EYE REGIONALIZATION AND SPECTRAL TUNING OF RETINAL PIGMENTS IN INSECTS

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Published in:
Trends in neurosciences

DOI:
10.1016/0166-2236(92)90038-A

Publication date:
1992

Eye regionalization and spectral tuning of retinal pigments in insects

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The spatial and spectral properties of an eye can often be directly linked to the behaviour and habitat of the animal. In a honey bee (Apis mellifera) *society, the drones use the well-developed dorsal part of the eye to detect the queen against the sky during her nuptial flight. Recently it has become clear that the dorsal area of the drone's eye serves its task by cleverly combining a number of optical mechanisms, thus achieving a high spatial acuity as well as a high sensitivity precisely in the wavelength range of interest – the ultraviolet to blue range. Since the various optical specializations in the drone eye have now been recognized, they can be traced in the eyes of other species: thus, the drone eye serves as a model to give a better understanding of the relationship between structure and function of compound eyes in particular, but also of visual systems in general.*

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The drone eye, like that of the worker honey bee, is a typical apposition eye (for compound eye typology, see, for example, Refs 1, 2). It is composed of about 10 000 ommatidia (compared to 5000 in the worker). Each ommatidium (Fig. 1), the morphological and functional unit, has nine visual sense cells (although insect ommatidia as a rule have eight sense cells). The rhabdomeres – the organelles that contain the visual pigment of the photoreceptors – are fused into one functional optical waveguide, the rhabdom. Together with the optical apparatus (facet lens and crystalline cone), the rhabdom samples light from a spatial angle in the order of one degree. Off-axis light is screened off by the surrounding pigment cells (Fig. 1).

The recent morphological study by Menzel *et al.*[3] shows that the drone eye consists of three distinct areas: (1) the ventral area, making up the lower third of the eye; (2) the dorsal area, covering the upper two-thirds of the eye; and (3) the dorsal rim area, which comprises a band of ommatidia, 3–4 facets wide, along the dorsal and dorsofrontal margin of the eye. The dorsal area differs from the ventral and dorsal rim area in several respects: the eye is less curved and the facet lenses are larger, resulting in interommatidial angles of 1–2°, compared with 2–4° elsewhere; the rhabdom is longer (i.e. 500 μm compared with 200–400 μm; see Fig. 2); and the rhabdom cross-section is twice as large[3].

Tightly connected to the difference in the structural aspects is a strong regionalization of the spectral characteristics. The ommatidia of the dorsal area contain a reddish screening pigment in their distal third, while no such pigment is found proximally or near the basement membrane that marks the inner limit of the retina at the proximal side. In the ventral area, a very dense dark-red pigment is not only abundant distally, but extends over the whole length of the ommatidia and, most strikingly, is prominently present at the basement membrane (the basal pigment) (Figs 1, 2). Intracellular recordings from the visual sense cells demonstrate a similar dichotomy[4,5]: two receptor types are encountered dorsally, an ultraviolet receptor and a blue receptor, with sensitivity spectra peaking at about 330 nm and 440 nm, respectively; the ventral area contains the same two

