BIOLOGICAL REVIEWS
Cambridge Philosophical Society
Check for updates
Biol. Rev. (2021), **96**, pp. 1676–1693.
doi: 10.1111/brv.12720

The seven ways eukaryotes produce repeated colour motifs on external tissues

Pierre Galipot[1,2*], Catherine Damerval[2] and Florian Jabbour[1]

[1]*Institut de Systématique, Evolution, Biodiversité (ISYEB), Muséum national d'Histoire naturelle, CNRS, Sorbonne Université, EPHE, Université des Antilles, 57 rue Cuvier, CP39, Paris, 75005, France*
[2]*Génétique Quantitative et Evolution-Le Moulon, Université Paris-Saclay, INRAE, CNRS, AgroParisTech, Gif-sur-Yvette, 91190, France*

ABSTRACT

The external tissues of numerous eukaryote species show repeated colour patterns, usually characterized by units that are present at least twice on the body. These dotted, striped or more complex phenotypes carry out crucial biological functions, such as partner recognition, aposematism or camouflage. Very diverse mechanisms explaining the formation of repeated colour patterns in eukaryotes have been identified and described, and it is timely to review this field from an evolutionary and developmental biology perspective. We propose a novel classification consisting of seven families of primary mechanisms: Turing(-like), cellular automaton, multi-induction, physical cracking, random, neuromuscular and printing. In addition, we report six pattern modifiers, acting synergistically with these primary mechanisms to enhance the spectrum of repeated colour patterns. We discuss the limitations of our classification in light of currently unexplored extant diversity. As repeated colour patterns require both the production of a repetitive structure and colouration, we also discuss the nature of the links between these two processes. A more complete understanding of the formation of repeated colour patterns in eukaryotes will require (*i*) a deeper exploration of biological diversity, tackling the issue of pattern elaboration during the development of non-model taxa, and (*ii*) exploring some of the most promising ways to discover new families of mechanisms. Good starting points include evaluating the role of mechanisms known to produce non-repeated colour patterns and that of mechanisms responsible for repeated spatial patterns lacking colouration.

Key words: colour patterns, Eukaryota, pattern classification, periodic patterns, repeated patterns, Turing patterns

CONTENTS

* Address for correspondence (Tel: +33(0)1 40795457; E-mail: pierre.galipot@edu.mnhn.fr)

I. INTRODUCTION

(1) Diversity of repeated colour patterns displayed on eukaryotic external tissues

The external tissues of many eukaryotic species are adorned with colour patterns, like the black and white stripes of the zebra, the red and white signal on the cap of the fly agaric or the black spots on the leaves of arums. Colour motifs can serve many functions, such as signalling to congeners [for partner recognition (Himstedt, 1979) or communication (Futahashi *et al.*, 2012)], attracting or repelling other species [pollination (Leonard & Papaj, 2011) and aposematism (Elias, 2019)], or avoiding detection or recognition [camouflage (Smith & Ruxton, 2020)], suggesting they may have an adaptive value. Some colour patterns may contribute to adaptation to abiotic conditions [for example through thermoregulation (Stuart-Fox & Moussalli, 2009)] or may not have any identified biological function, rather being by-products of reactions controlling other traits.

These colour patterns are extremely diverse in terms of colour [produced chemically (Kelsh *et al.*, 2009; Tanaka, Sasaki & Ohmiya, 2008) or by physical means (Berthier, 2007)] and the cell types involved (Nüsslein-Volhard & Singh, 2017), but also in terms of geometry (eyespots, stripes, spots, spattering, large colour domains). Most external colour patterns are described from tissues (skin, plant epidermis, shells) whose surface can be approximated as a two-dimensional surface that is folded, to a varying degree, in three dimensions. Repeated patterns are a well-represented category of colour patterns, and are defined by the presence of a unit (a spot, dot, stripe, hexagon, or a more complex motif) at least twice on an individual. However, it is more relevant to consider a pattern to be a repeated pattern when the motif is repeated many times. During development, repeated patterns are sometimes induced long before the production of colour: a pre-pattern is produced, which is subsequently decoded into colouration (Manceau *et al.*, 2010; Mallarino *et al.*, 2016). In other instances, colours are produced before or at the same time as patterning (Kondo, 2017), making pattern formation easier to observe and study.

Repeated colour patterns have long interested naturalists and other biologists (Hagen, 1881) and several attempts have been made to classify biological patterns, in the broad sense (for an example, see Meinhardt, 2008). One of the first models of pattern formation during morphogenesis was proposed by the mathematician and computer scientist Alan Turing, in a brilliant paper published in 1952 (Turing, 1952). This model consisted of a (bio-)chemical reaction–diffusion system comprising one activator and one inhibitor that interact to create periodic patterns induced by symmetry breaking. Some years earlier, the genetic origin of variegated colour patterns on maize kernels was elucidated by Barbara McClintock with the discovery of transposons. This can be considered the first biological mechanism to be described for the formation of a repeated colour pattern, although this was not the original aim of her study (McClintock, 1950). Periodic patterns (where motifs are regularly spaced) and random patterns (such as the variegation of maize kernels) constitute two main categories of geometry within repeated patterns. Turing's model was forgotten for a number of decades before simulations in the 1980s proved it effective, and then later by *in vivo* studies of angelfish (*Pomacanthus* sp.) (Kondo & Asai, 1995) and zebrafish (*Danio rerio*) skin and more recently of the flowering plant genus *Mimulus* (Ding *et al.*, 2020). Beyond these examples, biological mechanisms underlying repeated colour patterns remain an important area of research in developmental biology and new mechanisms are regularly being discovered (e.g. Manukyan *et al.*, 2017).

The aim of this review is to summarize and classify the mechanisms that produce repeated colour patterns across eukaryotes. We chose to differentiate the mechanisms that are sufficient to create a repeated pattern, which we call primary mechanisms, from those that are not able to produce patterns by themselves but which influence the final pattern by acting before, during, or after pattern induction (pattern modifiers). Pattern modifiers are of great importance in producing the actual diversity of repeated colour patterns in

nature because they are able to generate patterns that primary mechanisms alone cannot produce, such as the rosettes of leopards.

We define seven families of primary mechanisms [Turing (-like), cellular automaton, multi-induction, physical cracking, random, neuromuscular and printing; see Table 1] and six families of pattern modifiers (Table 2). We discuss the links between pattern geometry and the underlying mechanisms by detailing how information can be extracted from phenotypes. We also discuss the importance of carrying out functional studies in addition to phenotype-based inferences. Placing primary mechanisms in a phylogenetic context shows that the range of eukaryotic species used as model organisms for studying colour patterns is still limited, and we advocate a better coverage of the unexplored eukaryotic diversity. As repeated colour patterns require both the production of repetitive structures and colouration, we also discuss the nature of the links between these two processes. Finally, we propose three ways to discover new families of mechanisms.

II. PRIMARY MECHANISMS

(1) Turing(-like)

This family of mechanisms was theorized by the mathematician Alan Turing in 1952 but forgotten for decades. Turing-like systems have been reproduced *in chemico* (Castets *et al.*, 1990) and have proved their ability to produce repeated patterns, named Turing patterns. Phenotypically, they are characterized by a periodicity of their motifs (i.e. regularity in the distance between two consecutive motifs, which could be dots, stripes or labyrinths) (Kierzkowski *et al.*, 2019). Over the past 20 years, these patterns have been described *in vivo* in many species, as non-colour (Sick *et al.*, 2006; Economou *et al.*, 2012; Nagashima *et al.*, 2018) and colour patterns [Kondo & Asai, 1995; with a recent example in angiosperms (Ding *et al.*, 2020)]. Turing-like mechanisms are thought to be responsible for many periodic patterns in nature, not just colour patterns. The power of these mechanisms lies in the capacity of the reaction–diffusion system to produce a pattern from scratch, or more precisely from a noisy random initial condition, through the amplification of tiny variations (Turing, 1952) (Fig. 1). While the seminal model involved the interaction of two chemical species (one activator and one inhibitor, respectively diffusing over a short and long range), theoretical advances and *in vivo* experiments have demonstrated that numerous derivative systems can give rise to similar patterns, including systems with three or more interacting species, which may include not only diffusible molecules but also cells. Indeed, in the most precisely described model (zebrafish stripes), the pattern seems to arise from a Turing-like mechanism where the interacting agents are the coloured cells themselves rather than diffusible molecules (reviewed in Watanabe & Kondo, 2015). Although these systems are very different in nature, they are linked by common mathematical relationships (such as long-range inhibition and local activation). The Turing mechanism also explains flower colour pattern in *Mimulus* (Ding *et al.*, 2020), which shows that Turing-like systems have been used repeatedly in diverse eukaryotic lineages and confirms that, due to their simplicity and efficiency, these mechanisms can be recruited for different biological purposes. Given the diversity of the biological interacting agents in *in vivo* Turing systems, unifying models have been built to help test their properties, notably when the agents are still poorly understood (Kondo, 2017). Even though periodic colour patterns are common among eukaryotes, there are few *in vivo* examples of well-described Turing mechanisms underlying colour patterns, reflecting the fact that they are inherently difficult to study. Nevertheless, the numerous examples of Turing mechanisms described for other patterns suggest that this family of mechanisms could be responsible for many periodic colour patterns and clues suggesting Turing-like systems are regularly described, for example recently in cats (see C.B. Kaelin, K.A. McGowan & G.B. Barsh, in preparation).

(2) Cellular automaton

This family of mechanisms has so far only been described in ocellated lizards (*Timon lepidus*), which have bicoloured (green and black) scales organized in a quasi-hexagonal lattice (Fig. 2). Manukyan *et al.* (2017) showed that the colour state (green or black) of each skin scale changes over time and is determined by the state of its six neighbouring scales at the previous developmental stage. They suggest that this discrete biological cellular automaton is derived from continuous a Turing-like system by the reduction of the diffusion coefficients at the scale borders. The dotted pattern at the juvenile stage (which is also likely to be produced by a Turing-like mechanism) acts as the initial condition.

