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Light management lessons from nature for building applications

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Abstract

The increasing environmental awareness in the building context has raised the demands towards more efficient use of resources and the development of renewable energy solutions. Buildings are exposed to solar radiation at different intensities throughout multiple timescales, which requires efficient management of light. Managing light becomes more challenging when several elements are considered simultaneously, e.g. minimizing heat gain, while maximizing daylight, yet considering glare. Living organisms are equipped with unique strategies to manage light for survival, communication, and energy matters. In this context, developing biomimetic design solutions for buildings have a great potential for innovation.
The current work focuses on the initial phase of a biomimetic design process, presenting a structured framework of light managing strategies that facilitates the search for, and the selection of, appropriate strategies from the large database of nature. The framework encapsulates a basic array of strategies for managing light; elaborates on the involved factors; and lists examples of organisms and systems from nature, for the analogical development of biomimetic designs that respond to light.

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Keywords: light-interception; nature; buildings; architecture; biomimetics; design; harness; daylighting.

1. Introduction

Buildings are exposed to solar radiation at different intensities throughout the day, which requires systems to manage light conditions in a space for comfort, among others. Managing light becomes very challenging when

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several elements are considered simultaneously, e.g. minimizing heat gain, while maximizing daylight, yet considering glare. A common solution for managing solar radiation is a shading system. Shading systems are attached to buildings in order to control light intensities in the occupied spaces next to windows. Current shading technologies deal, primarily, with extensions either vertically or horizontally, or by adding an extra cladding to protect against radiation from glazed openings. Other solutions, based at the molecular level, have also emerged to control the amount of light penetrating inside, e.g. reflective and selective coatings, and thermo-chromic glass [1].

Responding to light is one of the common abilities of many forms of life [2]. The rotation of sun and earth creates unique light habitats on earth, where various strategies and mechanisms that manage light intensity and interception have evolved. Morphological, behavioral, and physiological means influence light management efficiency [3, 4]. For example, some plants tend to optimize light harvesting by solar tracking and enhancing body exposure, while others are able to transmit light due to their intricate structural assembly.

Exploring and learning from strategies and techniques found in nature can inspire the development of new light management systems for buildings [5, 6]. This discipline, where solutions are obtained by emulating strategies and principles from nature, is called biomimetics. Biomimetics is a rapidly growing field in engineering and materials science, though the application to architecture is still a challenge. One of the major challenges is the search for and the selection of relevant strategies from the vast database of nature [7]. Several attempts have been carried out to represent biophysical information systematically in analog context to buildings, e.g. [8-10], yet a systematic representation of light management strategies for applications to buildings is limited.

In this paper we distinguish three main functions for light management: illuminate spaces, filter light intensities, and harness light for energy purposes, see Fig. 1. The corresponding processes for light management are identified and several strategies from nature are presented in the following sections. Furthermore, some morphological means for light interception, particularly in plants, are distinguished, and their potential application to buildings is indicated.

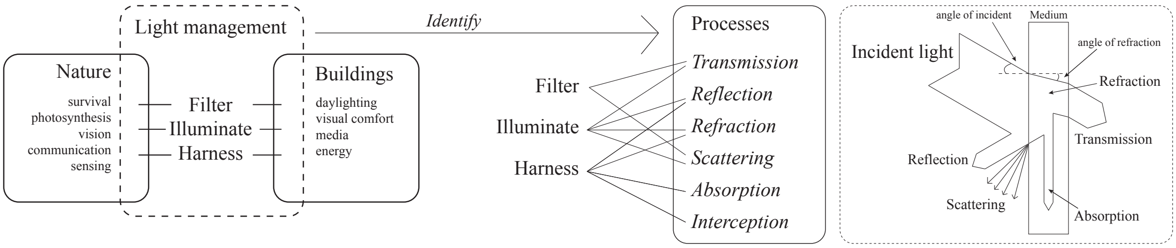

Fig. 1. Schematic diagram of the biomimetic design framework for light management. Left: three main functions and their corresponding processes are identified for buildings and natural systems. Right: the different processes of light when interacting with a medium.

2. Light management in nature

Solar radiation is the main source of light, which changes throughout various scales of time (i.e., hours, days, and seasons). Organisms perceive light for various purposes, such as gaining information from the surrounding environment for adequate response, or for energy matters [11]. Adaptation strategies to light are diverse, where plants and eye architectures dominate in literature for unique light interception adaptations. Compound eyes are a special case of eyes, which are either superposition or apposition. Superposition eyes are more sensitive to light than apposition eyes, and found in animals that are active at night (such as moths and fireflies) or organisms that inhabit the deep oceans with limited light [12]. The following processes introduce some examples found in nature for filtering, illuminating, or harnessing light.