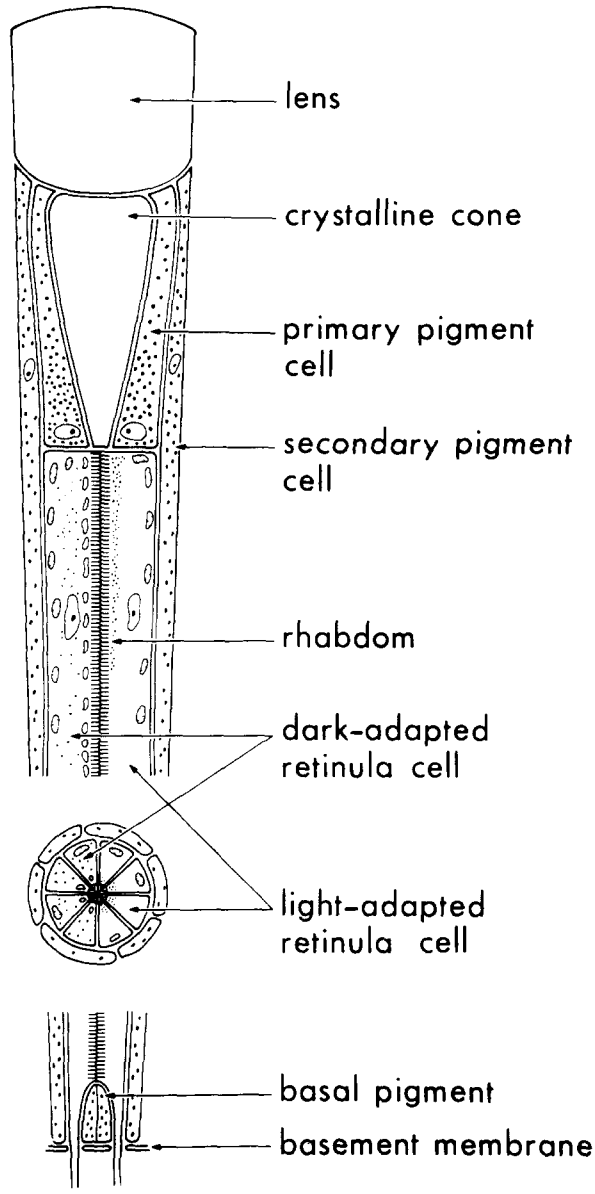

Fig. 1. *The structure of the ommatidium of a hymenopteran compound eye, which represents a 'typical' apposition eye. Incident light is focused by the optical apparatus (facet lens and crystalline cone) on the rhabdom, which contains the visual pigments. Screening pigment in the primary and secondary pigment cells blocks off-axis light, while the basal pigment absorbs stray light that comes eventually from behind the retina. Upon light adaptation pigment granules in the photoreceptor (or retinula) cells control the light flux, thus acting as a pupil mechanism.* (Taken from Ref. 28.)

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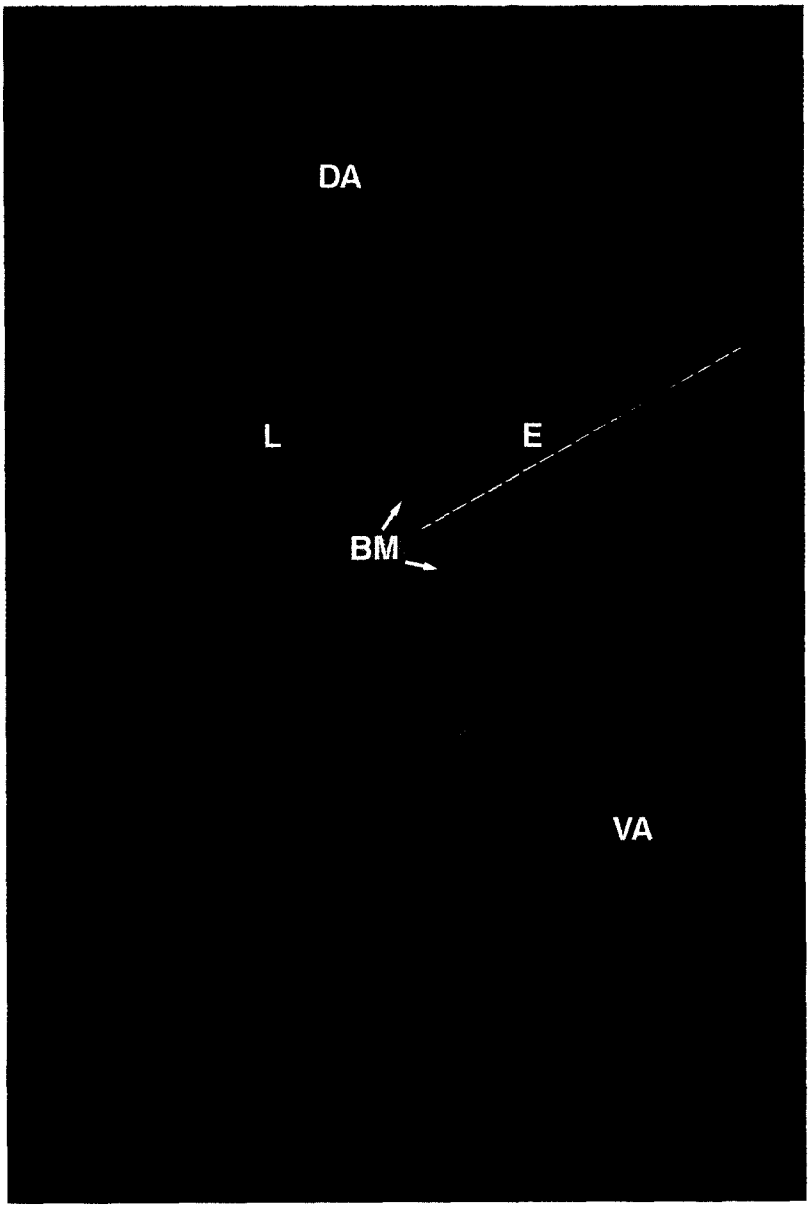