(3) Multi-induction

All families of primary mechanisms described in other subsections of Section II share the same feature: the colour motifs in a given repeated pattern have a common origin. In a Turing pattern, each stripe or dot comes from the interaction between the same activator and inhibitor. In a random pattern (see Section II.5), each spot results from a mutation affecting the same gene. Nevertheless, individual motifs in a repeated colour pattern, although they may look similar, could have different origins. Although not parsimonious, multi-induction systems are probably common in nature, like the one giving rise to the para-segments of *Drosophila* embryos (Yu & Small, 2008; Small & Levine, 1991). Although the underlying mechanism is not easy to unravel, examples of multi-induction of colour patterns have been described, notably in the fly *Drosophila guttifera*, which has black spots on its wings. This colour pattern results from the combined action of two independent induction pathways, which are under the control of two *cis*-regulatory elements of the *yellow* gene (Werner *et al.*, 2010) (Fig. 3A). Likewise, the

Table 1. Primary mechanisms involved in the production of repeated colour patterns across eukaryotes

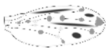
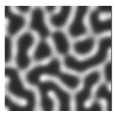
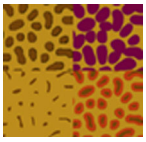
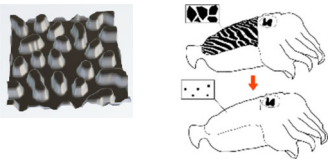
Attributes	Mechanisms						
	Turing(−like)	Cellular automaton	Multi-induction	Physical cracking	Random	Neuromuscular	Printing
Graphical examples of patterns							
Description of pattern	Periodic dots, stripes, eyespots	Labyrinths arranged in a periodic way	Variable; no intrinsic periodicity	Polygons (mostly hexagons); quasi-periodicity on a local scale	Dots, lines, stains (depends on geometry of cell lineage); no periodicity	Periodic bands	Dots, bands, broken lines, triangles; often periodic
Frequency of occurrence	Abundant (angiosperms, animals)	Rare (ocellated lizard *Timon lepidus*)	Probably frequent	Rare (fly agaric *Amanita muscaria*)	Rare in wild species, frequent in domestic breeds	Rare (Cephalopoda: flamboyant cuttlefish *Metasepia pfefferi*, common cuttlefish *Sepia officinalis*)	Abundant (Gastropoda: *Haliotis asinina*, many Conidae)
Number of evolutionary acquisitions currently known	Numerous	One	Probably numerous	One	Numerous	Probably unique	Unique
Pattern reproducibility among individuals (+++, mostly reproducible; ++ and +, some features are reproducible but not all (e.g. distance between two motifs, positions of the motifs); −, mostly non reproducible)	+	+	+++	+/−	–	++	+
Source of the pattern	Reaction/diffusion at the molecular or cellular level	Turing system discretized into a Von Neumann cellular automaton	Multiple	Mechanical stress	Random mutations	Neural, muscular and hormonal control	Progressive deposits of colours and material by the animal mantle and mantle colour state variation over space and time

Table 2. Pattern modifiers that affect the final colour pattern in eukaryotes

Pattern modifiers	Initial conditions and forcing	Tissue growth and deformation	Out-of-equilibrium patterning	Colour production	3D ornamentations	Rapid colour and pattern changes
Basic pattern						
Principal effects on colour patterns	Impose a particular geometry and/or directionality, which generates anisotropic patterning (e.g. stripes)	Induce pattern dilatation and, if the pattern mechanism is active and sensitive to scaling, new motifs (rosettes, reticulations) and/or intermediate colours (in interaction with out-of-equilibrium patterning)	Generate intermediate colours and motifs (in interaction with tissue growth)	Define the colour range and the spatial extension of colour domains. Enhance pattern complexity with: (*i*) multiple colour domains, as a result of multiple thresholds (French Flag Model); (*ii*) complex motifs, derived from a second wave of patterning	Highlight and enhance the visual effects of the colour pattern	Cause the appearance or disappearance of the pattern

black and yellow striped and dotted patterns of Japanese quail (*Coturnix japonica*) juveniles also rely on several distinct mechanisms (Fig. 3B). Haupaix *et al.* (2018) showed that the first lateral stripes are induced by the somite tissue where the *agouti* gene is expressed. By contrast, the outermost lateral bands and the dots on the head, legs and wings are induced by a mechanism which is unknown to date, but which could be a Turing-like patterning mechanism.

(4) Physical cracking

One of the most iconic fungal species, the fly agaric (*Amanita muscaria*) presents white spots on a red background that act as an aposematic signal (Michelot & Melendez-Howell, 2003). The fly agaric is not the only species of the *Amanita* genus displaying this pattern (Yangt & Oberwinklerr, 1999), but it may have the most visible pattern as a result of the contrast between the red and white colouration. The white dots are the remnants of a structure called the universal veil which protects the sporocarp during its early development, and which then undergoes physical cracking as the underlying structure, the red pigmented cap, grows (Yangt & Oberwinklerr, 1999) (Fig. 4A). For energy-minimizing reasons, the first cracks tend to form hexagons, in exactly the same way as other instances of physical cracking such as the formation of geological mud cracks (Li & Zhang, 2011), crocodile head scales (Milinkovitch *et al.*, 2013) and micrometric ornamentations on elephant skin (Martins *et al.*, 2018) (Fig. 4). As the cap grows, the white hexagons tend to retract, forming "warts" that gradually separate from each other. This generates a pseudo-periodic colour pattern and has only been described in fungal species (Yangt & Oberwinklerr, 1999).

(5) Random

In many wild angiosperm species, but primarily in many cultivated varieties, plant organs bear mosaic or variegated patterns, which consist of coloured patches that are irregularly spaced on the tissue. These patterns are not only present in flowers, but also on leaves, fruits and seeds, like the variegated colour pattern of maize kernels which led Barbara McClintock to discover transposons (McClintock, 1950) (Fig. 5C). Transposable elements are thought to be responsible for the majority of mosaic patterns in angiosperms, such as the one described in carnation (*Dianthus caryophyllus*) flowers by Itoh *et al.* (2002), although viruses, a fault in migration of coloured cells and other mechanisms are also candidates for producing these patterns in plants and animals (Caro & Mallarino, 2020). In maize kernels or in flowers, the general principle is that a transposon is inserted within or near a gene or a regulator of the anthocyanin biosynthesis pathway, suppressing (or activating if the gene/regulator is a pathway inhibitor) anthocyanin production.

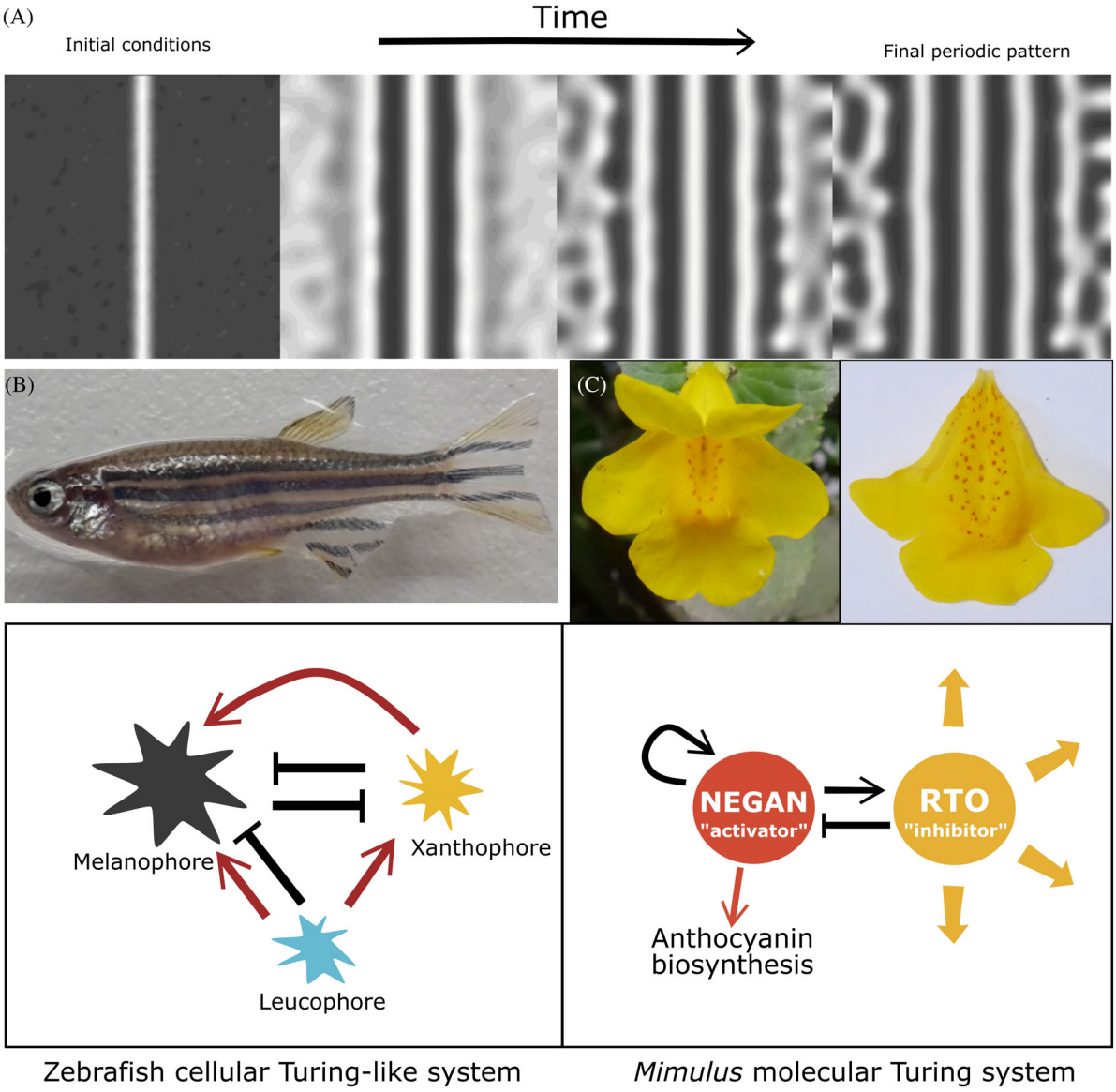


Fig 1. Turing-like mechanisms. (A) Turing systems are able to produce periodic patterns from scratch, or more precisely from random initial conditions. (B) Zebrafish (*Danio rerio*) stripes are produced by a system composed of three coloured cell types: melanophores, xanthophores and leucophores. Red arrows: activation; black T-lines: inhibition. Photograph courtesy of Christine Rampon, Collège de France. (C) *Mimulus* flowers exhibit a spot pattern produced by a Turing system composed of an activator (NEGAN) and an inhibitor (RTO) which interact to control anthocyanin biosynthesis. Red and black arrows: activation, black T-lines: inhibition; large yellow arrows: diffusion.

In every cell where the transposon is excised properly, anthocyanin synthesis can be restored (or suppressed), leading to differences in pigmentation between cells. Because excision is mostly random (but may be induced by stress factors), the distribution of 'abnormal' cells, and thus patches of colour, is also random. The size and shape of the coloured patches is determined by the lineage of the mutated cell and the time when excision takes place during development (Fig. 5D).

Such random patterns are also observed on animal skin, mostly on the coats of mammals (Caro & Mallarino, 2020). The over-representation of mammals may be due to a sampling bias but the most likely hypothesis is that random patterns are rare in wild species but arise frequently in domestic breeds (widespread in mammalian species) from artificial selection (e.g. the coat of Dalmatian dogs) or genetic drift. The reason why these patterns are relatively infrequent in natural populations may be due to the genetic instability of the colouration mechanisms entailing non-Mendelian transmission from one generation to the next (Kaelin & Barsh, 2013), or alternatively these phenotypes may be counter-selected.

