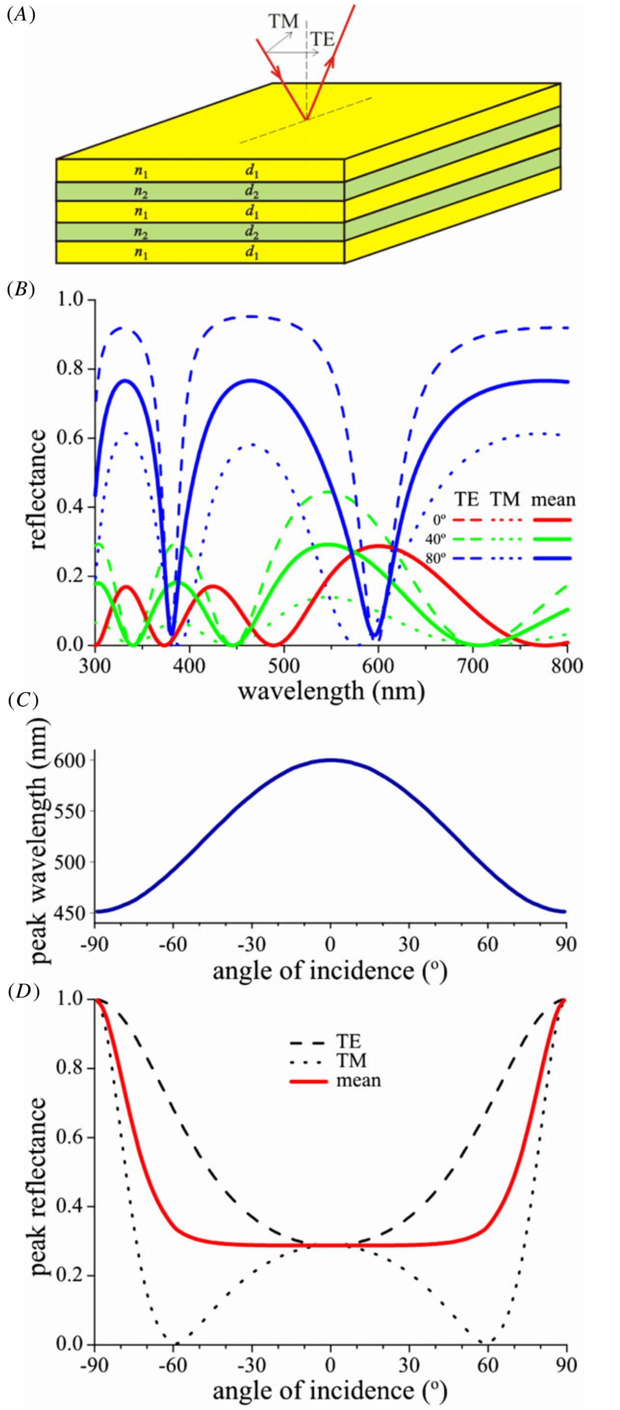

Figure 3. Quarter-wave multilayer and reflectance properties. (*A*) Diagram of a multilayer consisting of a stack of five plates with alternating refractive indices n_1 and n_2 and thicknesses d_1 and d_2. When the optical thickness, that is, the product of refractive index and thickness, of the plates is the same, then the multilayer is an ideal or quarter-wave multilayer and reflects maximally light with wavelength λ following from $n_1d_1 = n_2d_2 = \lambda/4$. Incident light is TE-(or TM-)polarized when the electric vector is perpendicular (or parallel) to the plane of incidence. (*B*) Reflectance spectra for TE- and TM-polarized light and their mean of an ideal multilayer with refractive indices $n_1 = 1.6$ and $n_2 = 1.5$, and thicknesses $d_1 =$ 93.8 nm and $d_2 = 100$ nm, when the angle of light incidence is 0°, 40° and 80°. (*C*) Peak wavelength as a function of light incidence. (*D*) Peak reflectance for TE- and TM-polarized light and their mean as a function of light incidence.

