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Perspective

Engineering color, pattern, and texture: From nature to materials

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SUMMARY

While most animals retain the same visual appearance over their lifetime, some species feature adaptive systems that enable changes in color, pattern, or texture for defense, signaling, temperature regulation, or reproduction. Many of these features have inspired the development of materials and devices with tunable optical and mechanical properties. However, current bio-inspired color-changing systems are often limited to controlling single facets of visual perception independently, necessitating new materials or composites that can perform multiple optical, electrical, or mechanical functions simultaneously under the control of integrated hardware with practical energy requirements. In this Perspective, we examine color-changing systems in nature and discuss the current state of materials and devices derived from or inspired by these systems. Additionally, we discuss important design and performance criteria for new multifunctional materials or devices that may sense and display both color and morphology in next-generation bio-inspired technologies.

Progress and potential

Biologically inspired optical materials have garnered attention for development of next-generation coatings, color-changing garments, and interactive/adaptive displays. While biological systems employ tightly coupled chemical, mechanical, and/or electrical controls to achieve changes in color, pattern, and texture with relatively low input energy, engineered systems typically provide less comprehensive function and have significant power requirements due to the limitations of off-the-shelf materials available for manufacturing. The stark differences in performance between bio-inspired, engineered materials and their sources of inspiration necessitate a re-evaluation of the approaches used to build systems designed to emulate biology. In this perspective, we highlight how adaptive display systems in nature have inspired emerging technologies and discuss important considerations for the design and development of future optical and photonic material systems.

INTRODUCTION

Greater than 80% of all impressions are registered optically,[1] making vision the most important sensory system in nature, yet many of the fundamental mechanisms underlying biological color and color sensing remain incompletely characterized. Since early descriptions of natural selection[2] and microscopic analysis of biological specimens,[3,4] pigmentary and structural coloration have been known to serve critical functions across biology. These include concealment within an organism's surroundings,[5] mimicry of other species[6] or objects in the surrounding environment,[7,8] and signals for defensive[9,10] and reproductive purposes.[11] As a result, some species have even evolved the ability to modify their overall appearance (i.e., color, pattern, and texture) across vastly different timescales to improve survivability in a variety of challenging environments.

Visible color, which can be classified as wavelength-selective absorption of light by molecules (i.e., pigmentary color), interference with periodically ordered micro- or nanoscale features (i.e., structural color), or chemical processes that generate light (e.g., bioluminescence), make up a considerable portion of an animal's overall appearance. However, the location (dorsal, ventral, proximal, or distal), shape (patterned versus unpatterned), and motility (static versus dynamic) of these coloration components must also be considered. For example, one of the most recognized classes of appearance-changing animals, cephalopods, rely on cooperative features of both structural and pigmentary elements distributed throughout their skin[12] to access a broad range of visible colors (Figure 1). These features can also be complemented and/or distorted by modulation of the shape and texture of a cephalopod's