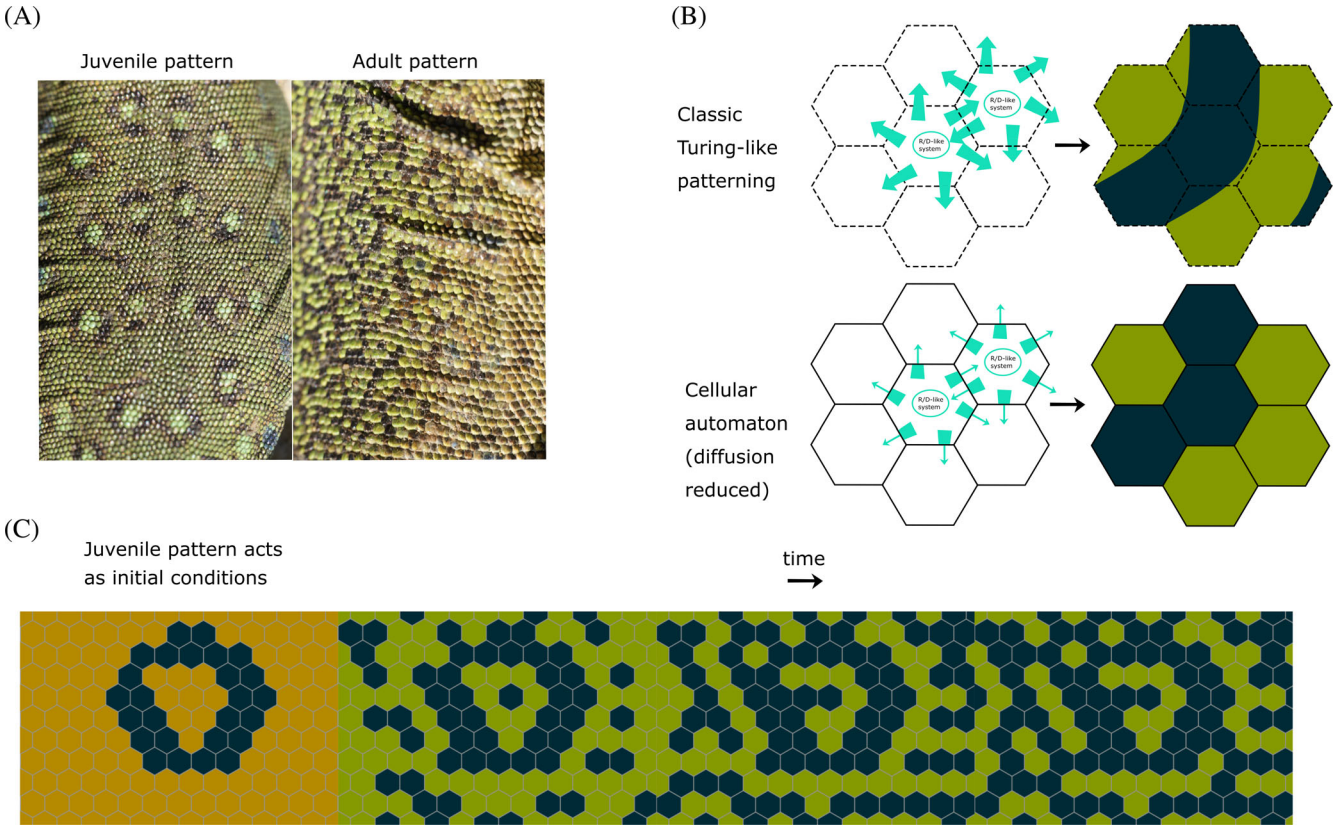


Fig 2. Cellular automaton mechanisms. A cellular automaton produces the black and green repeated pattern of the ocellated lizard *Timon lepidus*. (A) Juvenile and adult patterns. Photograph courtesy of Françoise Serre Collet, MNHN. (B) Unlike classic Turing patterning, the cellular automaton produces a discrete pattern by strongly reducing diffusion at the scale borders (R/D: reaction/diffusion). (C) The brown and white juvenile pattern acts as the initial conditions to produce the adult pattern. The colour state of a given scale is determined by the colour state of its six neighbouring scales.

(6) Neuromuscular

The skin of many cephalopods is adorned with periodic colour patterns, which are presumably produced by cellular Turing-like mechanisms and involve both pigments and structural colours (Williams *et al.*, 2019). Furthermore, like chameleons, many cephalopod species are able rapidly to change the colour of their epidermis, usually by making all or part of their pattern appear or disappear (Chiao & Hanlon, 2019) by changing the morphology of colour cells through neuromuscular control (Y.C. Liu, W.C. Wang & B. Grasse, in preparation) (Fig. 6).

In addition, and because of their ability to desynchronize the appearance and disappearance of parts of these patterns, some cephalopod species produce a unique type of repeated pattern. This consists of a striped pattern of black and white bands which appear to move in dynamic waves along their bodies (How *et al.*, 2017) (Fig. 6). Some species are characterized by bands with an antero-posterior movement, others display a postero-anterior movement and some are able to generate multi-directional waves. The processes underlying these dynamic patterns remain elusive but there are two main hypotheses: either they are generated by neuronal activity or by electrically coupled autonomous muscular activity (Y.C. Liu, W.C. Wang & B. Grasse, in preparation) (Fig. 6). This is the only example we could find of dynamic repeated colour patterning.

(7) Printing

Shells exhibit some of the most beautiful and diverse exoskeleton colour patterns to be found in animals. Since the 1970s, extensive theoretical work has been carried out to devise models of the formation of these patterns (for a review see Meinhardt, 2009). More recently, functional studies have begun to shed some light on the biological mechanisms underlying the formation of these colour patterns (Jackson *et al.*, 2006; Budd *et al.*, 2014), which are generated by pigmented material produced by the mantle during the secretion of the mineralized structure. Like a printer, the mantle border produces a colour pattern in one dimension which gives by addition a pattern in two dimensions (Fig. 7). The colour state of the border cells is dynamic and changes during shell development, which ultimately results in complex patterns in terms of geometry and colour (see Fig. 7A). Although it is known that colours and mineralized structures are produced by a rapidly evolving secretome (Jackson

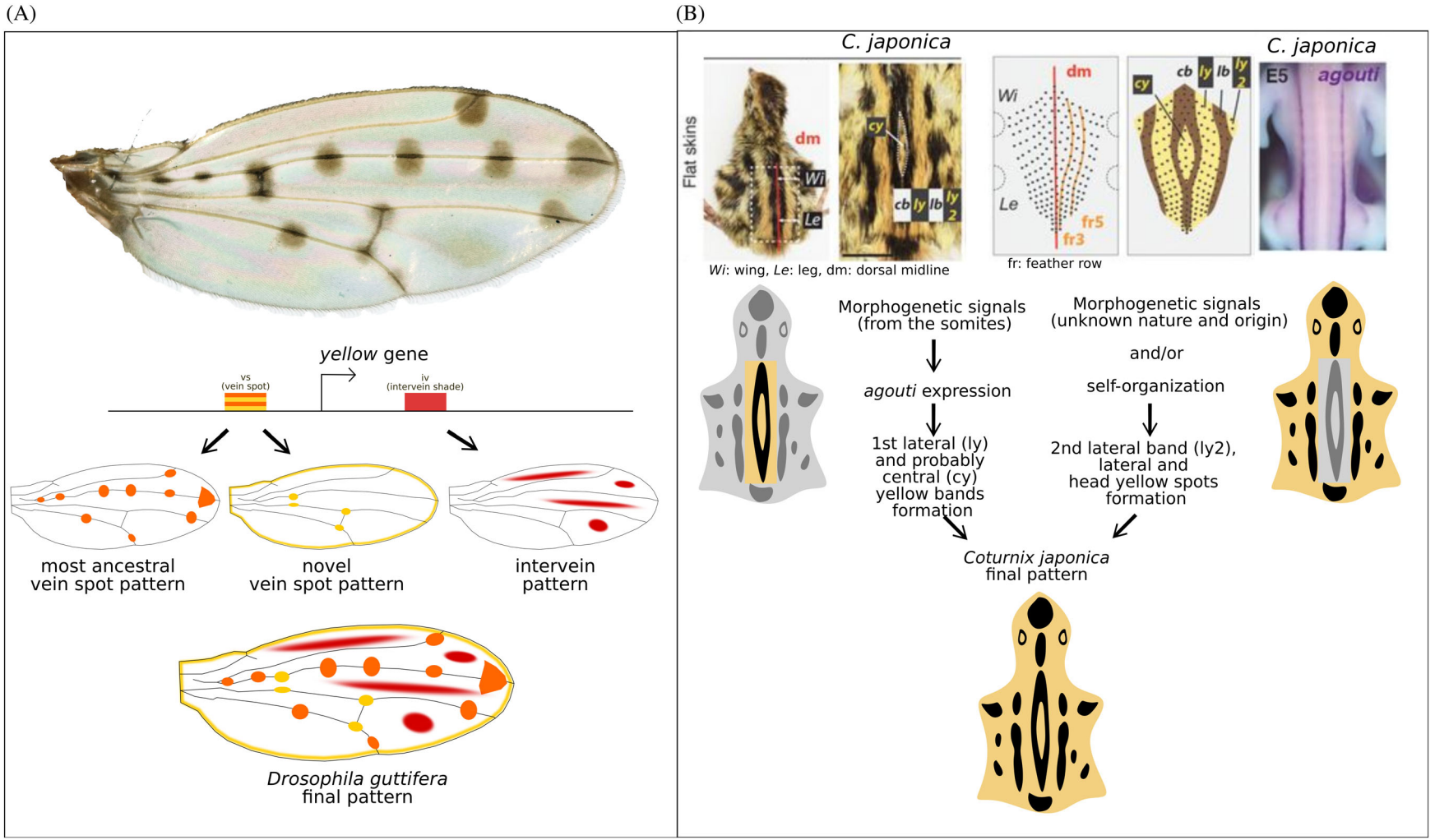


Fig 3. Multi-induction mechanisms. (A) *Drosophila guttifera* wings harbour a black spot pattern, induced by two different *cis*-regulatory elements (CREs) of the *yellow* gene: vs (vein spot) and iv (intervein shade). Photograph courtesy of Emmanuel Delfosse, MNHN). (B) The striped and dotted black and yellow pattern in quails (*Coturnix japonica*) is produced by at least two independent mechanisms: the central band (cb) and the first lateral (ly) yellow bands are induced by somite signalling through agouti expression. The bands that are in a more lateral position and the dotted pattern on the head, wings and legs are produced by another mechanism of unknown nature, probably a Turing-like mechanism. The upper part is adapted from Haupaix *et al.* (2018).