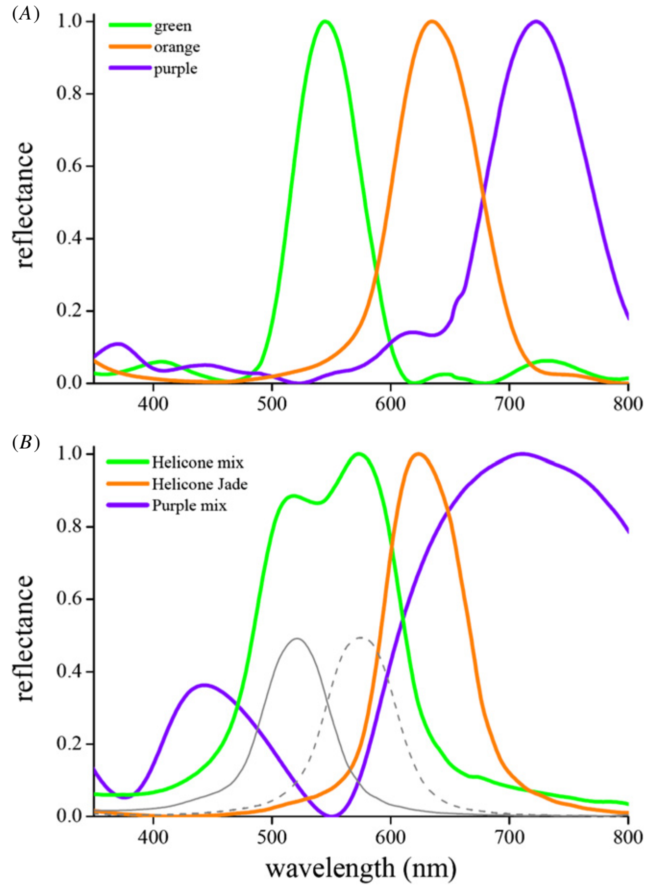

Figure 4. Normalized reflectance spectra with perpendicular illumination of the Japanese jewel beetle and effect paint. (*A*) The reflectance spectra of the green part of the elytra, the orange underside and the purple stripes of the elytra of the jewel beetle. (*B*) The spectra of the effect paints used in mimicking the beetle colours. The grey curves represent the reflectance spectra of the two components that together make up the green Helicone® mix spectrum.

thicknesses of the layers determine the colour of the reflected light (Kinoshita 2008, Stavenga *et al* 2011).

The first explanations of multilayer reflections go back to the early 19th century, where Sir George Biddell Airy, Astronomer Royal, derived a formal description for the reflection of light by a thin film. The reflectance, i.e. the fraction of incident light that is reflected, depends on wavelength and angle of light incidence. Subsequently, formal expressions were developed for a stack of thin films, where each layer has the same optical thickness (*nd*), the product of the refractive index (*n*) and the geometrical thickness (*d*) (Born and Wolf 1999). Such a multilayer is called an ideal or quarter-wave multilayer, because when a light beam enters normally (that is, perpendicularly), light with wavelength value, the quarter of which equals the optical thickness ($nd = \lambda/4$), is maximally reflected (figure 3).

Crucially, the layers present in the Japanese jewel beetle are not discrete but graded (figures 2(*D*)–(*F*)). As a consequence, the refractive index does not change abruptly from layer to layer, but its value oscillates between about 1.6 and 1.7, with a periodicity depending on the location (Stavenga *et al* 2011), thus causing different reflectance spectra (figure 4(*A*)), that is, a different colour (figures 2(*A*)–(*B*)).

Obviously then, the jewel beetle multilayers are far from so-called ideal, but the basic principle of interference reflection holds. When a light wave experiences a change in refractive index it is partly reflected. With a repetitive changing refractive index all reflected waves add together, resulting in a reflected light flux. The relative phases of the waves determine the magnitude of the resulting reflectance.

Figure 3 presents a characteristic example of an ideal multilayer, consisting of five layers, and its reflection properties. The refractive index of the layers is alternating, 1.5 and 1.6, and the thicknesses are such that $n_1d_1 = n_2d_2 = 150$ nm, so that with normal illumination the reflectance peak wavelength is 600 nm. When the angle of light incidence is not normal, the reflectance depends on the polarization of the light, which is called TE (or TM) when the polarization is perpendicular (or parallel) to the plane of light incidence (figure 3(*A*)). Figure 3(*B*) shows the TE- and TM-reflectance spectra for three angles of incidence (0°, 40° and 80°). The average of the TE- and TM-reflectance is the reflectance for unpolarized light, which is representative for a human observer, because the human eye cannot discriminate polarization directions. Interestingly, insect eyes generally do process polarization information, and the Japanese jewel beetles most likely can detect each other's presence via polarized reflections, meanwhile their predators, birds, do not possess polarization vision, like humans.