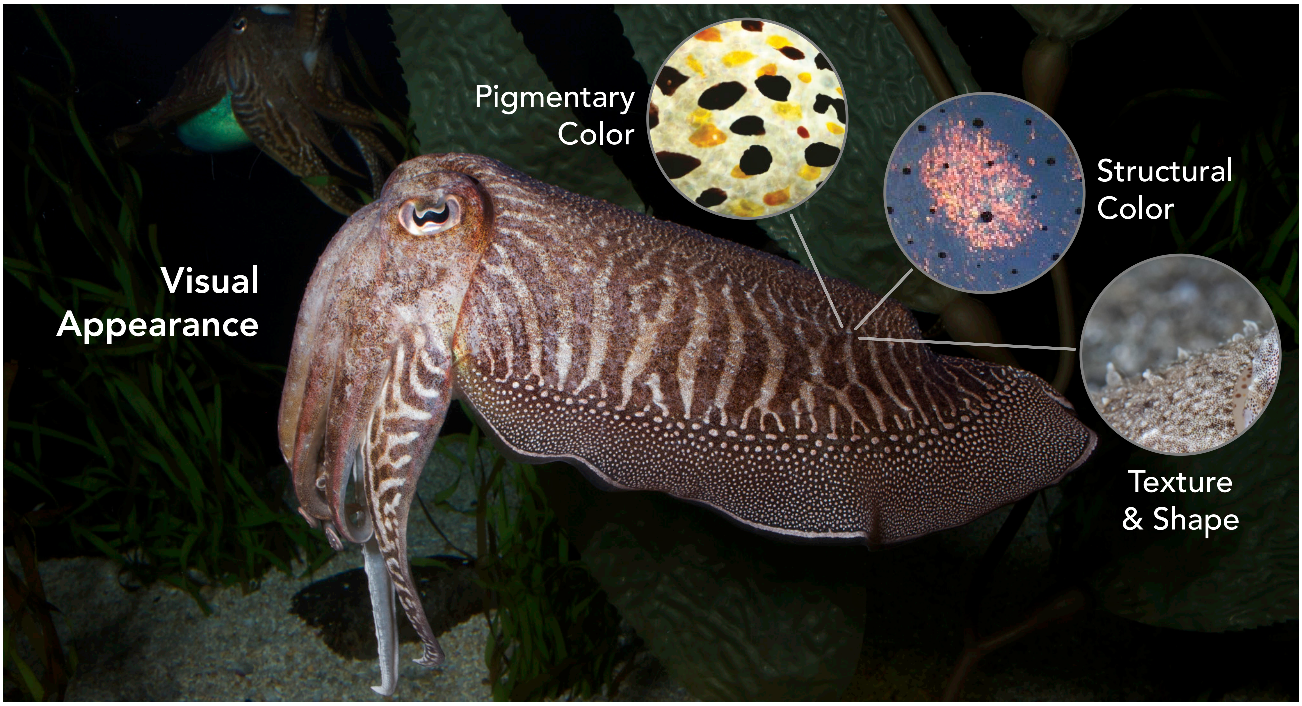

Figure 1. Dynamic display by cephalopods

In cuttlefish, which can rapidly alter color and pattern to carry out several biological functions, perceived visual appearance results from precisely controlled pigmentary components, nanostructured reflective elements, and active changes in three-dimensional geometries within the animal's skin. Cuttlefish image (*Sepia officinalis*) copyright Brian Gratwicke,[14] adapted under a Creative Commons license (CC BY 2.0). Pigmentary color image depicts chromatophores in the skin of *S. officinalis*, reprinted by permission from Springer Nature Customer Service Center GmbH: Springer Nature, *Nature*, "Elucidating the control and development of skin patterning in cuttlefish," S. Reiter et al., copyright 2018. Structural color image depicts an iridophore in the skin of *Loligo pealeii*, reprinted by permission from Springer Nature Customer Service Center GmbH: Springer Nature, *Cell and Tissue Research*, "Malleable skin coloration in cephalopods: selective reflectance, transmission and absorbance of light by chromatophores and iridophores," L.M. Mäthger et al., copyright 2007. Texture and shape image depicts papillae expression by *Sepia smithi*, copyright Rickard Zerpe,[15] adapted under a Creative Commons license (CC BY 2.0).

body to provide precise color and shape-shifting performance during camouflage.[13] However, cephalopods are unique in this regard, as not many other organisms are capable of such interactive dynamism in their environment.

The biological mechanisms that underpin an animal's appearance vary widely. For example, some species incorporate pigment translocation, whereby color changes are largely driven by endocrine and cellular mechanisms[16] to control the shape or distribution of pigment particles.[17] Other species use adaptive structural coloration by altering the size or periodicity of ordered surface features.[18,19] These changes can be triggered by direct visual cues[20] or light-sensitive elements in exposed animal tissues,[7,21] with timescales ranging from milliseconds to months to approximate the frequency of environmental variation (Figure 2).[16] While the complexity and response times of color-changing systems in nature vary widely with biological context, efforts to develop appearance-changing materials and devices in the laboratory have focused mostly on recapitulating high-contrast, rapidly actuating materials, often with the added consequence of extreme power requirements. In this Perspective, we explore mechanisms of color and pattern in nature that have inspired the development of dynamic materials and examine important obstacles and considerations for creating the next generation of stimuli-responsive optical technologies.