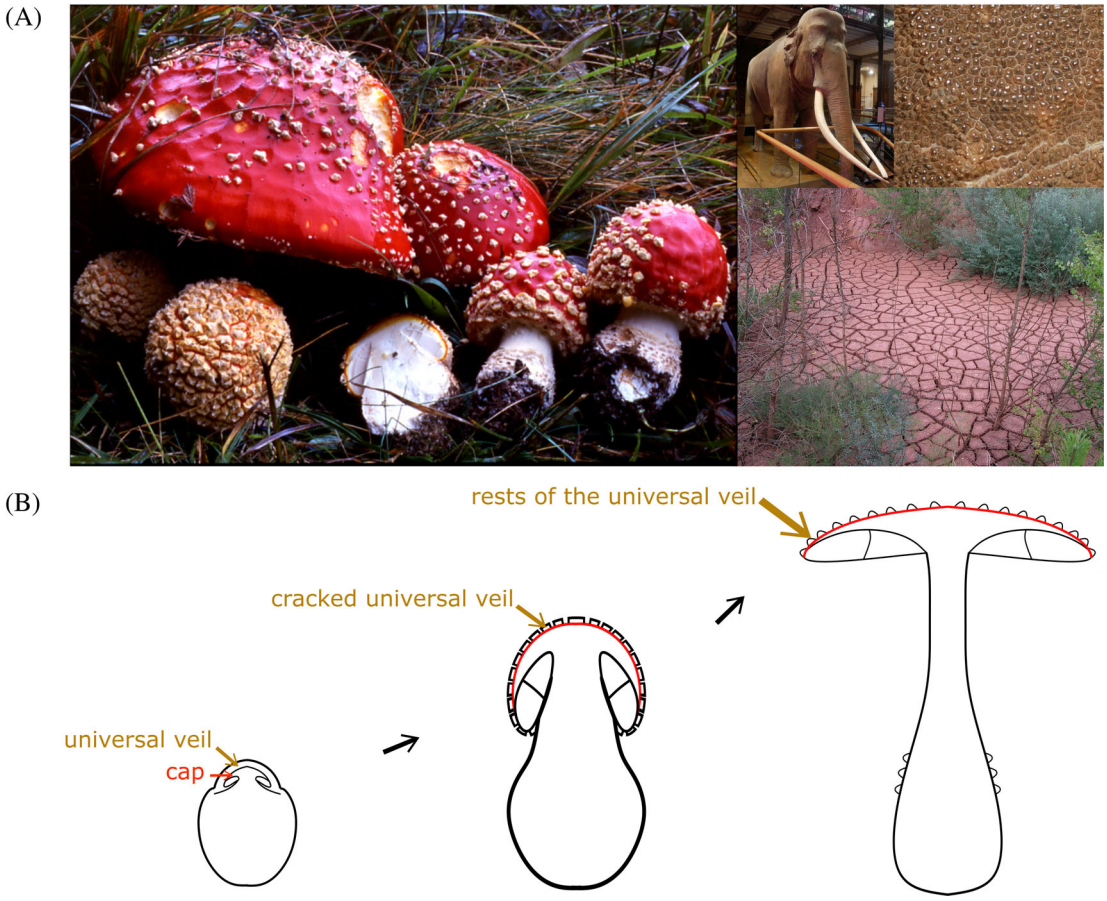


Fig 4. Physical cracking mechanisms. (A) Physical cracking patterns are common in nature: the colour pattern of the fly agaric *Amanita muscaria* (photograph courtesy of Bart Buyck, MNHN), elephant skin, and mud cracks (photograph courtesy of Cyril Langlois) are all produced by the same family of mechanisms. (B) In fly agaric, the white universal veil protects the cap during the first stages of its development then cracks during the expansion of the growing red cap, generating the aposematic colour pattern.

et al., 2006), the nature of the morphogenetic signals remains unknown. Nevertheless, several mechanisms have been suggested, involving Turing-like systems or neural activity (Boettiger & Oster, 2009). The final pattern repetitions stem from two distinct mechanisms: one temporal and one spatial (Fig. 7B–D). The axis of the first mechanism is perpendicular to the border: motifs are repeated along this axis, which means that the mantle is periodically in the same colour production state at different times during development. The axis of the second mechanism is parallel to the border. At a given colour production state, the mantle produces a repeated motif all along its border (e.g. alternating coloured and non-coloured regions). The signals leading to these repeated one-dimensional motifs remain unknown.

III. PATTERN MODIFIERS

Many parameters and pattern modifiers can affect the final aspect of the repeated colour pattern. Here, a factor is considered as 'pattern modifier' if its presence is not required for pattern production, but it affects aspects of the final pattern. These modifiers are common because the systems producing colour patterns rarely act independently and the tissues where these patterns are formed are themselves dynamic. These factors, although classed as secondary, may have strong geometric effects such as redefining the nature of the motifs (stripes, dots, labyrinthine patterns) or their directionality.

Despite the potential impact of pattern modifiers, most studies have focused on primary mechanisms, so that pattern modifiers are still relatively understudied. Table 2 summarizes the six families of pattern modifiers we propose herein. The second and third rows of Table 2 illustrates and describe how a pattern modifier can affect a pattern, in this case a periodic pattern.

(1) Effect of initial conditions and forcing

These two classical mechanisms, which are not specific to colour patterning, interact with dynamic systems and can be differentiated by their timing. Initial conditions define the state of the system at the beginning of colour pattern

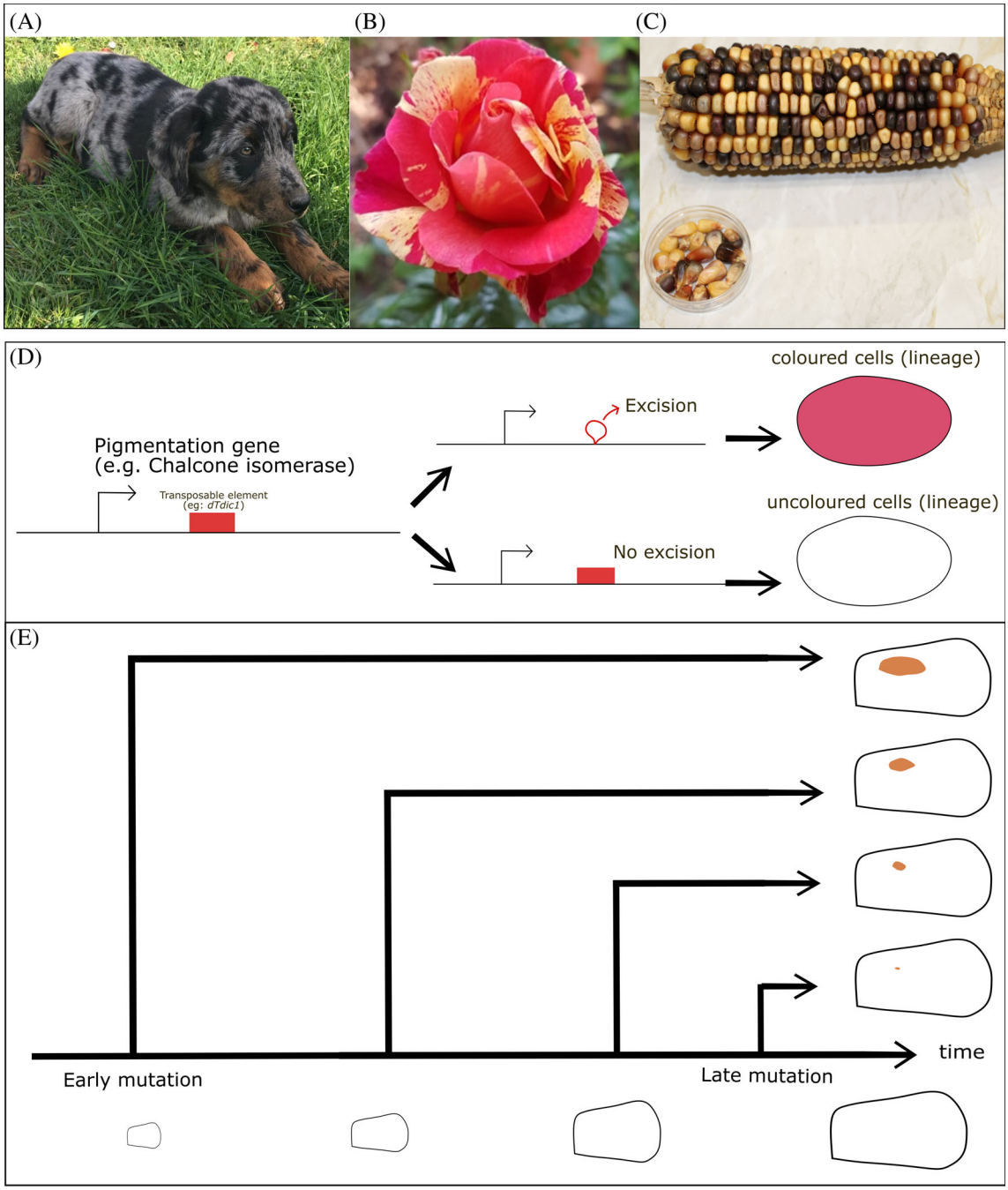


Fig 5. Random mechanisms. (A) An Australian shepherd dog (*Canis lupus*, photograph courtesy of Émilie P.) harbouring a merle coat. (B, C) Flecked patterns of a rose cultivar (*Rosa* spp.) and maize kernels (*Zea mays*). Educational collection of the Biology Department of the École Normale Supérieure de Lyon, photograph courtesy of Jean-Pierre Moussus. (D) The transposon mechanism responsible for many random colour patterns on flower petals with the example of the carnation (*Dianthus caryophyllus*) 'Rhapsody' cultivar. (E) Geometry of the final pattern is determined by the timing of the mutation and the lineage of the mutated cells.

formation. Modifying the initial conditions can have a strong effect on the final pattern as in many cases the system keeps a memory of its initial state (Arcuri & Murray, 1986). For example, in a classical Turing system, if the initial state is uniform with the exception of one stripe, under certain conditions this will impose a striped pattern at the final state. Without this initial stripe and with no other external effector, the pattern would have been anisotropic [with no preferential direction (Kondo & Miura, 2010)].

The mechanisms that determine the initial conditions are assumed not to interact with the system as the system starts

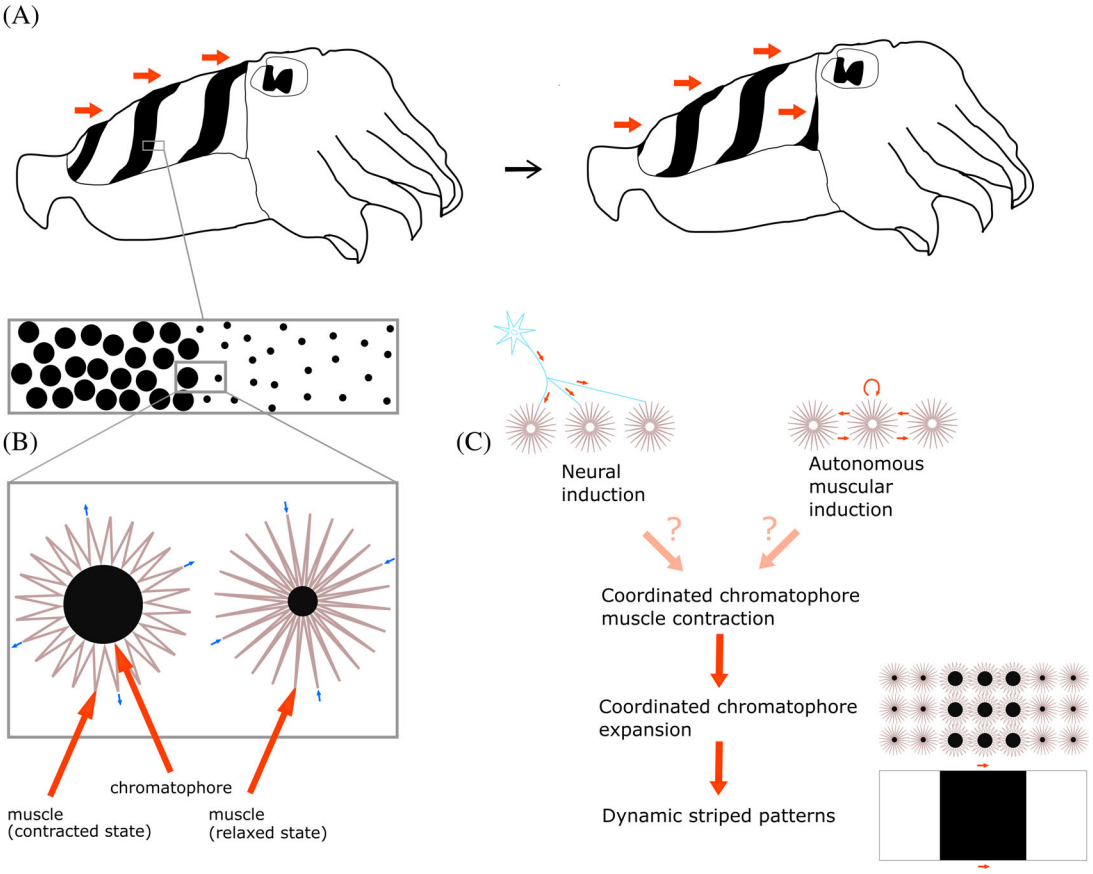


Fig 6. Neuromuscular mechanisms in cephalopods. (A) Many cephalopod species are able to produce repeated patterns (typically stripes) which move dynamically on the skin likes waves. (B) The contraction and relaxation of the muscles associated with the chromatophores generates colour change. (C) Neuromuscular wave patterns are probably generated by neural induction or autonomous muscular induction.