Fig. 2. *Anatomical section of the eye of the drone bee, showing the strong difference in pigmentation between the dorsal (DA) and ventral areas (VA) of the retina. The border line between the two areas is the equator (E). The border line between the retina and the lamina (L) is the basement membrane (BM). In the lamina the photoreceptor axons synapse with second-order neurons. Most noticeable in the ventral area is the dense pigmentation near the basement membrane (basal pigment in Fig. 1), while no such pigmentation occurs dorsally.* (Courtesy of Dr H. Wunderer.)

types and, in addition, a green receptor peaking at 530 nm. It is a logical step to assume that the regionalization in structure and screening pigmentation is functionally related to that of the visual sense cells. A functional link can indeed be inferred from our present knowledge of the photochemistry of invertebrate visual pigments.

Photochemistry of visual pigments

After absorbing light, a visual pigment molecule goes through a series of thermal steps, culminating in a metarhodopsin state, which acts as the trigger for the phototransduction process by coupling to a transducin G protein[6,7]. The triggering is short-lived, because the metarhodopsin is quickly phosphorylated and, at least in vertebrates, even more strongly 'locked up' by arrestins[6,8–11]. Vertebrate metarhodopsins decay thermally so that after about a second the chromophore (retinal) and the protein part (opsin) become separated. This makes sense, because the possible dephosphorylation of metarhodopsin that would lead to a renewed triggering of the phototransduction process is thus prevented[11]. However, although invertebrate metarhodopsins are thermostable, they also do not produce a persistent signal; apparently, they are sufficiently blocked by phosphorylation. All the same, owing to its thermostability a metarhodopsin molecule can be hit by another photon and be converted back to the original rhodopsin state, which, after dephosphorylation, is again able to participate in the phototransduction process (Fig. 3)[12].

Microspectrophotometry of the visual pigments of the drone in retina slices[13] and *in vivo*[3] has yielded a main visual pigment dorsally characterized by R446–M505; this pigment is a blue rhodopsin that has a maximal absorbance at 446 nm and a metarhodopsin form that peaks at 505 nm (Fig. 4A). The dorsal area also contains an ultraviolet rhodopsin (Fig. 4A), although in a much lower concentration[13]; it clearly is virtually identical to the ultraviolet rhodopsin first discovered in the owlfly *Ascalaphus macaronius*, which is characterized by R345–M475[14,15]. The green rhodopsin found in the ventral area (along with the ultraviolet and blue rhodopsins) is not yet fully characterized[3], but it is very similar to other green rhodopsins such as those of lepidopterans[16,17], which are characterized by R520–M480 (Fig. 4B). Microspectrophotometry does not identify the visual pigments in individual cells because the rhabdomeres are optically fused. Nevertheless, it is clear that in a given photoreceptor cell only one visual pigment type is expressed, since the electrophysiologically determined sensitivity spectra correspond well with rhodopsin absorbance spectra. (It must be noted, of course, that optical effects owing to the waveguide properties of the rhabdom and mutual spectral filtering of the visual pigments slightly modify the sensitivity spectra.)