The most prominent property of a multilayer reflector is its iridescence, the change in the displayed colour when the angle of illumination and/or observation changes. For the multilayer of figure 3(*A*), the iridescence is exemplified by the angle dependence of the reflectance peak wavelength, which shifts from the red (600 nm) at normal illumination to the blue (450 nm) at 90° light incidence (figure 3(*C*)). As noted above, the peak reflectance for TE- and TM-polarized light strongly depends on the angle of incidence, but for unpolarized, natural light, the reflectance at the peak wavelength remains fairly constant up to an angle of incidence of about 60°. Above this value the reflectance rapidly rises to 100% (figure 3(*D*)).

Generally, when the multilayer consists of layers with optical thickness alternatingly n_1d_1 and n_2d_2, the reflectance peak wavelength is given by the interference condition $\lambda_{max}(\theta_0) = 2\,(n_1d_1\cos\theta_1 + n_2d_2\cos\theta_2)$, where θ_0 is the angle of light incidence for the first layer and θ_1 and θ_2 are the angles at the interfaces of the multilayer, determined by Snell's law: $n_1\sin\theta_1 = n_2\sin\theta_2 = n_0\sin\theta_0$ (for the ideal multilayer with $n_1d_1 = n_2d_2 = 150$ nm, $\lambda_{max}(\theta_0)$ is given in figure 3(*C*), but the interference condition also holds for non-ideal multilayers).

Half a century ago, the optical theories for multilayers were extended to light reflections by an arbitrary stack of thin films (Macleod 1985). With the computational power of present day personal computers, the reflectance spectra of complex multilayers can now be easily calculated with so-called transfer matrix formulae for any angle of light incidence. In fact, measurements of the reflectance of jewel beetle elytra could be straightforwardly interpreted with modelled spectra using the by now classical matrix theory (Stavenga *et al* 2011).

In the case of multilayer effect pigments, just as with natural reflectors, the interference colour is determined by the intensification of specific wavelengths and, if two or more layers in a multilayer pigment possess the same optical thickness, the colour of the reflected light becomes more intense as the number of layers increases. These quarter-wave multilayer effect pigments generate an intense metallic-like reflection colour (visible at face angle) that shifts towards adjacent shorter wavelength at grazing angle (e.g. from red to orange). Featuring fewer layers but a larger difference in refractive indices than their natural counterpart, the most sophisticated examples to date being the effect pigment families Firemist® and Miraval®—both based on TiO_2-coated borosilicate flakes.

Notably, the reflectors present in the jewel beetle cuticle also give rise to angle-dependent colours that shift towards the shorter end of the spectrum, but across a wider range of wavelengths (e.g. from violet to red and yellow-gold). At present only synthetic non-quarter wave pigments that feature layers of varying optical thickness—such as Variocrom™, Colorstream® and Firemist® Colormotion—display a comparable range of colour travel. By a suitable choice of differing layer thicknesses these goniochromatic, multi-quadrant multilayer pigments achieve a particularly marked variation of colour in dependence of viewing angle.

The strategies adopted to select for colours with both—increased brilliancy and colour travel—differ for jewel beetles and effect manufacturers. While the number of layers present in the beetle's cuticle has increased to compensate for the limited refractive index range of organic materials, industry, pursuing similar aims, is instead opting for fewer layers and materials with a large difference in refractive index. However, the recent emergence of ground-breaking non-quarter wave multilayer coating technology has made it possible to simultaneously increase the number of layers and minimize the platelet's overall thickness.

Crucially, however, the overall iridescent effect is not solely determined by the reflector type. There are a number of additional factors to consider. Firstly, the black melanin pigment present in the beetle cuticle plays an important role in determining the metallic-like, changeable colours. The melanin absorbs the light fraction backscattered from deeper layers in the cuticle, which markedly contributes to an increase in the intensity and purity of the reflection/interference colour. Without the melanin the reflection colour would be pale and insipid. This considered, when working with effect pigments, it is advisable to choose a black (rather than white) substrate as this, due to the transmitted light being fully absorbed, results in the purest, most vivid colouration.