to 'run'. Mechanisms that do interact with the system during patterning are called forcing. Whether influenced by the initial conditions or by forcing, the nature of the interaction can be direct [e.g. the juvenile pattern acts as an initial condition for the automaton pattern in ocellated lizards (Manukyan *et al.*, 2017)], or indirect [e.g. the zebrafish myoseptum – a lateral structure – influences the migration of colour cells, imposing an antero-posterior directionality to the pattern (Frohnhöfer *et al.*, 2013)]. Boundary conditions, which determine how the system behaves at its borders, form a part of this pattern modifier family, and can be seen both at the initial conditions and during forcing.

Furthermore, using timing to distinguish between initial conditions and forcing is challenged by the existence of mechanisms that interact with the system before and during the patterning process, thus being both initial conditions and forcing interactors.

(2) Tissue growth and deformation

The first and trivial effect of tissue growth is to deform the tissue geometry, and consequently the pattern, after its establishment. Indeed, like many other parts of the organism, coloured tissues frequently undergo differential growth during development (and/or less frequently size reduction), which leads to allometric scaling and pattern distortion. The second effect of growth is to produce colour patterns directly, as described above for physical cracking. A third effect can be seen when tissues grow during patterning, if the pattern mechanism is sensitive to scale effects (Kondo & Shirota, 2009), as in Turing systems. In this case, growth is able to disrupt patterning by displacing equilibria (Crampin, Hackborn & Maini, 2002) and therefore creates new motifs and colour associations that could not exist without growth. For example, the rosettes of an adult leopard are derived from juvenile dots, which have been disrupted by skin growth and rearranged into rosettes (Liu, Liaw & Maini, 2006).

(3) Out-of-equilibrium patterning

Many pattern formations are dynamic, starting with initial conditions and culminating with a final state where the system has reached (or not) an equilibrium. The timing and duration of this competency period could have strong effects on the overall pattern. In particular, if the competency stops

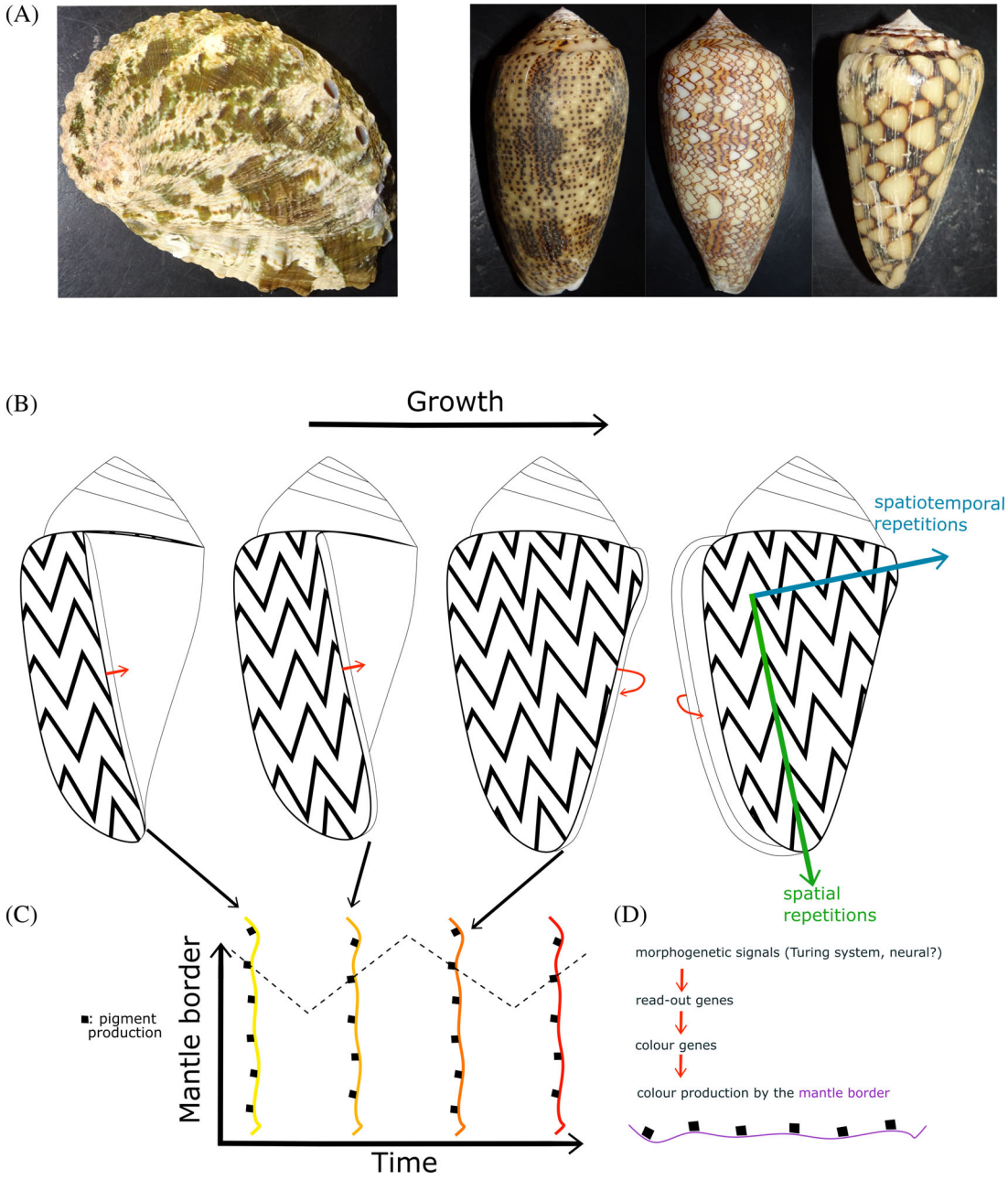


Fig 7. Printing mechanisms in mollusc shells. (A) Many gasteropods exhibit striking repeated colour patterns on their shells. Left, colour pattern of *Haliotis asinina*, a species used for the transcriptomic analysis of colour and mantle production (M11/BC 566, MNHN, Paris). Right, diverse repeated colour patterns of Conidae species (IM-2013-12451, IM-2013-46951, IM-2013-47292; MNHN, Paris). (B) Repeated patterns on shells are produced by the mantle during shell growth. (C) The colour state of the mantle produces a spatial repetition parallel to the shell border. The temporal evolution of the mantle colour state determines the orthogonal spatiotemporal repetitions. (D) The morphogenetic signals responsible for these patterns remain unknown but could have a neural origin.

before the system reaches equilibrium, it generates out-of-equilibrium patterns characterized by intermediate features [-i.e. intermediate colours or shapes (band insertions)]. Some species exhibit colour patterns with no end-of-competency (e.g. leopards), which means that patterns continuously evolve and respond to perturbations (typically growth) (Kondo & Asai, 1995). This does not mean that out-of-equilibrium patterns do not exist in these species, but that they are only transient.

(4) Colour production

Most of the time, patterns are established first as signals that are not colours. These pre-patterns are then interpreted into

colours. This two-step process could transform and add complexity to the pattern [e.g. with a multiple threshold system like the French Flag model (Wolpert, 1969)]. For example, many butterfly species exhibit conspicuous eyespots on their wings. The position of the centre of an eyespot seems to be determined by a Turing-like mechanism involving the expression of *Dll* (*Distal-less*) in the imaginal disc. After that, another system takes over to produce complex patterns that consist of several concentric circles (or arcs) of different colours (Connahs *et al.*, 2019).

(5) 3D ornamentations

In this review, we chose to simplify the structure of external colour tissues by considering them as more or less flat. Nevertheless, many species harbour 3D ornamentations (reliefs or appendages such as hairs, scales or feathers) that add a layer of complexity that can accentuate repeated colour patterns.

(6) Rapid changes in colour and pattern

While many species harbour colour patterns that change over a relatively long period of time (for example during the juvenile-to-adult transition), some species of chameleons and cephalopods are able to change their colour patterns rapidly and reversibly (within seconds or minutes), adding a layer of complexity to repeated colour patterns (Ligon & McCartney, 2016).

IV. DISCUSSION

(1) Distribution of the different families of mechanisms across the phylogeny of eukaryotes

The mechanisms for producing colour are very diverse across the eukaryotic tree of life, and affect different structures, tissues and cell types. Nevertheless, similar mechanisms have evolved repeatedly in phylogenetically distant clades. As discussed above, this is the case for the production of periodic patterns from Turing-like systems, which have been described in animals (i.e. fish, but likely in many other clades) and plants (i.e. *Mimulus* and also likely in many other clades). The distribution of the different families of mechanisms discussed herein is mapped onto a phylogeny of eukaryotes in Fig. 8. Although this phylogeny is far from representative of the taxonomic diversity of the eukaryotic models studied in terms of repetitive colour patterns, some (five of the seven) primary mechanisms are described for only a limited number of species to date. Consequently, the list is therefore exhaustive (i.e. up to date with the literature) for these five primary mechanisms (i.e. Turing-like, physical cracking, neuromuscular, printing and cellular automaton). The two other families of mechanisms (random and multi-induction) are shown for a selection of representative examples. Furthermore, some families of mechanisms have only been described in a limited number of species but, as in the case of Turing-like systems, are believed to be responsible for repeated colour patterns in many species that have not yet been documented. Others, like the neuromuscular family of mechanisms described in gastropods, are unlikely to be found in other taxa.

Among the seven primary mechanisms that we have defined, four seem to be restricted to a single taxon (physical cracking in *Amanita* fungi, cellular automaton in ocellated lizards, printing on mollusc shells, and neuromuscular mechanisms in cephalopods) and another one (random) seems rare in wild species. This means that almost all the known diversity of repeated patterns is likely to be produced by Turing-like or multi-induction as well as yet undiscovered mechanisms.