The visual pigment spectra in Fig. 4 show that the peak absorbance of a rhodopsin is substantially

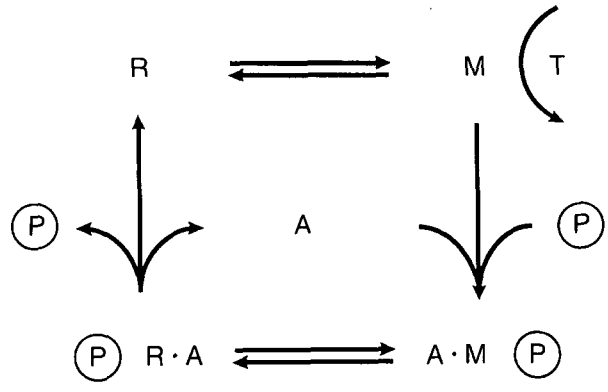

Fig. 3. *Simplified diagram of the photochemistry of invertebrate visual pigments. After photon absorption, rhodopsin (R) is converted into metarhodopsin (M). This state triggers phototransduction by coupling to the G protein transducin (T) until it is deactivated by phosphorylation and interaction with arrestin (A). (Note that this interaction with arrestin has not yet been firmly established in the case of invertebrates.) M can be photoreconverted back to R. Subsequent dephosphorylation yields a rhodopsin molecule that can be photoconverted again into active metarhodopsin.*

smaller than that of its metarhodopsin. This is due to the chromophore for rhodopsin being 11-*cis* and that for metarhodopsin being all-*trans*, respectively[11,15–17]. Furthermore, the ultraviolet and blue rhodopsins have bathochromically shifted metarhodopsin states (i.e. towards longer wavelengths), while the green rhodopsin has a hypsochromically shifted metarhodopsin (i.e. towards shorter wavelengths). This appears to be a common property of invertebrate visual pigments. A plot of the peak wavelengths of known pairs of invertebrate visual pigments and their thermostable photoproduct (Fig. 5) shows that below the borderline of $\lambda_{max(R)} \approx 500$ nm the shift of metarhodopsins is bathochromic and above 500 nm it is hypsochromic[17,18]. It is this dichotomy that determines the screening pigmentation in insect eyes (see below).

Coloured filters shift the photosteady state of invertebrate visual pigments

The reddish pigment of the dorsal area of the drone is quite transparent, as can be shown in a simple laboratory experiment. If the dorsal area is viewed with a normal dissecting microscope while illuminating the eye with white light from the side, a reddish eyeshine emerges from those facet lenses that look into the microscope aperture. Part of the obliquely incident light, after having strayed in the eye, is eventually backscattered through the rhabdoms out of the eye[3]. However, nothing like this is seen in the ventral area because stray light there is effectively absorbed by the dense, dark-red pigment. In order to understand the functional significance of the straying of red light dorsally it should be realized that a sufficiently prolonged illumination of an invertebrate visual pigment yields a photosteady state, where the ratio between the fractions of rhodopsin and metarhodopsin, f_R/f_M, depends on the spectral composition of the light. With monochromatic light, this ratio equals the ratio between the photosensitivities of the two thermostable states β_M/β_R (Fig. 4C)[15,17]. In the case of the ultraviolet and blue rhodopsin, broad-band (white) illumination will generally result in a reduced rhodopsin fraction. However, yellow–red light that is exclusively absorbed by the metarhodopsin states establishes a photosteady state with a high rhodopsin content, and thus yields a high sensitivity of the receptors.

Apparently, the honey bee drone makes extensive use of this mechanism in the dorsal area. The distal pigmentation is sufficiently dense in the short-wavelength range to absorb off-axis light, thus preventing deterioration of spatial acuity. However, the long-wavelength light that is not absorbed by the rhodopsins, and that thus does not lead to phototransduction, can more or less freely roam through the eye to reconvert the inactivated, metarhodopsin molecules (for a similar effect, first discovered in the blowfly *Calliphora vicina*, see Refs 18–20). Even red light that has traversed the retina but is backscattered from within the layers proximal to the basement membrane can execute this role.

The ventral area cannot use this trick, since red stray light would preferentially convert the green