In addition, observation of the beetle cuticle under the light microscope at high magnification offers further important insights, namely that the colour of each of the three areas identified above (i.e. the green, red/orange, purple) is not uniform but varies somewhat. For example, what appears green (when viewed with the naked eye) consists in fact of tiny patches of green, yellow and purple, which indicates that the properties of the colour-causing multilayers located below the surface locally vary (figures 2(*A*)–(*C*)). Yet, while the reflectors differ slightly in layer thickness and/or refractive index, the various individual hues blend into an overall colour (figure 1).

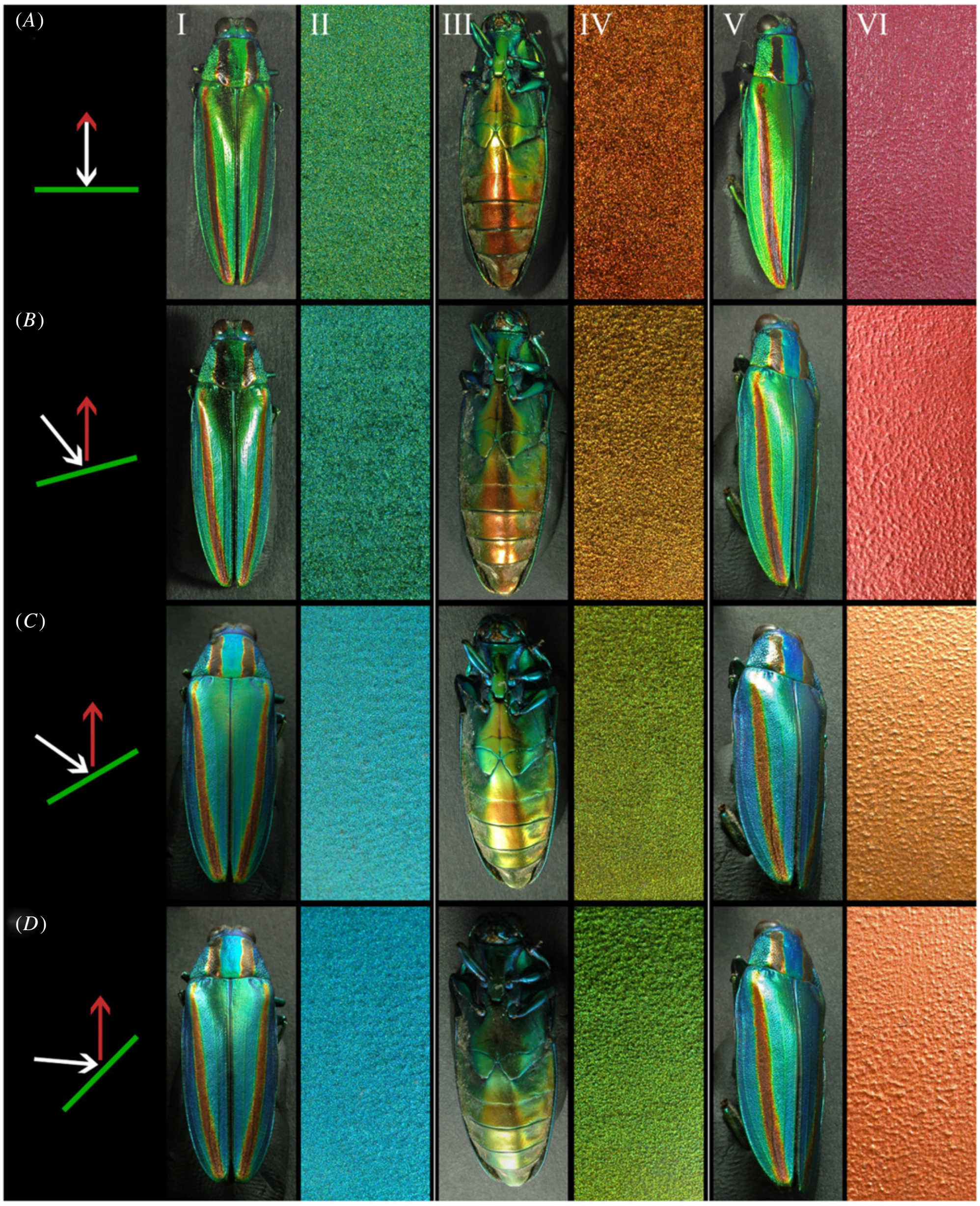

Figure 5. The three colour cases of the jewel beetle, the green part of the elytra (column I), the orange underside (column III) and the purple stripes of the elytra (column V), together with the mimicking effect paints (columns II, IV, VI) illuminated from various angles and observed from the mirror angle. From row A to row D the angle of light incidence increased in steps of about 10°. The animal and the colour samples were rotated around an axis perpendicular to the longitudinal (viewing) axis.