(2) Strengths and limitations of our classification of primary mechanisms

Although diverse repeated colour patterns have been described, our theoretical and experimental knowledge

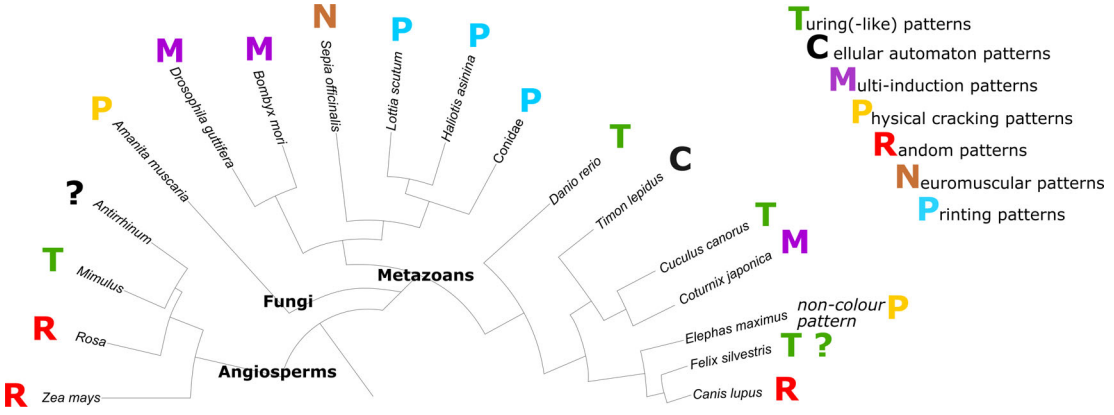


Fig 8. Summary of the eukaryotic taxa described in this review, and of the different families of mechanisms responsible for repetitive colour patterns, mapped on a phylogenetic tree built from NCBI Taxonomy database (https://www.ncbi.nlm.nih.gov/Taxonomy/CommonTree/wwwcmt.cgi?fbclid=IwAR1pRMTFDhM8jw438eCoIp6lh8eykg8qpO8h6HR-HFojQRT6gOQVNnyCItY) using the 'Common Tree' tool based on a diverse array of resources (NCBI taxonomy database). The tree file was uploaded and visualized using ITOL (Interactive Tree of Life) software (https://itol.embl.de/, 5.6.3 version).

regarding the underlying mechanisms is still fragmented. The classification system we propose herein reflects the current knowledge in this field and will need updating when new mechanisms are inevitably discovered.

Characterizing the geometry of a given colour pattern provides valuable clues regarding the possible underlying mechanisms and also can be an indicator of other features, such as population genetic health (see Larison *et al.*, 2021). Indeed, several of the seven families of mechanisms we defined produce characteristic patterns (i.e. random patterns produced by random mechanisms, labyrinths produced by cellular automaton mechanisms, cracks produced by physical cracking mechanisms).

However, many of the other families of mechanisms are able to produce periodic patterns (i.e. Turing(−like), neuromuscular, printing and to a lesser extent multi-induction mechanisms), which underlines the need for caution when inferring mechanisms from phenotypes, as this is not a one-to-one relationship. Functional investigations remain essential. A single family of mechanisms, defined by certain characteristics, can involve different processes. For example, Turing(−like) mechanisms can rely on reaction–diffusion systems of chemical compounds (such as those conceived by Alan Turing), but also on systems based on cell–cell interactions [e.g. zebrafish (Frohnhöfer *et al.*, 2013)]. Similarly, random pattern production involves very different processes [e.g. transposon insertion/excision, X chromosome inactivation, defective neural crest migration (Caro & Mallarino, 2020)]. Admittedly, although the mechanisms assigned to a given family are undoubtedly similar, the way we organized them into families was also influenced by the patterns they produce.

Additionally, it has to be noted that Turing systems are not restricted to the periodic patterns obtained from the mechanisms grouped in the family we referred to as Turing-like. They can also play (or are believed to play) indirect roles by acting upstream and/or in conjunction with other families of mechanisms (like cellular automaton, printing, or neuromuscular). The almost ubiquitous involvement of Turing systems in many different processes underlines their importance in nature, and in particular in colour patterning. If the suspected roles of Turing systems are confirmed, it might be valuable to consider an additional super-family, called 'Turing-related mechanisms', containing all the families of mechanisms that directly or indirectly involve Turing systems.

(3) Evolutionary and mechanistic coupling between the repetition of structural units and colouration: three ways to organize colours into repeated patterns

The production of a repeated colour pattern requires (*i*) the production of a repeated structure and (*ii*) the production of colours. The relationship between the two processes can be very tight from both an evolutionary and a mechanistic perspective, or conversely these processes may be independent. Consequently, we propose two categories (Type I and Type II; Fig. 9A) representing the diversity of the repetition/colour relationship. This discrete representation does not necessarily capture all the subtleties of repeated colour patterns and is intended as a basis for discussion.

The first type includes instances where the colours and structure are the same (observed in many Turing-like patterns) or when colours are the only repeated structure on the tissue (observed in random patterns, Fig. 9B). Conversely, colours can be produced on a pre-formed repeated structure, which may have functions other than providing colour. The appearance of the repeated structure could precede the appearance of colour during development and may have evolved first. Therefore, through co-option, many repeated structures have been used as a framework to produce repeated colour patterns. We consider two separate cases: either the repeated structure is itself coloured during development [Type II (colouration); Fig. 9C], or the repeated structure serves as a geometric template and its geometry is transferred to a distinct structure that produces colours [Type II (transfer); Fig. 9D].

(*a*) Type I: entanglement of repetition and colouration: when repetitions are produced directly by colouration

In some cases, repeated colour patterns do not require pre-existing repeated structures. It is the coloured regions themselves that organize and generate repetitions. As an example, patterns generated by random mutations do not rely on pre-existing structures, and consequently repetition and colouration derive from the same event/mechanism. Similarly, zebrafish stripes and the dots of *Mimulus* flowers are produced by colour cells and colour genes, respectively, through the self-organizing processes described above.

This tight link between repetition and colouring does not necessarily mean that these processes evolved simultaneously at the same time. Indeed, we can imagine that in zebrafish, the ability of cells to self-organize into periodic structures appeared during evolution before the ability to produce colours, or *vice versa*.

(*b*) Type II: colouring a pre-existing repeated structure or transferring pre-existing repeated geometry, when pre-formed repeated structures are co-opted to generate repeated colour patterns

Eukaryotic organisms harbour countless examples of repeated structures, such as the metameric body plan (Couso, 2009) and the repetition of external organs and appendages [e.g. feathers and petals (Diggle, 2014)]. These repeated structures provide an endless toolkit for generating repeated colour patterns, since each repetition only needs to produce a single colour motif to generate a repeated colour pattern on a large scale. Here, the production of the repeated structure is independent from colour production, in terms of timing (repeated structures are produced before colour) and the mechanism involved (the molecules, cellular events and physical forces act in independent pathways).

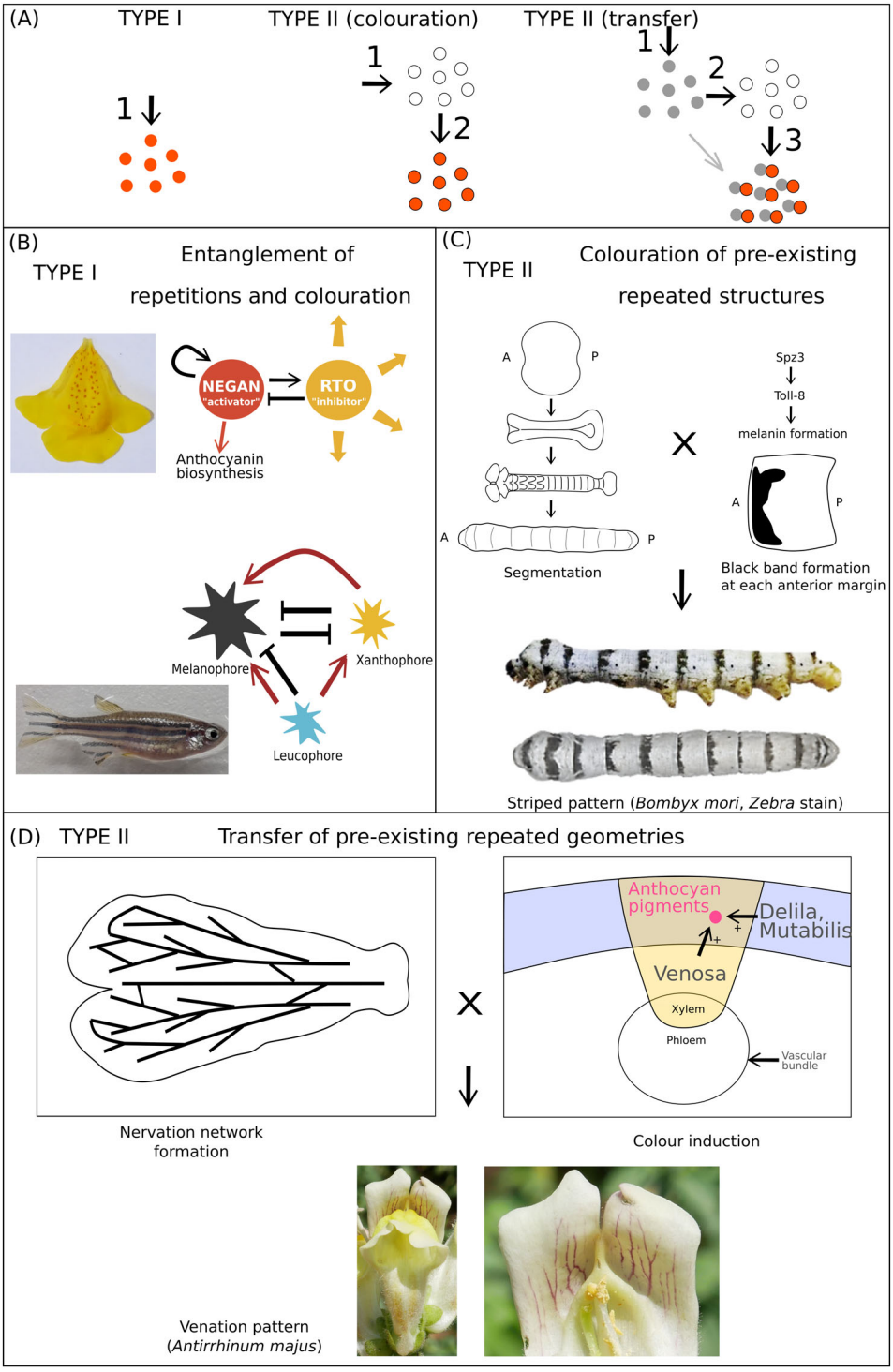


Fig 9. Two types of repetition/colouration coupling. (A) Three examples of the links between repetition and colour patterns. (B) Type I: coupling of repetition and colour production. In self-organizing systems like those generated by Turing-like or random mechanisms, there is no pre-existing repeated structure prior to colouration. Both repetitions and colours are generated by the same process. (C) Type II (colouration): colouring a pre-existing repeated structure. The zebra strain of *Bombyx mori* combines a metameric organization of the body with the formation of a black band at each anterior margin through the expression of Spz3 (Spätzle 3) and Toll-8 pathway, generating a striped black and white pattern (photograph courtesy of H. Fujiwara and S. Yoda). (D) Type II (transfer): transferring pre-existing repeated geometry. The repeated geometry of the venation network of *Antirrhinum majus* is transposed onto a colour pattern of the epidermis. Anthocyanin pigments are produced when VENOSA (produced by the xylem and transported locally to the nearby epidermis) and DELILA factors (produced in the epidermis) are present in the same cell.