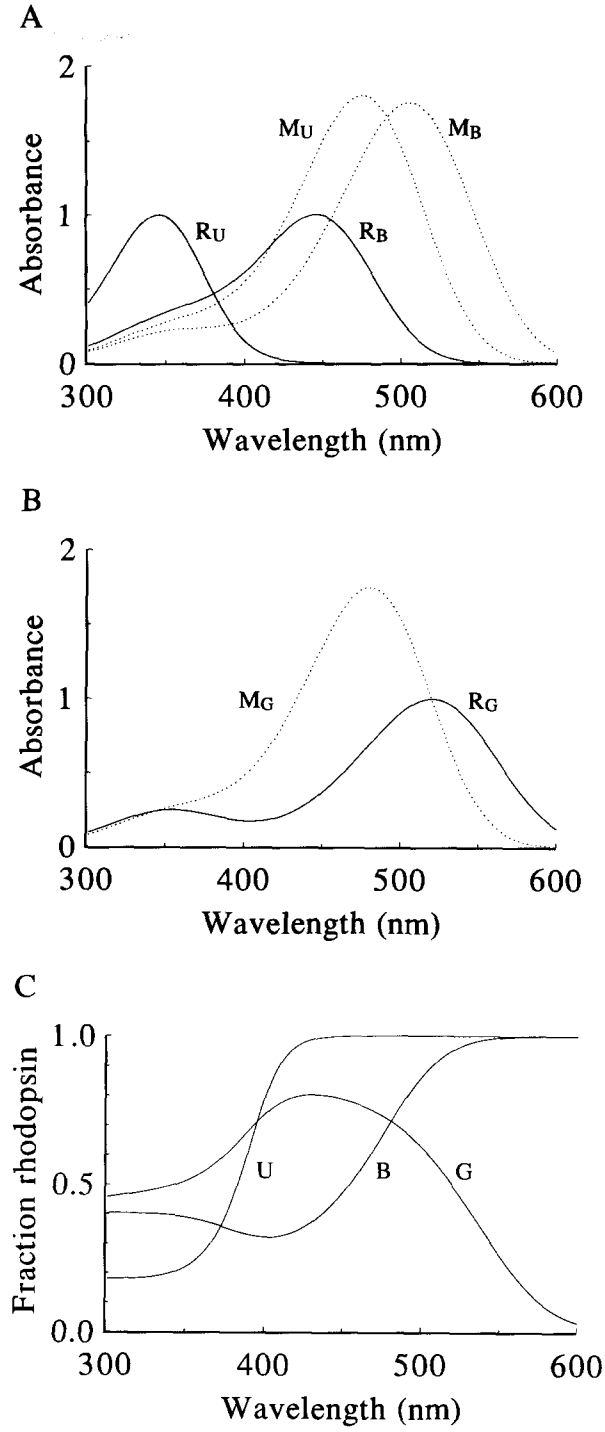

Fig. 4. *Spectra of drone bee visual pigments.* **(A)** *The dorsal area contains two visual pigments: the ultraviolet (U) rhodopsin R345, which after photon absorption is converted into a thermostable metarhodopsin state M475, and the blue (B) rhodopsin R446, which is photoconverted into metarhodopsin M505 (Ref. 13).* **(B)** *The ventral area contains both the ultraviolet and the blue rhodopsin and in addition a green rhodopsin R520 that is converted into metarhodopsin M490. All the metarhodopsins can be photoconverted back into their respective rhodopsins.* **(C)** *Monochromatic light establishes a photosteady state with a rhodopsin fraction: $f_R = \beta_M/(\beta_R + \beta_M)$, where β_R and β_M are the photosensitivities of rhodopsin and metarhodopsin, respectively, at the wavelength of illumination. With long-wavelength light, the rhodopsin fraction in the photosteady state is high for the ultraviolet and blue visual pigments, but low for the green rhodopsin. Hence, incident broad-band, natural light filtered by screening pigment that is transparent in the red pushes only the blue and violet visual pigment population into the rhodopsin state, thus causing a high sensitivity of the receptors. In the case of the green rhodopsin, exhaustion of rhodopsin has to be prevented by a black screening pigment.*