The pointillist mixing principles observed in the beetle do in turn suggest useful colour-mixing strategies for the effect painter.

4. Mimicking the jewel beetle's colours

Adopting a biomimetic approach, the scientific data presented above was drawn on to arrive at vital clues on how to best reproduce the Japanese jewel beetle in painting. Comparative optical measurements, performed on the beetle and on paint samples (incorporating interference flakes), confirm that the beetle's iridescent colouration can indeed be matched.

Figure 4(*A*) shows the reflectance spectra of the three cases when illuminated normally (that is, perpendicularly), and figure 4(*B*) presents the spectra of the mimicking effect pigments. Not only the appearance with normal illumination but also the colour impression at various angles of incidence could be satisfactorily mimicked (figure 5). Upon an increasing angle of light incidence, the colour of the reflected light is shifted towards the shorter wavelengths. The iridescence, that is the angle-dependency of the colouration of beetle and paint, was further studied by imaging scatterometry (figure 6).

The various attempts and procedures leading to this result are described below. In an attempt to faithfully reproduce the colour of the Japanese jewel beetle, all multilayer pigments currently available were investigated. There is, however, one notable exception: a second class of special effect pigments exists, namely metallic effect pigments. Nature's

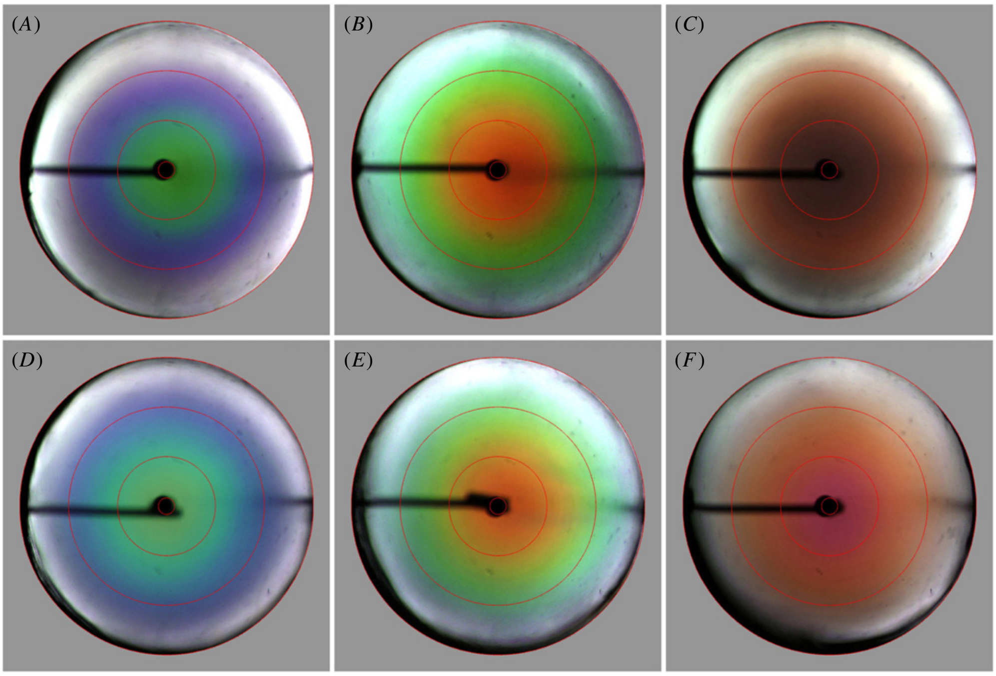

Figure 6. Scatterograms of the Japanese jewel beetle and effect paints. (*A*) Scatterograms of the green part of the elytra. (*B*) The orange underside. (C) The purple stripes of the elytra. (*D*)–(*F*) Scatterograms of the effect paints mimicking the three beetle cases. The red circles indicate angular reflection directions of 5°, 30°, 60°, and 90°. The black bars at 9 o'clock are due to a glass pipette holding a piece of cuticle (*A*)–(*C*) or a piece of effect paint (*D*)–(*F*). The central black circle is due to a small central hole in the scatterometer's ellipsoidal mirror (for details of the method of imaging scatterometry, see Stavenga *et al* 2009, 2011).

metallic-looking reflectors, on the other hand, are non-metallic, i.e. they consist of dielectric materials that are often colourless and transparent.