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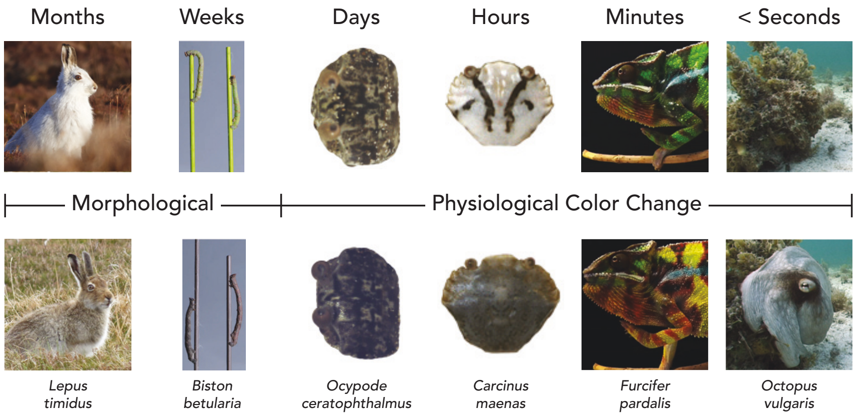

Figure 2. Timescales of biological color change

Morphological color change, whereby organisms (e.g., mountain hare, peppered moth caterpillar) shed unnecessary features to develop coloration elements suited to their surroundings, often occurs when the frequency of environmental variation is months or weeks. In *Lepus timidus*, color change is controlled by the seasonally expressed pigmentation gene Agouti,[22,23] which regulates melanin production. To masquerade as twigs during development,[24] *Biston betularia* larvae control their pigmentation in response to both visual and extraocular measurements of the surrounding environment.[7] Active transportation and rearrangement of coloration elements, known as physiological color change, supports responses to higher frequency variation (e.g., days to minutes) in an animal's surroundings. Longer-term physiological color changes are demonstrated by crabs. *Ocypode ceratophthalmus* and *Carcinus maenas* control their brightness and color by dispersing pigment according to circadian rhythm and background.[25,26] The chameleon *Furcifer pardalis* changes color more rapidly, using a combination of pigmented cells and an actively tuned lattice of guanine nanocrystals.[18] The fastest changes in observed appearance (ca. hundreds of milliseconds) are unique to cephalopods, which also employ pigmentary and structural color components, as well as precisely controlled mechanical tissue features, to rapidly change appearance. *L. timidus* and *B. betularia* images copyright Marketa Zimova et al.[27] and Amy Eacock et al.,[7] respectively, adapted under a Creative Commons license (CC BY 4.0). *O. ceratophthalmus* image adapted from M. Stevens et al., "Color change and camouflage in the horned ghost crab *Ocypode ceratophthalmus*," *Biological Journal of the Linnean Society*, 2013, 109, 2, 257–270, by permission of Oxford University Press.[25] *C. maenas* and *F. pardalis* images copyright M. Stevens et al.[26] and J. Teyssier et al.,[18] respectively, adapted under Creative Commons licenses (CC BY 4.0 and CC BY 3.0). *Octopus vulgaris* images reprinted from *Current Biology*, 17, R. Hanlon, "Cephalopod dynamic camouflage," R400–R404, copyright 2007, with permission from Elsevier.

COLOR IN LIVING SYSTEMS

As one of the two major mechanisms of coloration in nature, the manipulation of small-molecule dyes and pigments is one of the most common evolutionary processes to support visual changes in living organisms. In some species, stationary coloration elements may be revealed, obscured, or geometrically altered by surrounding mechanical elements. Alternatively, soluble dyes or insoluble pigmented particles may be transported throughout an organism's tissue in response to a triggering stimulus. Examples of these pigments and their respective biological systems are highlighted in Table 1. In many of these cases, pigments are selectively absorbing visible light to produce their observed colors throughout compartmentalized chambers (e.g., chromatophores or melanophores). These chambers are typically arrayed throughout the dermal tissue of an animal's skin as a first line of action during dynamic color change. For example, in fish,[32] frogs,[33] and cephalopods,[12] chromatophores control the local distribution of pigments to provide broad color change over the surface of the animal. In the red hind fish,[32] orange erythrophores (i.e., chromatophores containing carotenoid pigments)[34] work in tandem with their

Table 1. Broad diversity in the chemical composition of biological pigments provides access to a wide variety of displayed colors to support critical biological functions