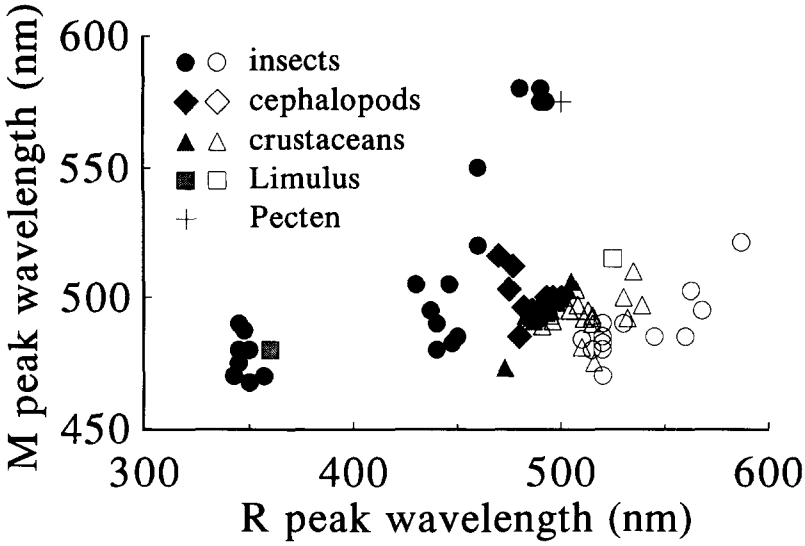

Fig. 5. *Peak wavelengths of invertebrate visual pigments and their thermostable photoproduct. The peak wavelength of the metarhodopsin, $\lambda_{max(M)}$, appears to be bathochromically shifted with respect to that of its rhodopsin, $\lambda_{max(R)}$, when $\lambda_{max(R)} \leqslant 500$ nm (closed symbols), and hypsochromically shifted when $\lambda_{max(R)} \geqslant 500$ nm (open symbols).* (Taken from Refs 17, 18, 40.)

rhodopsin instead of the metarhodopsin (Fig. 4C), thus hopelessly degrading both visual sensitivity and acuity. Hence, dense screening pigment encases the visual sense cells on all sides, except for the narrow, forward-looking rhabdom tip.

Tuning screening pigments to visual pigments

Screening pigments acting as long-pass spectral band filters can be recognized in several insects. In a broad survey of insect eyes, Dietrich[21] introduced the term 'divided eye' for those cases where the structure in the dorsal part differs distinctly from that of the ventral part. Notably this occurs in male horseflies and deerflies (tabanids: *Tabanus, Haematopota, Chrysops*) and mayflies (*Cloeon*)[21]. Physiological studies on blackflies (*Simulium*)[22] and mayflies[23] have demonstrated that males have only ultraviolet receptors dorsally; in these cases, the screening pigment is not only transparent in the red, but also in the blue–green[22,23].

Predatory insects like dragonflies, which catch their prey after spotting it from below against the blue sky, have a divided eye essentially like the drone[24,25]. Certain species have only short-wavelength receptors dorsally (*Sympetrum*[26]), while the ventral eye can have up to five types: ultraviolet, violet, blue, green and red (e.g. in *Hemicordulia*[27]). Even with the naked eye it is obvious that the specialized dorsal area of libellulid dragonflies (e.g. *Sympetrum*; see front cover of this issue) has a reddish pigmentation. Ventrally, a dense, black pigment is hidden behind a lighter pigment cover[24,28]. Clearly, discrimination of a potential mate or a prey as a spot against the ultraviolet–blue sky is best achieved by short-wavelength receptors, the sensitivity of which is maximized by the well-tuned, red screening pigment. A similar organization occurs, for example, in owlflies[14,29]. Apparently, the benefit of this tuning has been discovered several times in the evolution of insect eyes[3,28]. However, as most insects contain green receptors throughout their eyes (presumably related to their life among foliage), the screening pigment must be sufficiently dense to black out spurious stray light[28].

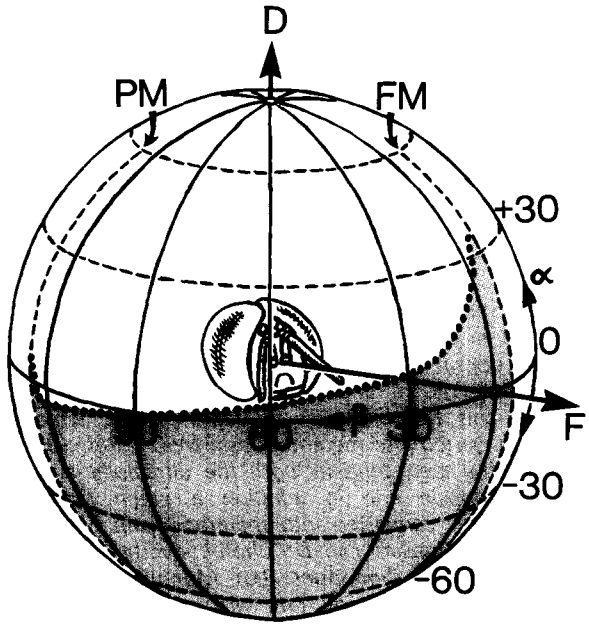

Fig. 6. *The borderline (or eye equator; see also Fig. 2) between the dorsal and ventral area (dotted line) projected onto the visual field of the right eye of the drone bee. The ventral field of view is tinted grey. Abbreviations: D, dorsal; F, frontal; FM and PM, approximate projection of frontal and posterior eye margin.* (Taken from Ref. 3.)

