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Photobiology: A New Scientific Frontier

Kendric C. Smith

"Directly beneficial effects of light produced by artificial sources include the photorepair of ultraviolet damage; treatment of jaundice of the newborn infant with blue light; destruction of the virus of herpes simplex when stained by certain photosensitizing dyes; diagnosis of some hereditary diseases in utero by activation of fluorescent dyes in fetal cells; and recently, the destruction of certain cancer cells by visible light irradiation after their incorporation of photosensitizing agents."

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Sunlight is probably the most important single element of our environment, yet it has been largely ignored by the scientific community. Previously, there have been no compelling reasons to study the biological effects of light except to satisfy the curiosity of a small number of scientists. This situation is now changing as people become more aware of the affects of light other than as an aid to vision. The publicity about the supersonic transports (the SST's) and the consequences of a possible SST-induced increase in solar ultraviolet radiation reaching the surface of the earth; publicity about the treatment of congenital jaundice in premature babies with light therapy, the treatment of Herpes infections (the common cold sores), and even of malignant tumors with dyes plus visible light; and, the concern over the energy crisis and its possible solution by harnessing solar energy have all helped focus attention on the properties of sunlight.

The purpose of this report is to describe the highlights of the scientific discoveries presented by a number of workers in the field at the American Society for Photobiology in June, 1973.

Detrimental Effects of Excessive Exposure to Sunlight

To avoid the sun would be to exist without one of the great pleasures of life. But as with most enjoyable things, indiscriminate exposure and lack of understanding of the possible unpleasant consequences can result in unhappiness and even serious illness.

Among the known effects on the skin of man of natural and artificial ultra-violet radiation are sunburn, changes in skin which are interpreted as signs of "aging," and premalignant and malignant skin tumors. A better understanding of the cell constituents affected, the kinds of alterations produced, the type of repair mechanisms, and the effect of interactions among these is needed in order to combine the maximum benefits with the least damage from ultra-violet radiation.

Chemicals present in soaps, cosmetics, medicine, and environmental pollutants can sensitize people to sunlight, leading to intense sunburn-like reactions even in the absence of ultra-violet radiation (example, sunlight filtered through window glass). Two mechanisms exist for this type of photosensitization: (1) Phototoxic reactions are mediated by the absorption of radiation by the photosensitizer, and the transfer of this absorbed energy to biological molecules, leading to their chemical alteration. (2) If the absorption of light photochemically changes the structure of a molecule such that it is now recognized by the body as foreign, antibodies are produced leading to a photoallergic response.

Man's sensitivity to sunlight is controlled by heredity. This is exemplified by genetic deficiencies in melanin formation and thus the absence of tanning in Irish, Scottish, and Welsh peoples; deficiencies in cellular capacity to repair solar radiation damage, as in the inherited disorder xeroderma pigmentosum; metabolic over-production of porphyrin (a natural photosensitizer); and altered tryptophan metabolism.

The wavelengths of sunlight below 320 nm, those modulated by the presence of ozone in the stratosphere, are the most detrimental to biological systems. Yet it is this same wavelength region of light that produces the essential vitamin in the skin of man—vitamin D. Thus, the situation is one of balance: sunlight is necessary for life, yet in excess, it is harmful.

Repair of Ultra-Violet Radiation-Induced Damage to Cells

Most organisms, with the notable

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exception of man, tend to shun sunlight unless they are well protected from the damaging effects of ultra-violet radiation by external shields such as feathers, hair, shells, and pigments. When cells are exposed to radiation, their sensitivity, measured in terms of lethality, depends mainly upon their ability to repair radiation-induced damage in their deoxyribonucleic acid (DNA). This point is dramatically exemplified by the observation that mutant cells that are genetically deficient in DNA repair systems are much more easily killed by ultra-violet radiation.

The Roles of Light in the Human Environment

The development of varied and powerful sources of artificial light from electricity has led to sophisticated knowledge of illumination and its measurement, usually in terms of its perception by the eye. But visible light, as much as ultra-violet or infrared radiation, has the ability to exert measurable biological effects. Medical uses of the visible spectrum have been virtually ignored by physicians for the past 90 years. However, there is a new appreciation of these uses by medical scientists, stimulated in great part by the advent of phototherapy of the jaundiced newborn.

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Not all the effects of visible light are beneficial, however. Marked detrimental effects on the retina have ben demonstrated under circumstances previously thought innocuous. Certain enzymes and other substances in blood and tissue will absorb light in vivo and thus undergo photochemical decomposition. Photosensitizing drugs given to pregnant women readily cross the placenta to the fetus. If, after delivery, the infant is exposed to light of high intensity, as in phototherapy, the chance of photosensitization is increased.

The psychological effects of light, particularly of colored light, are well known but not well understood. These effects may bear a causal relationship to purely biological processes in the brain induced by light, which in turn will affect psychic behavior. Light in turn will affect psychic behavior. Light intensity as well as wavelength specificity may alter productivity and mood. In the infant, sensory overload by prolonged exposure to highly intense illumination may produce undesirable effects on development. Indeed, the

manipulation of the lighting environment of adults as well as of infants can have consequences of which we may be quite unaware.

Effects of Near Ultra-Violet Light (320-400nm).

Near ultra-violet light has been considered by many to be a harmless form of radiant energy. A typical source of this type of radiation is the so-called "black light" bulb to display fluorescent posters. However, in vitro studies have shown that light between 320 and 400nm can photooxidize aromatic amino acids into toxic compounds. This light also inhibits the growth of bacteria and destroys ubiquinone within bacterial cells. It causes the drug psoralen to combine with the DNA of mammalian cells, and it inactivates transforming DNA.