2.1. Transmission

The molecular structure of a substance influences the fraction of radiation passing through, which is described as transmittance. In dark environments, organisms need to adapt to the very limited radiation available, thus a high transmittance substances are advantageous. For example, the Venus flower-basket a deep-sea sponge, *Euplectella*, living up to 5000 m in the deep ocean has high transmittance characteristics [13]. Its structural support is composed of a lattice of fused spicules that provide structural rigidity, generally 5-15 cm long and 40-70 µm in diameter [13, 14]. Beyond the structural anchorage support characteristics of the Venus flower-basket, it has a remarkable effective fiber-optical network for light distribution in the deep-sea environment [15]. The spicules of the Venus flower-basket are made of silica, which is the main ingredient of glass, but with better structural stability [16].

2.2. Refraction

Refraction is the bending of a light wave when entering a medium with different physical properties. The eyes of nocturnal insects, krill, and mysid crustaceans refract perceived light [2], see Fig. 2(a). Different geometries of eye structure affect the interception of light, which allow a focused or defocused image. The large compound eyes allow the fly to respond quickly on the smallest movement in its neighborhood with a 360 degrees vision, despite the unfocused perceived image [17]. The compound eye consists of a large number of independent visual receptors, called facets or ommatidium (singular of ommatidia). The ommatidia are densely packed and arranged in a hexagonal array. The ommatidium ensures the interception of light from one specific area, and prevents perceiving duplicated images from several ommatidia. In this case, the total image is the assembly of the information perceived from each independent ommatidia, just like the pixels of a digital monitor.

2.3. Reflection

Some portion of light is reflected when striking an interface, at the same angle of incidence. Eyes of *decapod crustacean* (such as shrimps, prawns, crayfish, and lobsters) are different than those of flies; where image is formed by reflection rather than refraction [2], which are described as *reflecting superposition compound eyes* [18]. The eye consists of densely arranged square facets on a spherical surface connected to square tubes, see Fig. 2(b). The inner surfaces of the square tubes are highly reflective. Specific geometrical alignments of the square tubes reflect the entering light and focus it on one focal point on the retina. The angle of the alignment is very crucial to reflect and focus numerous rays on one point [18]. Additionally, the length of the tube is believed to be twice the width to focus the reflections on the retina on one point [19].

2.4. Scattering

Diffuse reflection of light is the scattering of an incident light by a surface or a medium (e.g. clouds). Diffuse reflection, and in particular, the scattering of light from objects, is the major process causing the vision of these objects by organisms' eyes. Some organisms are able to release pigments in the cornea (the transparent layer of the eye) when encountering excessive light. For example, the balloon fish has iridescent eyes, allowing certain wavelengths of light to pass through the eye, whereas others are strongly reflected by glittering colors. The balloon fish, among other shallow water fish, can release yellow pigments (a reversible process) in cornea to filter light intensity [20]. These pigments absorb and reflect a significant portion of light and thus reduce the light intensity on the retina of the fish [21-24].

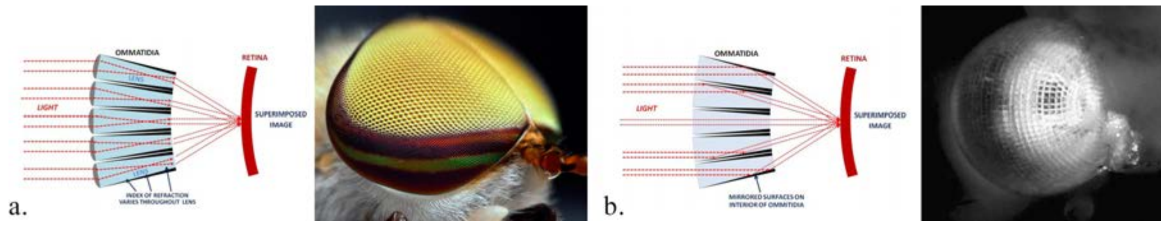

Fig. 2. (a.) left: schematics of a refraction superposition compound eye, reproduced from [25], and right: visible hexagonal facets of a fly eye (photo by © Thomas Shahan); (b.) left: schematics of a reflection superposition compound eye, reproduced from [25], and right: square facets visible on the grass shrimp eye, reproduced from [26].