Pigment	Reference	Class	Example organism	Localization	Function (in example organism)	Color	Compositional features
Chlorophylls	Horton et al.[28]	Porphyrins	*Chlorella vulgaris* (algae), *Quercus robur* (common oak)	chloroplasts	sensing and regulation of incoming light energy	green	tetrapyrrole ring binding magnesium and various side chains
Micromatabilin	Oxford and Gillespie[29]	Bilins (Bilichromes)	*Micrommata virescens* (green huntsman spider)	hemolymph and interstitial tissues	signaling of sexual maturity to potential mates	green or blue	tetrapyrrole chain, metabolic product of porphyrins
Eumelanin	Rodionov et al.[30]	Indole	*Gymnocorymbus ternetzi* (black tetra)	melanophores found in the scales	color, appearance, and photoprotection	black, dark brown, and buff	quinone-based, derived from tyrosine
Xanthommatin	Williams et al.,[12] Hanlon et al.[31]	Ommochromes	*Doryteuthis pealeii* (longfin inshore squid)	chromatophores, ommachromosomes	color, maturation, and signaling	yellow, red, and brown	phenoxazone-based, derived from tryptophan

melanophores (i.e., cells containing granules of the black pigment melanin) and guanine-based reflectors called iridophores to attract the interest of potential mates. In squid such as *Doryteuthis pealeii*, the expansion and contraction of radially arranged muscle cells anchoring the pigment sacs of chromatophores mechanically modulate the presented surface area of different colors during camouflage.[12]

In addition to physical manipulation of stationary pigments, some organisms actively transport color throughout their tissues in a process commonly known as pigment translocation. One example of this phenomenon is the melanophore microtubule system found in flounder, which relies on transportation of melanin-containing granules called melanosomes across these flat-bodied fish. Similar strategies are also employed by guppies, in which transportation of melanosomes supports darkening of the eyes to display aggression toward predators.[35] While energetically expensive, these strategies are highly effective at balancing the biological requirement of attracting mates with avoiding the dangers of unwanted attention from predators.

Alternatively, many systems in nature contain highly ordered nanoscale structures that produce coloration based on light interference and/or diffraction (e.g., opals, seashells, butterfly wings, and bird feathers).[36] Perhaps the most familiar natural material endowed with structural color is the opal, which displays angle-dependent iridescent colors that originate from periodically ordered arrays of silica nanospheres.[37] Such periodically arranged optical nanostructures, known as photonic crystals, are capable of diffracting and/or reflecting light to produce a broad spectrum of bright colors.[38] By adjusting physical features such as size, spacing, and refractive index, certain biological creatures can leverage these nanostructures to also change their full visible appearance. For example, chameleons such as *Furcifer pardalis* adapt their body color in response to stress or other environmental signals by actively changing a lattice of guanine crystals within their dermis.[18] Many tropical fishes also display bright structural colors that can undergo rapid and dramatic transformations in response to the intensity of light in the surrounding environment.[39,40] In these species, the tilt angles of rigid, reflective guanine platelets embedded in iridophores are controlled to adjust their spacing to reflect different colors. Alternatively, structural coloration in birds typically arises from combinations of keratinous nanostructures and melanin-based particles in their feathers. While birds generally display static colors, some species can change their appearance as a result of variation in environmental conditions. For example, in *Tachycineta bicolor*, reversible swelling of hydrophilic keratin proteins in the outer cortex of feathers produces blue-green to yellow-green colors as a result of humidity.[41] While many of these fundamental color-changing mechanisms are unique to specific organisms, some common features can be generalized and applied to support the development of appearance-changing materials, devices, or sensors.

COLOR-CHANGING MATERIALS AND DEVICES

Prototypes designed to emulate biological display systems incorporate a wide variety of control strategies and coloration mechanisms. For instance, pressure-driven microfluidic systems can be used to pump solutions of soluble dyes through prepatterned display zones[42] or create unique, multicolor pixel patterns using reconfigurable arrays[43] to mimic pigment translocation. Alternatively, electrochromic devices enable rapid (ca. seconds)[44–46] changes in the colors of biological pigments[45] and can be arranged as image-displaying pixels[47] to approximate the speed of biological color changes.[48] These systems use an alternating potential to control the oxidation states of materials patterned on conductive electrodes. This strategy differs from the approach used to displace charged pigment particles via electrophoretic forces in e-ink and e-paper technologies,[49] which have succeeded as commercial products (e.g., e-readers, price tags) but have not yet been used to approximate the functions of living systems. An alternative approach incorporating localized changes in temperature to actuate thermochromic materials provides controlled signaling in response to external stimuli such as light, bringing these systems closer to mimicking the color sensing and display feedback loops observed in nature.[50] In this case, direct manipulation of light-absorbing materials supports on-demand display of defined patterns in response to measured signals by a multilayered composite optical system.