We therefore focused our search for suitable materials to mimic beetle colouration on pearlescent technology and the respective pigment lines launched over the last decade. Because it proved easiest to match the orange underside of the jewel beetle we first describe how this particular colouration can be mimicked.

5. The orange underside

Imaging scatterometry and angle-dependent reflectance measurements of a piece of cuticle from the underside shows that the reflected light is orange for angles up to about 45°; at larger angles the colour changes first to yellow than green and green-blue to finally, at angles above 70°, turns into a broad-band white. The effect pigment initially selected by eye was subsequently confirmed, via imaging scatterometry and spectrophotometry, to be indeed a very close match (figures 5 and 6). The interference pigment in question, LCP Helicone® Maple, incidentally belongs to the first ever effect pigment family (introduced in the mid 1990s) to generate distinct angle-dependent colour effects.

A subtle point to be emphasized here is that the optical properties of the chosen flake differs, 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 (LCPs), known as cholesteric effect pigments. Unlike thin-film multilayers, LCPs 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 (Pfaff 2008). 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. 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 colour of the resulting flake (figure 7).

According to Parker (2003), this can be best understood by considering the platelet in its entirety as a stack of thin layers. Each half turn of the helical molecules covers a quarter of a wavelength in distance or 'thickness', and is equivalent to a single thin film. Consequently the whole cholesteric platelet, from top to bottom approximates many thin films piled up (figure 7). In analogy to a stack of thin-films, the intensity of the total reflection is strengthened by reflections from each of the various layers of the helix. To obtain maximum reflectivity, at least six helices or a thickness of approx. 4 μm is required (Makow 1986). However, as with other effect pigments, the overall particle diameter is also important. The larger the circumference, the brighter the effect; here pigments with particles having an average diameter of 35 μm have been used.

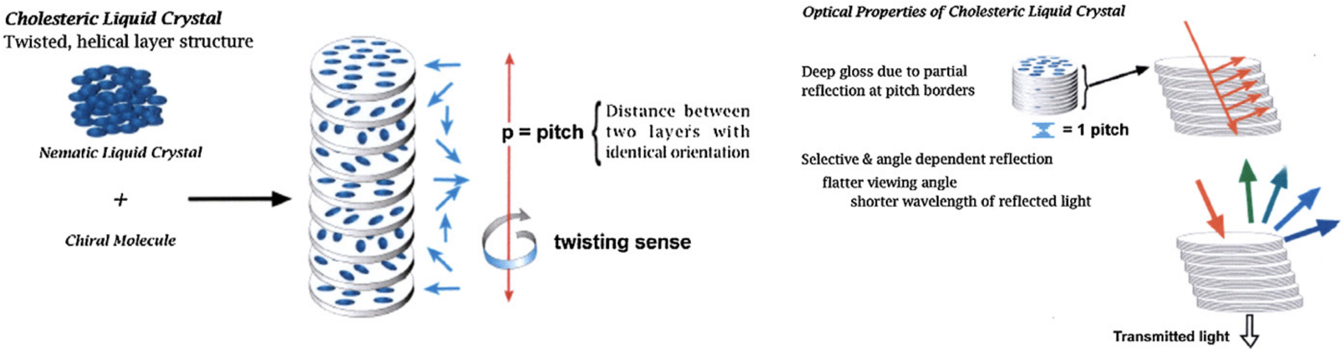

Figure 7. Optical principles of cholesteric liquid crystal pigments (Kobo Products Inc. 2008).

6. The elytral green

After careful consideration, two effect pigments were chosen by eye as possible matches for 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 (Stavenga *et al* 2011, figures 5–7). However, while neither flake proved entirely suitable, when combined, the resulting colour mix closely resembles the beetle's green—as confirmed by subsequent imaging scatterometry and spectrophotometry (figures 4 and 6).