2.5. Absorption

In plants, light can be absorbed by proteins known as photosynthetic reaction centers in order to perform photosynthesis. These proteins contain Chlorophyll (a green pigment), which is responsible for light absorption. The absorbed light is converted into chemical energy by using carbon dioxide and water, and releasing oxygen as a waste product. Absorbing radiation via dark colors is one of the ways to reduce reflections that could interfere with visual comfort and minimize glare. For example, the meerkat has a black region of fur surrounding its eyes for a better vision at high radiation intensities in the desert. A class of fungi, known as radiotrophic fungi, absorbs high frequency electromagnetic rays (e.g., gamma-rays), which are biologically hazardous [27]. Radiotrophic fungi use pigment melanin to convert the absorbed gamma rays into chemical reaction used for its growth [28].

3. Morphological means for light interception

Morphological, physiological, and behavioral factors influence light interception in nature. Plants in particular need to adapt to different light intensities for optimal photosynthesis rates. Plants' planar area, angle of incidence, and distribution play significant roles in influencing the exposure to sun radiation [29]. Several morphological adaptations are employed in organisms to enhance or decrease light exposure, that could provide inspirations for the development of new systems for buildings [30]. In this paper, we categorize the morphological means under: *orientation*, *distribution*, and *form*.

3.1. Orientation

Plants tend to vary their orientation and inclinations corresponding to different climate conditions. Reorientations are caused by inclination of leaves and by differential growth in the expanding leaves, especially at the petiole, resulting in leaf curvature [31]. At hot and dry climates leaves face east, maximizing light interception in the early morning and late afternoon while keeping a minimum interception at noon [32]. Leaves becoming more vertical is a method for protection from over exposure of sunlight [33, 34]. Leaves facing the equator acquire a gradual warming during the morning and gain maximum light at winter noon's [32]. According to Mullen, Weinig and Hangarter [31], when the environment of the leaves changes from dark to light the leaves change their inclination to a more horizontal situation. Faster reorientation was reported when plants were placed in a darker place than when they entered darkness at the end of the day [31]. Leaf movement can be recognized in reorientation from a horizontal to a vertical position at night [35]. Leaves with flatter and smaller angle inclination are found in forested sites with lower light levels [36]. Inclinations at lower canopy leaves are lower than at upper canopy leaves, and more constant and lower inclinations of leaves were reported at cloudy days than sunny days [37].

There are three types of plant reorientation [38]: *Nyctinastic* (sleep movements), *Seisonastic* (movements in response to shaking), and *Heliotropic* (leaf movements tracking the sun). In heliotropic movements, leaves move either to a perpendicular position (diaheliotropism) to solar radiation throughout the day or to a parallel position (paraheliotropic), where higher photosynthetic rates occur in leaves perpendicular to solar radiation (such as sunflowers [39]), and lower temperatures and less transpiration rates occur in leaves parallel to radiation [40]. In some plants when new leaves are developing, causing self-shading, the lower leaves, which are getting shaded by the new ones, rotate in the horizontal plane to minimize the shade caused by the new leaves [41]. A schematic representation of leaf inclination for shade avoidance is presented in Fig. 3.

3.2. Distribution

Leaf distribution for effective photosynthesis is achieved by mono-layer with high density or multi-layer with loose distribution [42], see Fig. 4(a). Leaf density of plants, influences plant's projected area, which leads to the relation between plants' projected area and sunlight interception capability [43]. Uniformly distributed leaves in all azimuthally directions with a steep inclination, have a relative well performance in all seasons at all hours of the day, where high leaf angles reduce noon canopy heat-loads in dry regions [33]. In shaded environments, species tend to have taller stems in order to overtop neighboring plants [44], whereas under-story species tend to expand horizontally investing in the growth of their leaves for increased light interception [45]. By expanding horizontally they maximize their planar area for maximum exposure of diffused light.

Some plants have special geometrical arrangements that can be described mathematically, e.g. Fibonacci series found in understory plants with low light conditions; these arrangements are adapted for compact and dense packing of leaves in order to maximize light exposure. The Fibonacci pattern could be applied in two or three dimensions. It was observed in a succulent (*Aeonium tabuliforme*) that forms compact flat overlapping rosettes, where leaves grow in size retaining their shape, see Fig. 4(b).