Regionalization of insect eyes and visual ecology

The fact that insect metarhodopsins fluoresce distinctly[18] has been exploited by mapping out those drone ommatidia having only short-wavelength rhodopsins and also those having additional green rhodopsins[3]. The border line between the dorsal and ventral areas, called the eye equator, corresponds strikingly to those ommatidia that have their visual axis directed horizontally during flight[3] (Fig. 6). The ommatidia in the dorsal area of the eye of the drone sweep the sky and those in the ventral area watch the earth. The three types of receptor that occur ventrally provide the drone with a colour vision system that is only marginally different from that in the worker bee[5,30,31].

A minor but quite special region in the drone eye is the dorsal rim area. Several anatomical reports now show that the dorsal rim area is a common feature of insect eyes[32,33]. The function of this unique area has been uncovered due to the work of Wehner and Rossel and co-workers on the desert ant *Cataglyphis bicolor* and worker bees[34,35]. The purposefully arranged receptors in the dorsal rim area discriminate the polarization of ultraviolet light in the sky, as shown by neurophysiological and behavioural experiments[34,35]. The receptors in the large dorsal rim area in the cricket *Gryllus campestris* are maximally sensitive in the violet wavelength range[32]. Curiously, the area is devoid of screening pigment[18,36] – which is readily observed using a fluorescence microscope[18]. Presumably this is related to the extremely high sensitivity of the polarization detection system of the cricket[37].

The properties of the drone eye demonstrate the diverse visual characteristics of a single eye: the ventral part is responsible for colour vision, the dorsal part is especially sensitive to light contrast, and the dorsal rim is sensitive to polarization. The strong sexual dimorphism that is immediately apparent from the prominent dorsal areas of many male insects[20–23,38,39], together with the general occurrence of the dorsal rim[33], indicates that regionalization is a common property of insect eyes. A recent study on two co-occurring species of the *Lycaena* family of butterflies[40] underscores this conclusion. The organization of the eyes of the males is essentially like that of the drone: dorsally only an ultraviolet (R360) and a blue rhodopsin (R437) exist, while ventrally a yellow rhodopsin (R568) exists as well. The females possess these three visual pigment types both dorsally and ventrally, but the female of one species has a fourth pigment ventrally: a blue–green rhodopsin, R500. The visual-pigment spectra appear to be well matched to wing-reflectance spectra for effective discrimination of wings of conspecific males from those of other species. The yellow rhodopsin is specifically important in ovipositing females for long-range detection of the red coloration of the plants from which they feed[40]. Another example with a distinct regionalization of the eye is the swallowtail, *Papilio xuthus*[41]. Intracellular recordings in the eye of this insect have yielded five receptor types; however, in contrast to the drone and dragonfly, the ventral part of the eye appears to be more sensitive to light of shorter wavelengths compared with the dorsal part. Presumably, this is related to the preference of papilionid butterflies to feed on blue and violet flowers[41].

Concluding remarks

The study of insect eyes shows that different parts of the eye can subserve distinctly different behavioural functions that are clearly based on a careful selection of spectral receptors and supporting pigments. Presumably, a similar situation holds for other eyes as well[11]. The tuning of the absorbance spectrum of a visual pigment to the ambient spectral distribution is considered to be a property of all eyes[42]. Regionalization of different spectral receptor types has so far received little attention but may be widespread. For instance, 44% of the visual pigment in the dorsal retina of the bullfrog is rhodopsin and 56% is porphyropsin (i.e. the chromophore is derived from vitamin A_1 and A_2, respectively), while in the ventral retina the fractions are 95% and 5%, respectively[43]. In this case, tuning of the visual pigment occurs apparently by altering the chromophore and not by the more common mechanism of modifying the protein. The retinal regionalization of certain birds, (e.g. pigeons) is distinctly apparent from the colour of oil droplets in the cone cells; in this case, tuning is achieved by various carotenoid colour filters[44,45]. Another, somewhat bewildering, example is the case of crustacean stomatopods that have at least ten spectral types of photoreceptors, concentrated in a few rows of ommatidia that together form a central band[46].