Once again, at closer interrogation, the pigments in question turned out to belong to the Helicone® family (i.e. Helicone® Jade and Scarabeus). This further confirms that 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. Both reflector types cause visually identical angle-dependent shifts in iridescence, and thus it does not really matter which of the two the effect pigment painter chooses. The same holds true for other decorative applications. With no immediate advantage over 'true' thin-film technology, the relative thickness of first-generation cholesteric flakes, together with stability/workability problems in certain applications (Maile *et al* 2005), has led to the Helicone® pigment line being discontinued in early 2012. However, other special effect pigment manufacturers are springing into the breach, developing ever more sophisticated and thinner cholesteric effect pigments—the main incentive being specialist security applications.[7]

For there is yet another unexpected twist to LCP technology: the reflected light is circularly polarized in the same rotational direction as the helix of the liquid crystal line phase. While this property is not visible to the naked eye, it is easily revealed: when viewed through an appropriate polarizing filter, the reflected light vanishes. This can be exploited when using cholesteric pigments for anti-counterfeiting markings on documents or banknotes (Jiang *et al* 2002, Pfaff 2008).

Circular polarization can also be found in certain beetles, predominantly in scarabs, and may well have evolved for similar reasons: to generate signals not detectable by potential predators (Michelson 1911, Caveney 1971, Goldstein 2006, Sharma *et al* 2009). Notably certain scarab beetles with circular polarization, such as *Potosia aeruginosa jousselini*, do display colours that, to us at least, look almost identical to those of the Japanese jewel beetle. Non-normal illuminations of the thin-films present in the jewel beetle's cuticle, on the other hand, give rise to linear polarization. There might be good reasons for this diversity in nature's polarization patterns: various studies have suggested that species-specific polarized reflectance-signatures may act as a receiver-dependent signal system in beetles, detectable by polarization-sensitive conspecifics but invisible to vertebrate predators (Seago *et al* 2009, Brady and Cummings 2010).

7. The purple stripes

Angle-dependent reflectance measurements demonstrate that the reflectors positioned beneath the stripes adorning the back of the jewel beetle reflect 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° (figures 5–7 of Stavenga *et al* 2011). To mimic this colouration, effect pigments whose colour travel to some degree echoes this angle-dependent colouration were initially selected by eye—in the process sampling the key thin-film multilayer systems currently in existence.

An initial comparison with the beetle's purple suggested that, due to the noticeable colour shift across a range of wavelengths, non-quarter wave pigment technology might be most appropriate. With this in mind, Variocrom™ Magic Purple, Colorstream® Royal Damask and Firemist® Colormotion Ruby (all suspended in the same binder and applied to a black substrate) were singled out for investigation (more information on the platelets' composition and architecture is in table S1 available from stacks.iop.org/BB/8/045002/mmedia). Incidentally, as their trade names suggest, the three 'reds' in question do each belong to a different effect pigment family—each of which, in turn, marks a further stage in the evolution of pearlescent thin-film systems (see supplementary material available from stacks.iop.org/BB/8/045002/mmedia).

Neither of the classical multilayer effect pigments perfectly matches the deep-purple colouration of the jewel beetle. Consequently colour-mixing proved essential and,

[7] www.chelix.com/products_pigment.html.