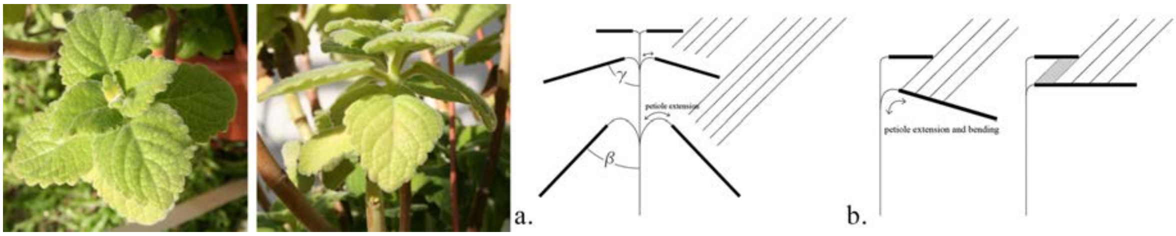

Fig. 3. Lower layers of leaves bend for maximum light interception. (a) Lower leaves get bigger with smaller inclination ($\beta < \gamma$). Alternation of 90 degrees is adopted in this plant for more space between the layers in order to catch more sunlight. (b) Preventing self-shading by leaf inclination.

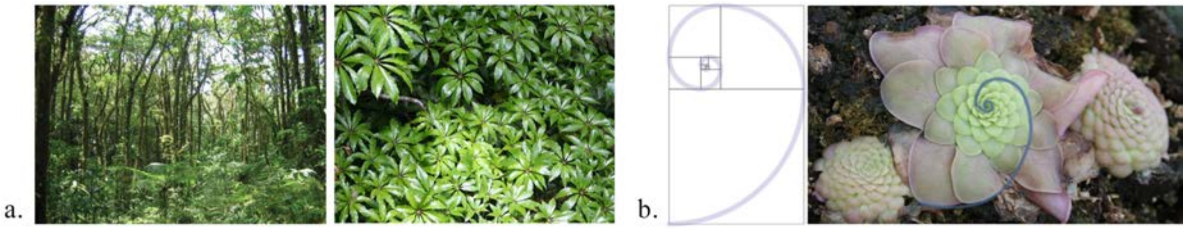

Fig. 4. (a.) Left: multilayer and loose distribution of leaves at forested sites, and Right: monolayer and dense distribution of leaves at understory plants. (b.) Fibonacci pattern adapted by *Aeonium tabuliforme* for optimal light exposure, [30].

3.3. Form

Some succulents are characterized by their ribbing morphology, where “the main physiological function of ribs may be to allow swelling of the cactus stems and hence storage of water following rainfall” [46], see Fig. 5(a). Furthermore, the ribbed morphology might generate turbulent flow with thinner boundary layer next to the surface, thus contributing in cooling [46, 47]. In terms of light, the ribbing morphology, despite the increased surface-area to volume ratio, creates situations of self-shading, thus reducing transpiration rates [46, 47]. The geometrical variations in cacti are considered as a result of adaptations to active radiation interception [46].

The pupil of human eye is surrounded by an adaptive muscle, which is called iris. According to Hooker [48], the iris makes the pupil larger or smaller in order to regulate light intensities, which contains a set of radial and circular fibers to regulate the dilation of the pupil, see Fig. 5(b). When the pupil is wide open the circular fibers of the iris are relaxed while the radial ones are contracted. When the pupil is small, the radial fibers of the iris are relaxed while the circular ones are contracted [48].

Morphological adaptation exists at the microscopic scale as well, such as the microstructure of the surface of silver ragwort. Trichomes (microscopic fibers) enhance hydrophobicity and shield light [49]. Furthermore, microscopic variations in the structure can create different colors by reflecting certain wavelengths, such as the blue appearance of the *Morpho* butterfly due to its microscopic multilayered structure [50].