There are many examples (but few studies) of the production of repeated colour from existing repeated structures in eukaryotes. For instance, the black and white stripes found on the throat of the cuckoo (*Cuculus canorus*) are produced by a succession of bicoloured feathers, giving the impression that a colour mechanism produces these stripes. In fact, this striped pattern results from the combination of a discrete distribution of feathers and a bicolour mechanism. Many experiments and models suggest that the formation and distribution of feather buds result from a reaction–diffusion (and chemotaxis) mechanism (Ho *et al.*, 2019; Bailleul *et al.*, 2019), providing further evidence that repeated colour motifs in nature can rely directly or indirectly on Turing systems.

Repeated colour patterns are commonly reported in metamerous organisms, metamery being the repetition of structurally similar body segments. The Zebra strain of the silkworm (*Bombyx mori*) harbours a striped black and white pattern (Fig. 9C) that results from the production of a black band on every segment and is controlled by the Toll ligand Spätzle3 (KonDo *et al.*, 2017).

The angiosperm genus *Antirrhinum* is a model for evo-devo studies of floral traits (Whibley *et al.*, 2006). Among the vast range of floral colourations seen in cultivated and wild species, some have striking branching network colourations on the upper petals that have been shown to attract pollinators and guide them to the nectar (Whitney *et al.*, 2013). The pigmentation pattern of the epidermis matches the underlying venation system. Shang *et al.* (2011) showed that venation acts as a spatial frame for anthocyanin production, which is regulated by proteins produced in the epidermis [the bHLH (basic helix–loop–helix) transcription factors DELILA and MUTABILIS] and a protein produced only in cells radiating from the vein [the MYB (myeloblastosis) transcription factor VENOSA] (Fig. 9D).

(4) Seven or more? Discovering novel ways for eukaryotes to produce repeated colour patterns

While the purpose of this review was to define families of the primary mechanisms producing repeated colour patterns in eukaryotes based on the available data, it is likely that additional mechanisms exist in nature and thus our classification is likely to evolve to integrate new findings. We suggest that additional sources of repeated colour patterns could be identified based on two criteria. First, by looking for biological mechanisms that are already known to produce repeated spatial patterns, but which at present are not known to produce any colour patterns. This probably includes many examples of patterns that take advantage of pre-existing repeated structures. Second, by looking for biological mechanisms that produce colour patterns that are not repetitive and imagining how they could produce repetitions as parsimoniously as possible.

(*a*) Tinkering with pre-existing patterns, a promising toolkit for the evolution of repeated colour patterns

Because of the evolutionary simplicity of using pre-existing repeated structures to generate colour patterns, it could be expected that pre-existing repeated structures are the source of many unstudied examples of repeated colour patterns. This includes the great diversity of mechanisms responsible for metamerism in many eukaryotes (e.g. the silkworm body plan, Fig. 9C).

(*b*) Structural colours and repeated patterning

Among the four ways used by animal and plant species to generate colours, namely pigment production, structural colouration, fluorescence (Iriel & Lagorio, 2010; Welch *et al.*, 2012) and bioluminescence (Haddock, Moline & Case, 2010; Viviani, 2002; Weitz, 2004), pigment production and structural colouration account for the large majority of natural colour patterns. Structural colours are responsible for many conspicuous types of colouration and iridescence (when colour changes with the angle of view or the angle of illumination) in almost every animal phylum (Berthier, 2007), as well as in plants [flowers (Whitney *et al.*, 2009), fruits (Vignolini *et al.*, 2012) and leaves (Thomas *et al.*, 2010)]. They are generally produced when light interacts with repeated, more-or-less ordered nanostructures (Berthier, 2007). By taking advantage of the periodicity of light at that scale and of the structures producing these colours, it is possible, at least in theory, to generate periodic patterns at the macroscopic scale (millimetres or centimetres) without relying on any tissue periodicity at the macroscopic scale. As an example, a regular decrease or increase of the crystal pitch along a tissue composed of photonic crystals (one of the structures producing structural colours *in vivo*) could generate repeated macroscopic patterns, typically stripes. Insects, with the tremendous diversity of structural colours exhibited on their cuticles, are a prime target for searching for these kinds of mechanisms.

(*c*) Mechanochemical induction of repeated colour patterns

So far, colour patterns generated by mechanical forces have only been reported in *Amanita muscaria* (physical cracking). Nevertheless, mechanochemical patterning has recently been attracting strong interest from researchers. According to these models, self-organized mechanical patterns precede chemical and molecular patterns. Many experiments and modelling demonstrate their ability to generate patterns that are similar to those produced by chemical systems, in particular periodic patterns produced by Turing systems (Naganathan & Oates, 2017; Brinkmann *et al.*, 2018). They are therefore prime candidates for the discovery of new colour patterning mechanisms.

V. CONCLUSIONS

(1) Eukaryotes present a remarkable diversity of repeated colour patterns that are generally associated with crucial biological functions. Based on a literature survey, we classified the mechanisms responsible for their formation into seven families, and discuss their relative

importance. Exploring the diversity of repeated colour patterns in eukaryotes and understanding their underlying mechanisms are thriving research topics in evolutionary and developmental biology.

(2) Relying on the ubiquitous and powerful Turing systems to explain repeated colour patterns should not hinder the progress of research focusing on other types of primary and secondary mechanisms. In addition, we only know a fraction of the likely mechanisms underlying the phenotypic diversity of repeated colour patterns observed in nature, which should motivate a broader investigation of eukaryotic diversity with respect to colour patterning.

(3) We advocate the use of a classification system of the mechanisms explaining the formation of repeated colour patterns. Providing a unified framework for the way repeated colour patterns are discussed will help promote dialogue between researchers with different backgrounds (e.g. geneticists, developmental biologists, and evolutionary biologists) and will help to build bridges between such disciplines.

VI. ACKNOWLEDGEMENTS

We acknowledge the Institut de Systématique Evolution Biodiversité (ISYEB) and the Muséum national d'Histoire naturelle (MNHN) for financial support. We are grateful to the curators at the MNHN (Emmanuel Delfosse, Barbara Buge, Nicolas Vidal) who allowed us access to biological specimens, and to Marie Manceau for comments on an earlier version of the manuscript. We warmly thank Morgan Gostel and Hélène Citerne for critically reading our manuscript and making constructive comments. We also thank Pr. Serge Berthier for useful discussions on the potential contribution of physical colours to repeated colour patterns. We thank Shigeru Kondo and one anonymous reviewer for their comments and suggestions. P.G. was supported by a fellowship from ENS de Lyon.

VII. REFERENCES

Arcuri, P. & Murray, J. D. (1986). Pattern sensitivity to boundary and initial conditions in reaction-diffusion models. *Journal of Mathematical Biology* **24**, 141–165.

Bailleul, R., Curantz, C., Dinh, C. D.-T., Hidalgo, M., Touboul, J. & Manceau, M. (2019). Symmetry breaking in the embryonic skin triggers directional and sequential plumage patterning. *PLoS Biology* **17**, e3000448.

Berthier, S. (2007). *Iridescences: The Physical Colors of Insects*. Springer Science & Business Media, Berlin/Heidelberg, Germany.

Boettiger, A. N. & Oster, G. (2009). Emergent complexity in simple neural systems. *Communicative & Integrative Biology* **2**, 467–470.

Brinkmann, F., Mercker, M., Richter, T. & Marciniak-Czochra, A. (2018). Post-Turing tissue pattern formation: advent of mechanochemistry. *PLoS Computational Biology* **14**, e1006259.

Budd, A., McDougall, C., Green, K. & Degnan, B. M. (2014). Control of shell pigmentation by secretory tubules in the abalone mantle. *Frontiers in Zoology* **11**, 62.

Caro, T. & Mallarino, R. (2020). Coloration in mammals. *Trends in Ecology & Evolution* **35**, 357–366.

Castets, V., Dulos, E., Boissonade, J. & De Kepper, P. (1990). Experimental evidence of a sustained standing Turing-type nonequilibrium chemical pattern. *Physical Review Letters* **64**, 2953–2956.

Chiao, C.-C. & Hanlon, R. T. (2019). *Rapid Adaptive Camouflage in Cephalopods*. Oxford Research Encyclopedia of Neuroscience, Oxford, UK. Electronic file available at https://oxfordre.com/neuroscience/view/10.1093/acrefore/9780190264086.001.0001/acrefore-9780190264086-e-182 Accessed 28.07.2020.

Connahs, H., Tlili, S., van Creij, J., Loo, T. Y. J., Banerjee, T. D., Saunders, T. E. & Monteiro, A. (2019). Activation of butterfly eyespots by distal-less is consistent with a reaction-diffusion process. *Development* **146**, dev169367.

Couso, J. P. (2009). Segmentation, metamerism and the Cambrian explosion. *International Journal of Developmental Biology* **53**, 1305–1316.

Crampin, E. J., Hackborn, W. W. & Maini, P. K. (2002). Pattern formation in reaction-diffusion models with nonuniform domain growth. *Bulletin of Mathematical Biology* **64**, 747–769.

Diggle, P. K. (2014). Modularity and intra-floral integration in metameric organisms: plants are more than the sum of their parts. *Philosophical Transactions of the Royal Society B: Biological Sciences* **369**, 20130253.

Ding, B., Patterson, E. L., Holalu, S. V., Li, J., Johnson, G. A., Stanley, L. E., Greenlee, A. B., Peng, F., Bradshaw, H. D., Blinov, M. L., Blackman, B. K. & Yuan, Y.-W. (2020). Two MYB proteins in a self-organizing activator-inhibitor system produce spotted pigmentation patterns. *Current Biology* **30**, 802–814.e8.

Economou, A. D., Ohazama, A., Porntaveetus, T., Sharpe, P. T., Kondo, S., Basson, M. A., Gritli-Linde, A., Cobourne, M. T. & Green, J. B. A. (2012). Periodic stripe formation by a Turing-mechanism operating at growth zones in the mammalian palate. *Nature Genetics* **44**, 348–351.

Elias, M. (2019). Evolution of aposematism and mimicry in butterflies: causes, consequences and paradoxes. *Comptes Rendus Biologies* **342**, 256–258.

Frohnhöfer, H. G., Krauss, J., Maischein, H.-M. & Nüsslein-Volhard, C. (2013). Iridophores and their interactions with other chromatophores are required for stripe formation in zebrafish. *Development* **140**, 2997–3007.

Futahashi, R., Kurita, R., Mano, H. & Fukatsu, T. (2012). Redox alters yellow dragonflies into red. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 12626–12631.

Haddock, S. H. D., Moline, M. A. & Case, J. F. (2010). Bioluminescence in the sea. *Annual Review of Marine Science* **2**, 443–493.

Hagen, H. A. (1881). On the color and the pattern of insects. *Proceedings of the American Academy of Arts and Sciences* **17**, 234–267.

Haupaix, N., Curantz, C., Bailleul, R., Beck, S., Robic, A. & Manceau, M. (2018). The periodic coloration in birds forms through a prepattern of somite origin. *Science* **361**, 631. https://doi.org/10.1126/science.aar4777.

Himstedt, W. (1979). The significance of color signals in partner recognition of the newt *Triturus alpestris*. *Copeia* **1979**, 40–43.