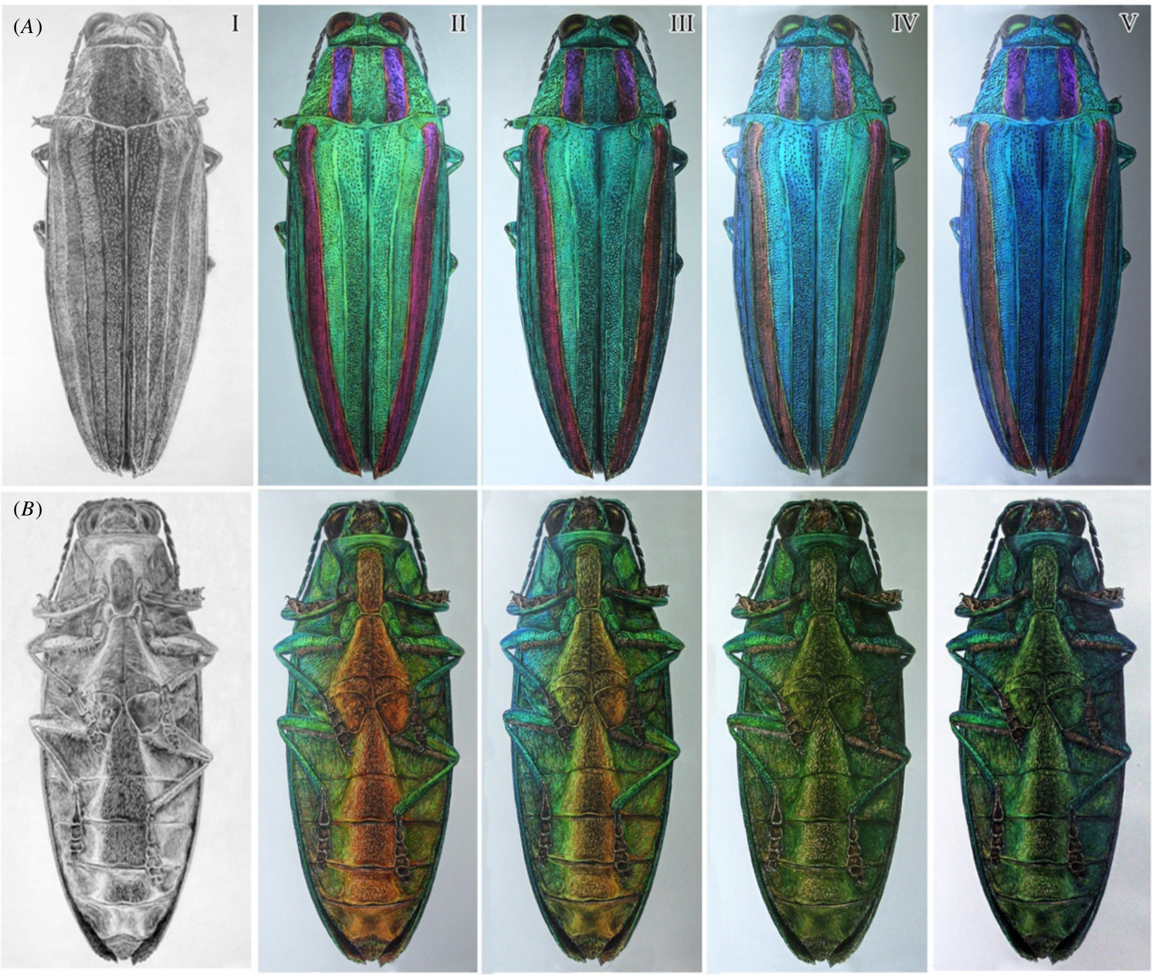

Figure 8. Final painting of Japanese jewel beetle, mixed media on board, 90 × 60 cm^2, © F Schenk. Two stages of the painting process are shown. Stage 1: carbon drawing of the dorsal and ventral side (panel I). Stage 2: introduction of iridescent colour and angle-dependency for different illumination of the painting (panels II–V, compare to figure 5).

to this end, we intermixed non-quarter wave pigments with quarter-wave pigments in order to extend and adjust the hue and range of colour travel (see supplementary material available from stacks.iop.org/BB/8/045002/mmedia). The resulting colour mix, of Variocrom^{TM} Magic Purple and Iriodin® Lava Red, indeed closely resembles the beetle's purple stripe—as confirmed by subsequent imaging scatterometry (figure 6). Spectrometry shows a strong difference in the reflectance spectra, especially in the short wavelength range. This difference, however, is negligible for human observers.

8. Conclusions: the final artwork

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 the jewel beetle's cuticle—where the overall colour effect is due to black melanin overlaid with structural colour. Notably, as additive colour 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. Finally, drawing on our optical measurements, these were overlaid with iridescent paints based on the effect pigments selected to fully mimic the Japanese jewel beetle's colouration (figure 8). 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 change, movement and transience into painting, traditionally a stationary medium.

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 the Japanese jewel beetle demonstrates, however, that with the help of latest iridescent colour technology, biological structural colours can finally 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.

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 colour-variable flakes continue to present to the contemporary painter. Given time and continued research, iridescent colour technology has the potential to revolutionize fine art painting.

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