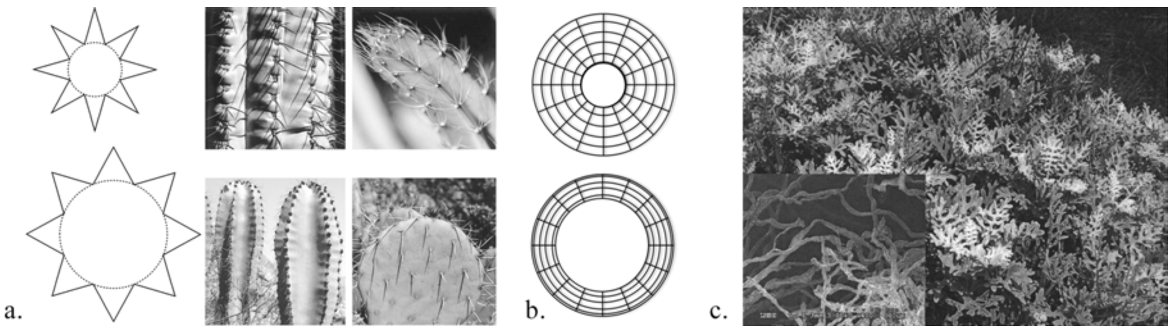

Fig. 5. Effect of form on light interaction. (a) Ribbed/pleated morphology allows flexibility and provides self-shading, reproduced from [47], American Journal of Botany. (b) Adaptation of human pupil to different light intensities: radial fibers relaxed and circular ones contracted (top), and radial fibers contracted and circular ones relaxed (bottom), after [48]. (c) Photo of silver ragwort showing its reflective property, and a SEM image showing its microscopic structure, reproduced from [49].

4. Summary and application visions

Table 1. Examples from nature for illuminating, filtering, and harnessing light and their potential applications to buildings

Functions	Processes	Factors	Pinnacles	Mechanism	Application
Illuminate	Transmission	Structure	Venus flower-basket	The distinct hierarchical assembly of the structure provides, besides the remarkable mechanical performance, an effective network for light distribution [15, 16]	Lighting
	Reflection	Structure	Butterfly wing	Structural colouration by multi-film interference [50]. The hierarchical nanostructure of scales, closely packed ridges with horizontal lamellae and micro-ribs, highly reflects certain wavelengths [51]	
			Black-billed magpie	Structural colouration by thin-film interference [50]. A hexagonal lattice of parallel air micro-channels in the cortex (a thin film of keratin) of the barbules reflects yellowish-green light [52]	
	Scattering	Structure	Amphibians	Multiple layers filter, scatter, and absorb certain wavelengths and result in a greenish colour [53]	
Filter	Transmission	Orientation	Cuttlefish	Parallel alignment of photoreceptors and their orthogonal arrangement is believed to serve as a polarization analysing system [54]	Reducing glare
	Scattering	Distribution	Canopy-storey plants	Small leaves (instead of big ones) distributed at various levels allowing diffused solar penetration between leaves [42]	Reducing intensity
		Form	Silver ragwort	Hairy surfaces scatter light and reduce incident light [49]	
Harness	Interception	Distribution	Sunflower	Fibonacci arrangement of seeds results in an efficient dense and compact packing for maximized light exposure [55, 56]	Generating energy & Shading
			Canopy-storey plants	Loose and multi-layered distribution of leaves [42]	
			Under-storey plants	Dense and mono-layered distribution of leaves [42]	
		Orientation	Cornish Mallow	Maintain surfaces perpendicular to solar radiation for maximized exposure [57]	
	Reflection	Structure	Lobster's compound eye	Spherically arranged square tubes reflect light and focus it on one focal point on the retina [19]	
	Refraction	Structure	Fly's compound eye	Hexagonal array of ommatidia (facets) superposes refracted light on a specific area [58]	
	Absorption	Structure	Butterfly	Variations in film thicknesses can result in 96% absorption of the incident solar radiation [59]	Generating energy
		Pigment	Chlorophyll	Chlorophylls absorb light for photosynthesis [60]	

Nature has abundant strategies to manage light for survival, communication, and/or energy matters. Table 1 presents examples from nature for potential applications to buildings. Some of the examples demonstrate the structural and morphological significance for light management. Succulents, canopy, under-story, and diaheliotropic plants manage light interception by applying special distributions, orientations, and forms. These morphological means are sometimes enhanced by the plasticity of plant's architecture responding to different light intensities [41]. The wide field of view of compound eyes in some insects and deep-sea creatures is achieved through the structural assembly of numerous tubes that direct light (reflection or refraction) to a specific focusing area, which exhibit a compact vision system with efficient energy consumption [61]. Some colors in nature arise due to special surface microstructures, where reflection, diffraction, and scattering of wave ranges are manipulated. These microstructures can, among others, enhance radiation absorption [59], and provide a selective vapor response [62].

Seeking solutions from nature for the development of new optical technologies and materials is a widely growing field for innovation [50, 63, 64], yet the application to buildings is very limited. It is hoped that this paper will shed more light on the possible applications to buildings by emphasizing the relevant mechanisms for the common functions and providing a platform with relevant research sources for designers. By applying solutions inspired by nature we anticipate the development of a new class of functional systems that raise the environmental awareness of buildings. Further research is required to test and validate the concepts and their application to the building context and their corresponding scales.

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