Unlike the examples above in which light-absorbing and light-reflecting molecules display color changes in response to actively directed signals, bio-inspired materials that feature structural coloration can be actuated by active or passive mechanisms. For example, Wang et al. reported a reversible electrodeposition of silver ions onto gold nanodome arrays that enabled tunable color change across the visible spectrum (450–670 nm).[47] This approach, termed plasmonic modulation, was demonstrated as a chameleon mimetic system that could measure and respond to colors in its surroundings. Separately, moisture-responsive structural materials inspired by the function of melanin nanostructures in bird feathers provide reversible, humidity-induced color changes across blue, red, and green colors.[51] Similarly, reversible swelling of poly(acrylic acid-co-acrylamide) coatings cast and polymerized *in situ* on the wings of the *Papilio paris* butterfly provided a hydroscopic, lamellar nanostructure responsive to changes in environmental pH.[52] Reorganization of structural components has also been achieved using other stimuli such as mechanical force[53] and temperature change,[54] demonstrating that a variety of environmental stimuli can be used to control materials that display programmable color, and also the potential application of these materials as sensors.

CONTROLLING SHAPE AND TEXTURE

In addition to displaying visible color using pigmentary or structural elements, animals also control their visible appearance by manipulating light through alterations to their shape and surface texture. For example, the mimic octopus, *Thaumoctopus mimicus*, rearranges the shape of its entire body to appear as other species, such as a flounder, in an effort to deceive predators.[6] This process is triggered by muscular hydrostats, which are hydraulic biological muscles that lack skeletal support. On the microscale, similar structures called papillae control the smoothness or roughness of cephalopod skin, allowing these animals to mimic the textures of their surroundings[5] while selectively revealing and obscuring coloration components.[55] The capabilities of cephalopods and other soft-bodied animals have inspired the development of robotic systems in which mechanical actuation controls appearance. For example, soft robotic systems that feature pneumatic actuation of elastomeric materials have been developed with direct inspiration from octopus tentacles[56] and papillae[57] to provide access to a range of three-dimensional, shape-shifting geometries. Recently, light- and temperature-responsive mechanical actuators were used to manipulate stretchable hydrogels in a manner inspired by the architecture of cephalopod chromatophores.[58] Beyond cephalopods, soft materials can be programmed to approximate a variety of biologically inspired shapes[59] and behaviors.[60] Such mechanical control of microscale texture can also be used to tune the visible transmittance and infrared performance of thin films.[61,62] These applications highlight the importance and future possibilities of integrated shape and color-changing technologies.

In recent years, several hydrogel-based films and composites have also been developed with complementary mechanical and optical features that change in response to applied external stimuli such as temperature, humidity, pH, chemical solutes or solvents, magnetic fields, or light.[63] In these examples, geometric changes resulting from a mechanical response (e.g., swelling/shrinking, bending, wrinkling, locomotion)[64] to the applied stimulus elicit simultaneous color change by modulating physical features (e.g., periodic spacing of embedded nanomaterials)[65] or chemical composition (e.g., accessibility of reactants for reversible chemical reactions).[66] Although these approaches do not directly require external hardware such as pumps and power supplies to control actuation, some stimuli (e.g., temperature, humidity) may not be universally accessible across challenging or uncontrolled environments, limiting the practicality of these approaches for specific applications. Nonetheless, eliminating the need for direct connection to power and signaling components supports development of technologies that approximate the soft and deformable nature of biological tissues—an important advancement that should continue to be iterated for the future of deployable color- and texture-changing materials.

OUTLOOK

Despite the countless bio-inspired material prototypes designed and fabricated to manipulate color for applications in wearable consumer goods, displays, robotics, biosensing, and defense, the realization of fully integrated and independently controlled optical units within conformable substrates that span large areas (e.g., square meters) remains a major technological challenge. This limitation can be attributed, in part, to difficulties in developing multifunctional but mechanically robust material composites that are capable of sensing, signaling, and displaying color across a variety of uncontrolled environments. To meaningfully bridge the performance gap that separates the molecular and anatomical blueprints regulating the speed, power requirements, and mechanical features of natural systems from the less comprehensive function and utility of bio-inspired technologies, quantitative characterization of living systems must be paired with simplified, self-contained design strategies to catalyze the development next-generation color- and shape-changing materials and devices.