More examples and possibly new principles will probably emerge in the near future. Faced with the vast diversity in photoreceptors, the ultimate task of the investigator is to explain such diversity in terms of the animal's life style. The drone eye, at least, has taught us that its pigments are tuned to the spectral characteristics of the environment but also to each other in order to optimize acuity and sensitivity for both lofty and down-to-earth affairs.

Acknowledgements
I thank J. Schwemer and H. Wunderer for reading the manuscript and for their support.

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Temporal coding in the visual cortex: new vistas on integration in the nervous system

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Although our knowledge of the cellular components of the cortex is accumulating rapidly, we are still largely ignorant about how distributed neuronal activity can be integrated to contribute to unified perception and behaviour. In the visual system, it is still unresolved how responses of feature-detecting neurons can be bound into representations of perceptual objects. Recent crosscorrelation studies show that visual cortical neurons synchronize their responses depending on how coherent features are in the visual field. These results support the hypothesis that temporal correlation of neuronal discharges may serve to bind distributed neuronal activity into unique representations. Furthermore, these studies indicate that neuronal responses with an oscillatory temporal structure may be particularly advantageous as carrier signals for such a temporal coding mechanism. Based on these recent findings, it is suggested here that binding of neuronal activity by a temporal code may provide a solution to the problem of integration in distributed neuronal networks.

During the past few decades, neuroscience has been pervaded by the idea that the relevant level for describing how nervous systems work is that of the single cell. Guided by this assumption, which has been addressed by Barlow as the 'single neuron doctrine'[1], considerable progress has been made in understanding the constituents of neuronal systems at the cellular and molecular level. In contrast, our knowledge about the integrative functions of the nervous system is still poorly developed. This problem is particularly evident in cortical neurobiology. Although much has been learned concerning the structural and functional properties of single neurons and their connections, crucial questions concerning integration of cortical activity are still unresolved[2,3]. Increasing evidence suggests that many cortical functions are based on distributed processes that occur in parallel at different sites. However, it is still enigmatic how relationships are established between such distributed neuronal activities, even though this seems required to represent information about the environment or the internal states of the organism and finally to achieve coherent perception or action.

Visual information processing may be taken as an example to illustrate this need for integration, which is commonly addressed as the 'binding problem'[3]. It is well known by now that the visual system exhibits a high degree of functional specialization[4–8]. Neurons in most areas of the visual cortex process information only from a limited part of the visual field and respond only to a restricted range of feature constellations. Thus, the outputs of numerous cells must be integrated to create a complete representation of a particular object. Moreover, neurons detecting different attributes of an object tend to be compartmentalized in a modular fashion, and it has been argued that different features such as form, colour or motion are analysed independently by separate processing streams[4–8]. Accordingly, object representation requires integration across these different pathways. Unfortunately, there is no evidence for convergence of these processing streams onto a single target region that could provide the basis for a unified percept[3,8]. In the visual system, the binding of features pertaining to individual objects appears to be a prerequisite for figure–ground segregation and scene segmentation, i.e. for the distinction between several objects present in the visual field. Of course, similar problems arise in other sensory modalities, and mechanisms for binding are also required where sensory events have to be linked with motor acts or when stored information must be recombined during memory recall[3].

Classical approaches to the binding problem

In the framework of the 'single neuron doctrine' it is assumed that the binding problem can be solved by convergence of input from the primary processing stages onto single cells with highly specific response properties[1]. Such 'cardinal cells' are supposed to be located in 'higher' integrative cortical areas that correspond to the presumed final stages of visual information processing. However, a number of arguments suggest that single cell representations, while perhaps effective for specialized functions, cannot provide a general solution to the binding problem[2,3]. (1) This model suffers from a 'combinatorial explosion'. Since every new feature constellation would require a new 'cardinal unit', far too many cells would be needed to cope with the complexity of the perceived world and the variability of its aspects. (2) A large number of uncommitted cells would have to be reserved for the representation of new objects. (3) The model lacks unequivocal experimental support. The discovery of

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