The wavelengths of sunlight which are modulated by the ozone in the stratosphere, 280-320 nm, are the wavelengths of light that produce sunburn and skin cancer. Wavelengths longer than 320 nm are very ineffective in this regard. However, if both types of light are used together they produce a greatly enhanced sunburn reaction in human skin and an increased incidence of skin cancer in mice.

Photosynthesis

One investigator reported on different mechanisms by which plants take carbon dioxide from the air to form sugars, which are then converted into other forms of plant food. The first process, discovered and described in the 1950's, is the classical "pentose cycle." A newly discovered "four-carbon cycle" operates in grasses and sugar cane. This process is much more efficient, since it takes place at low carbon dioxide concentrations and at higher light intensities, and such plants do not perform photorespiration. With the intense need for increased food production in the world, information concerning the natural mechanism by which certain plants use sunlight more efficiently in photosynthesis would be of great importance in planning for increased food production throughout the world.

Light Perception Without Eyes

Light is perceived by structures other than the eyes in all classes of non-mammalian vertebrates. Most of the experimental evidence supporting this statement comes from studies on the role of light in controlling biological rhythms and seasonal reproductive cycles. While the photoreceptive structures involved have not been precisely localized or identified, it is clear that in some cases, they are located in the brain but are not the eyes nor the pineal gland. The interrelationships and adaptive significance of these extra-ocular photoreceptors present a challenge to the ingenuity of photobiologists.

Photomotion

Plants can orient themselves with respect to light so that they are in an optimum position for carrying out photosynthesis. Motile one-celled plants share this ability with the more familiar flowering plants. Some concentrate in a light beam while others are able to move toward or away from a light source. The intriguing question is: How does a microbial cell detect light direction? Basically there are two possible mechanisms: (1) It may compare light absorbed in two regions of the cell at one point in time, or (2) It may compare light absorbed in one region of the cell at two points of time. Information is minimal as to the nature of these photoreceptors in microorganisms, and almost nothing is known about the transmission of photomotion signals from receptor to effector.

Chronobiology

The ability to distinguish time of day without reference to external light and darkness is found in plants and animals of all sizes and levels of complexity. This was discovered by study of rhythmic changes in activity or other physiological functions which can continue in constant light and temperature, a discipline now called chronobiology. One example of such a rhythm is the nocturnal activity of cockroaches which continues in cycles when these insects are kept in constant darkness.

Light has a number of important effects on this time sense or circadian clock, as it is sometimes called. Light keeps the timing cycle synchronous with environmental day and night and adjusts it to long or short days, even stops or starts it under certain conditions..

The Ultraviolet World of Insects

For man the visible spectrum ends at about 380–400 nm, but for many insect species vision extends to 300 nm in the ultraviolet region. Moreover, near ultraviolet light is a distinct color for many species of insects and has special significance in influencing the behavior of this large and ecologically important group of animals. For example, because near ultraviolet light is the most effective in attracting insects, insect traps are fitted with ultraviolet lamps. Conversely, because lamps that are poor in blue and ultraviolet light offer much less stimulation to insects, yellow bulbs are frequently used to illuminate porches and patios. There are other examples, less obvious but vastly more important ecologically. Flower colors frequently involve patterns of differential ultraviolet light reflectance that can be appreciated by insect pollinators but not by the unaided human eye. The wings of butterflies also contain patches of high ultraviolet reflectance which flag prospective mates. In flight these signals can be quite conspicuous to other members of the species but remain unseen by vertebrates.

Vision

Considerable attention was given at this meeting to a problem which has long plagued the scientist studying photobiological processes such as vision; namely, how light absorbed by an organism is eventually converted into metabolic or sensory information for the organism. In vision science, this problem centers on attempts to describe how light impinging on the retina is eventually translated into a signal that goes to the brain. Some investigators reported that upon light exposure, calcium released within the photoreceptor cells of the retina is partially responsible for producing the electrical signals which eventually reach the brain.

Solar Energy Conversion

A number of researchers surveyed various schemes for solar energy conversion, some involving biological processes: (1) Direct heating, (2) Growth of grain and hence of cattle and chickens. Growth of algae, aided by nutrient wastes. (3) Photosynthetic production of hydrogen from water. (4) Solar batteries: Inorganic, organic, cells patterned on photosynthetic models.

In terms of the converson of solar energy, the most promising mechanisms appear to be solar powerhouses; in other words, the trapping of heat to run conventional turbines or to run chemical reactions leading to the splitting of water thus yielding hydrogen gas. Certain types of solar batteries also look promising. Energy conversion based upon photosynthesis of chemical models of photosynthesis may require many years to develop. Solar energy conversion, however, is probably the only ecologically acceptable source of power.

Summary

One cannot help but be impressed by the great number of ways that plants and animals are affected, beneficially and detrimentally, by light. Yet, in most scientific experiments using animals and cells, the quality and quantity of light and its cyclicity are totally ignored. Clearly, because of the unique physiological importance of light to all living things, the light environment in experiments must be accurately controlled in the same way that, for example, temperature and pH are controlled.

The future of the science of photobiology seems bright. Its goals can be roughly divided into four categories: (1) The development of ways to protect oranisms, including man, from the detrimental effects of light; (2) The development of ways to control the beneficial effects of light upon our environment; (3) The continued development of photochemical tools for use in studies of life processes; and (4) The development of photochemical therapies in medicine. The science of photobiology appears to have come of age as a major new scientific frontier.