In recognition of the long-term applications for systems that can actively modify their visible appearance in response to measured stimuli from the surrounding environment, there are important criteria to consider during the development of color-and shape-changing materials and devices. First, applications of color, texture, and signaling should all communicate with each other. In nature, animals leverage the simultaneous coordination of dermal organs that manipulate pigments, micro- and nanostructured materials, and musculoskeletal systems to control their appearance and ensure their survival. However, man-made prototypes are often limited to control over only one of these features. This challenge can be attributed, at least in part, to incompatibility of material properties, control mechanisms, or power requirements across separate but potentially complementary technologies. While integration of multimodal appearance control should not be required for demonstration of a new material, device, or approach, awareness of potential obstacles to combining complementary technologies may preserve opportunities for development of more comprehensive systems.

A second criterion is integrating a sensing component with the display. To effectively mirror natural mechanisms of adaptive color change, biologically inspired systems must be capable of measuring external stimuli, processing measured signals to determine an appropriate response, and displaying color, pattern, and/or shape accordingly. Such closed feedback loops, depicted in Figure 3, require active communication between sensing and display features. This requirement for connectivity should raise a number of questions. Could the control signals for a prototype display technology be reasonably interfaced with measurement components? Is external equipment required to generate those signals, and could it be miniaturized? Most importantly, how would the completed system appear and work in a "real" scenario? Technologies designed to modulate visible appearance by controlling pigmentary color, structural color, or shape and texture are often created to display static or pre-defined information via single-channel controls. Building such technologies into active feedback loops, whereby independently controlled components display information based on signals generated in response to measurements of the surrounding environment, provides opportunities for more accurate approximation of the adaptive display behaviors demonstrated by living systems. Further situational considerations, such as reasonable power requirements for a target environment or application and compatibility with possible companion technologies,

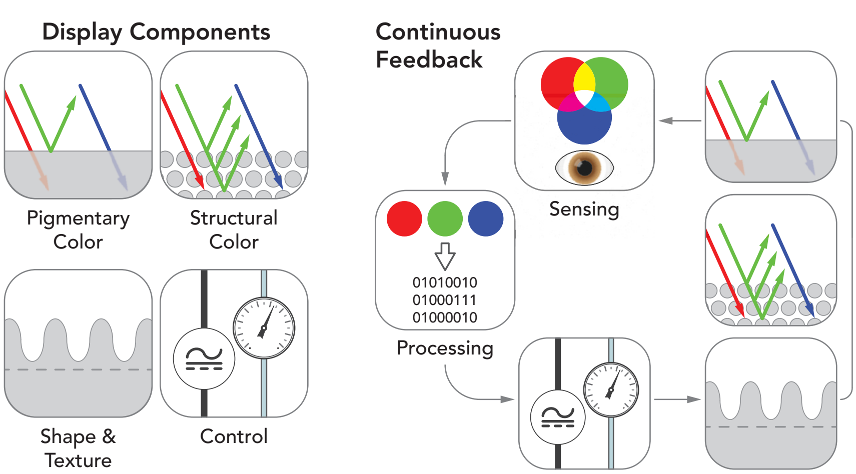

Figure 3. Modeling adaptive feedback loops
Building bio-inspired, adaptive technologies capable of sensing and responding to environmental stimuli requires direct feedback between integrated sensing and processing elements with common display components that can provide pigmentary and structural color or variations in shape and texture using voltage- or pressure-based controls.

may help to inform the utility of a given prototype as part of a larger, integrated system fully mimetic of biology.

These assessments are largely based on the capabilities of existing technologies that show promise as components of integrated, adaptive display systems, but are not necessarily demonstrated as completed products for a specific target application. Such systems will likely result from collaborative efforts across multiple disciplines (e.g., biology, chemistry, materials science, computer science, electrical engineering) enabled by new multifunctional materials and composites that streamline the aforementioned connectivity required for rapid responses to continuous environmental variation. Ultimately, these types of considerations will shed new light on biological mechanisms of adaptive coloration and support the development of next-generation multifunctional materials that will enable comprehensive, application-ready systems capable of rapid and multifaceted dynamic display.

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AUTHOR CONTRIBUTIONS

D.J.W. and L.F.D. conceptualized the manuscript narrative, and D.J.W. generated figures. All authors contributed to written content.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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