Ho, W. K. W., Freem, L., Zhao, D., Painter, K. J., Woolley, T. E., Gaffney, E. A., McGrew, M. J., Tzika, A., Milinkovitch, M. C., Schneider, P., Drusko, A., Matthäus, F., Glover, J. D., Wells, K. L., Johansson, J. A., et al. (2019). Feather arrays are patterned by interacting signalling and cell density waves. *PLoS Biology* **17**, e3000132.

How, M. J., Norman, M. D., Finn, J., Chung, W.-S. & Marshall, N. J. (2017). Dynamic skin patterns in cephalopods. *Frontiers in Physiology* **8**, 393.

Iriel, A. & Lagorio, M. G. (2010). Is the flower fluorescence relevant in biocommunication? *Naturwissenschaften* **97**, 915–924.

Itoh, Y., Higeta, D., Suzuki, A., Yoshida, H. & Ozeki, Y. (2002). Excision of transposable elements from the chalcone isomerase and dihydroflavonol 4-reductase genes may contribute to the variegation of the yellow-flowered carnation (*Dianthus caryophyllus*). *Plant and Cell Physiology* **43**, 578–585.

Jackson, D. J., McDougall, C., Green, K., Simpson, F., Wörheide, G. & Degnan, B. M. (2006). A rapidly evolving secretome builds and patterns a sea shell. *BMC Biology* **4**, 40.

Kaelin, C. B. & Barsh, G. S. (2013). Genetics of pigmentation in dogs and cats. *Annual Review of Animal Biosciences* **1**, 125–156.

Kelsh, R. N., Harris, M. L., Colanesi, S. & Erickson, C. A. (2009). Stripes and belly-spots—a review of pigment cell morphogenesis in vertebrates. *Seminars in Cell & Developmental Biology* **20**, 90–104.

Kierzkowski, D., Runions, A., Vuolo, F., Strauss, S., Lymbouridou, R., Routier-Kierzkowska, A.-L., Wilson-Sánchez, D., Jenke, H., Galinha, C., Mosca, G., Zhang, Z., Canales, C., Dello Ioio, R., Huijser, P., Smith, R. S., et al. (2019). A growth-based framework for leaf shape development and diversity. *Cell* **177**, 1405–1418.e17.

Kondo, S. (2017). An updated kernel-based Turing model for studying the mechanisms of biological pattern formation. *Journal of Theoretical Biology* **414**, 120–127.

Kondo, S. & Asai, R. (1995). A reactiondiffusion wave on the skin of the marine angelfish *Pomacanthus*. *Nature* **376**, 376765a0.

Kondo, S. & Miura, T. (2010). Reaction-diffusion model as a framework for understanding biological pattern formation. *Science* **329**, 1616–1620.

Kondo, S. & Shirota, H. (2009). Theoretical analysis of mechanisms that generate the pigmentation pattern of animals. *Seminars in Cell & Developmental Biology* **20**, 82–89.

KonDo, Y., Yoda, S., Mizoguchi, T., Ando, T., Yamaguchi, J., Yamamoto, K., Banno, Y. & Fujiwara, H. (2017). Toll ligand Spätzle3 controls melanization in

the stripe pattern formation in caterpillars. *Proceedings of the National Academy of Sciences* **114**, 8336–8341.

Larison, B., Kaelin, C. B., Harrigan, R., Henegar, C., Rubenstein, D. I., Kamath, P., Aschenborn, O., Smith, T. B. & Barsh, G. S. (2021). Population structure, inbreeding and stripe pattern abnormalities in plains zebras. *Molecular Ecology* **30**, 379–390.

Leonard, A. S. & Papaj, D. R. (2011). 'X' marks the spot: the possible benefits of nectar guides to bees and plants. *Functional Ecology* **25**, 1293–1301.

Li, J. H. & Zhang, L. M. (2011). Study of desiccation crack initiation and development at ground surface. *Engineering Geology* **123**, 347–358.

Ligon, R. A. & McCartney, K. L. (2016). Biochemical regulation of pigment motility in vertebrate chromatophores: a review of physiological color change mechanisms. *Current Zoology* **62**, 237–252.

Liu, R. T., Liaw, S. S. & Maini, P. K. (2006). Two-stage Turing model for generating pigment patterns on the leopard and the jaguar. *Physical Review E* **74**, 011914.

Mallarino, R., Henegar, C., Mirasierra, M., Manceau, M., Shradin, C., Vallejo, M., Beronja, S., Barsh, G. S. & Hoekstra, H. E. (2016). Alx3 regulates the spatial differences in hair pigment underlying stripe patterns in rodents. *Nature* **539**, 518–523.

Manceau, M., Domingues, V. S., Linnen, C. R., Rosenblum, E. B. & Hoekstra, H. E. (2010). Convergence in pigmentation at multiple levels: mutations, genes and function. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**, 2439–2450.

Manukyan, L., Montandon, S. A., Fofonjka, A., Smirnov, S. & Milinkovitch, M. C. (2017). A living mesoscopic cellular automaton made of skin scales. *Nature* **544**, 173–179.

Martins, A. F., Bennett, N. C., Clavel, S., Groenewald, H., Hensman, S., Hoby, S., Joris, A., Manger, P. R. & Milinkovitch, M. C. (2018). Locally-curved geometry generates bending cracks in the African elephant skin. *Nature Communications* **9**, 3865.

McClintock, B. (1950). The origin and behavior of mutable loci in maize. *Proceedings of the National Academy of Sciences* **36**, 344–355.

Meinhardt, H. (2008). Models of biological pattern formation: from elementary steps to the organization of embryonic axes. In *Current Topics in Developmental Biology* (ed. G. Schatten), pp. 1–63. Elsevier, Cambridge, MA.

Meinhardt, H. (2009). *The Algorithmic Beauty of Sea Shells*, Fourth Edition. Springer-Verlag, Berlin Heidelberg.

Michelot, D. & Melendez-Howell, L. M. (2003). Amanita muscaria: chemistry, biology, toxicology, and ethnomycology. *Mycological Research* **107**, 131–146.

Milinkovitch, M. C., Manukyan, L., Debry, A., Di-Poï, N., Martin, S., Singh, D., Lambert, D. & Zwicker, M. (2013). Crocodile head scales are not developmental units but emerge from physical cracking. *Science* **339**, 78–81.

Naganathan, S. R. & Oates, A. C. (2017). Mechanochemical coupling and developmental pattern formation. *Current Opinion in Systems Biology* **5**, 104–111.

Nagashima, Y., Tsugawa, S., Mochizuki, A., Sasaki, T., Fukuda, H. & Oda, Y. (2018). A rho-based reaction-diffusion system governs cell wall patterning in metaxylem vessels. *Scientific Reports* **8**, 1–17.

Nüsslein-Volhard, C. & Singh, A. P. (2017). How fish color their skin: a paradigm for development and evolution of adult patterns: multipotency, plasticity, and cell competition regulate proliferation and spreading of pigment cells in Zebrafish coloration. *BioEssays* **39**(3).

Shang, Y., Venail, J., Mackay, S., Bailey, P. C., Schwinn, K. E., Jameson, P. E., Martin, C. R. & Davies, K. M. (2011). The molecular basis for venation patterning of pigmentation and its effect on pollinator attraction in flowers of *Antirrhinum*. *New Phytologist* **189**, 602–615.

Sick, S., Reinker, S., Timmer, J. & Schlake, T. (2006). WNT and DKK determine hair follicle spacing through a reaction-diffusion mechanism. *Science* **314**, 1447–1450.

Small, S. & Levine, M. (1991). The initiation of pair-rule stripes in the *Drosophila* blastoderm. *Current Opinion in Genetics & Development* **1**, 255–260.

Smith, M. Q. R. P. & Ruxton, G. D. (2020). Camouflage in predators. *Biological Reviews* **95**, 1325–1340.

Stuart-Fox, D. & Moussalli, A. (2009). Camouflage, communication and thermoregulation: lessons from colour changing organisms. *Philosophical Transactions of the Royal Society B: Biological Sciences* **364**, 463–470.

Tanaka, Y., Sasaki, N. & Ohmiya, A. (2008). Biosynthesis of plant pigments: anthocyanins, betalains and carotenoids. *The Plant Journal* **54**, 733–749.

Thomas, K. R., Kolle, M., Whitney, H. M., Glover, B. J. & Steiner, U. (2010). Function of blue iridescence in tropical understorey plants. *Journal of the Royal Society Interface* **7**, 1699–1707.

Turing, A. M. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society of London Series B* **237**, 37–72.

Vignolini, S., Rudall, P. J., Rowland, A. V., Reed, A., Moyroud, E., Faden, R. B., Baumberg, J. J., Glover, B. J. & Steiner, U. (2012). Pointillist structural color in Pollia fruit. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 15712–15715.

Viviani, V. R. (2002). The origin, diversity, and structure function relationships of insect luciferases. *Cellular and Molecular Life Sciences* **59**, 1833–1850.

Watanabe, M. & Kondo, S. (2015). Is pigment patterning in fish skin determined by the Turing mechanism? *Trends in Genetics* **31**, 88–96.

Weitz, W. H. J. (2004). Naturally bioluminescent fungi. *Mycologist* **18**, 4–5.

Welch, V.L., Van Hooijdonk, E., Intrater, N. & Vigneron, J.-P. (2012). Fluorescence in insects. The Nature of Light: Light in Nature IV. Proc. SPIE8480, 848004-1–848004-15

Werner, T., Koshikawa, S., Williams, T. M. & Carroll, S. B. (2010). Generation of a novel wing colour pattern by the wingless morphogen. *Nature* **464**, 1143–1148.

Whibley, A. C., Langlade, N. B., Andalo, C., Hanna, A. I., Bangham, A., Thébaud, C. & Coen, E. (2006). Evolutionary paths underlying flower color variation in *Antirrhinum*. *Science* **313**, 963–966.

Whitney, H. M., Kolle, M., Andrew, P., Chittka, L., Steiner, U. & Glover, B. J. (2009). Floral iridescence, produced by diffractive optics, acts as a cue for animal pollinators. *Science* **323**, 130–133.

Whitney, H. M., Milne, G., Rands, S. A., Vignolini, S., Martin, C. & Glover, B. J. (2013). The influence of pigmentation patterning on bumblebee foraging from flowers of *Antirrhinum majus*. *Die Naturwissenschaften* **100**, 249–256.

Williams, T. L., Senft, S. L., Yeo, J., Martín-Martínez, F. J., Kuzirian, A. M., Martin, C. A., DiBona, C. W., Chen, C.-T., Dinneen, S. R., Nguyen, H. T., Gomes, C. M., Rosenthal, J. J. C., MacManes, M. D., Chu, F., Buehler, M. J., et al. (2019). Dynamic pigmentary and structural coloration within cephalopod chromatophore organs. *Nature Communications* **10**, 1004.

Wolpert, L. (1969). Positional information and the spatial pattern of cellular differentiation. *Journal of Theoretical Biology* **25**, 1–47.

Yangt, Z. L. & Oberwinklerr, F. (1999). Die Fruchtkörperentwicklung von *Amanita muscarta* (Basidiomycetes). *Nova Hedwigia* **68**, 441–468.

Yu, D. & Small, S. (2008). Precise registration of gene expression boundaries by a repressive morphogen in *Drosophila*. *Current Biology* **18**, 868–876.

(*Received 5 January 2021; revised 29 March 2021; accepted 31 March 2021; published online 6 May 2021*)