

24 Correction of Some Misinterpretations, Misleading Nomenclatures, Misbelieves and Errors Concerning Polarized Light and Polarization Sensitivity

In this chapter I deal with some common misbelieves, misleading nomenclatures, errors and misinterpretations concerning polarized light and polarization sensitivity I found during surveying the literature. The majority of these mistakes occur in publications of biologists. I would like to emphasize that although these misbelieves, errors or misleading usage of technical terms never have concerned the correctness of the final conclusions drawn. However, it is worth correcting them in order to avoid their possible repeated occurrence in future publications. The common misbelief that the degree of linear polarization of light from the clear sky is highest in the UV is treated in Chapter 8.1.

24.1 The Relative Positions of the Arago, Babinet and Brewster Neutral Points

A frequently occurring error in text-books is that the relative positions of the Arago, Babinet and Brewster neutral points of skylight polarization are represented as if all three unpolarized points were observable at the same time in the sky. Figure 24.1 shows two examples for such erroneous representations. As we have seen in Chapter 7.4, in the sky only two neutral points can be observed simultaneously, either the Arago and Babinet points for lower solar elevations, or the Babinet and Brewster points for lower solar zenith angles. The reason for this is that the angular distance of the Arago point from the antisun is approximately the same as that of the Babinet and Brewster points from the sun. Thus, when the Brewster point rises above the horizon, the Arago point sets below the horizon. Consequently, all three neutral points can never be seen at the same time under normal atmospheric conditions.

The reason for such erroneous representations (e.g. Fig. 24.1) is probably the lack of space for voluminous figures rather than incorrect knowledge. To display correctly the relative positions of the neutral points, two figures are necessary, like Figs. 7.4.1A,B. Several authors spare one of these two figures and simply merge them into a single one, which leads to the mentioned error. Budó and Mátrai (1980) has known that at a particular time the angular distance of the Arago point

is about 160° from the Brewster point, and thus, the Arago point should already be below the horizon at higher solar elevations, but in their figure (Fig. 24.1A) they displayed the Arago point above the horizon with a much shorter angular distance from the Brewster point. Although Czelnai (1979), as an outstanding Hungarian meteorologist, has also been aware of the correct relative positions of the neutral points, in his meteorology text-book one of the figures comprises erroneously all three neutral points (Fig. 24.1B).

24.2 Correction of Some Misleading Representations of the Celestial E-vector Pattern

In the literature dealing with animal polarization sensitivity, there are some frequently cited figures of the celestial polarization pattern, which are erroneous or at least misleading. The drawing of the sky polarization pattern of Stockhammer (1959, p. 35) reproduced in Fig. 24.2A as well as the two-dimensional representations of the celestial polarization patterns presented by Wehner (e.g. 1989a, figs. 1b,c, p. 354; 1989b, figs. 1b,c on p. 67 and figs. 8A,B on p. 75; 1991, fig. 4A, p. 94; 1992, figs. 3.24a,b, p. 88) contain an error concerning the directions of the E-vectors. The mentioned figure of Stockhammer has been reproduced in many articles and text-books (e.g. Frisch 1965, fig. 328, p. 387; Grzimeks 1974; Duelli 1975, fig. 1, p. 45; Czihak et al. 1990; Frisch 1993, fig. 330, p. 382; Frisch and Lindauer 1993, fig. 88, p. 135) without any criticism. Schwind and Horváth (1993) corrected this error and presented a revised figure of the polarization of skylight (Fig. 24.2B).

Stockhammer based his polarization pattern on the data of Sekera (1957b), who represented the E-vector directions as isolines of the angle of polarization relative to the vertical. In transferring the angles so indicated to the radii of a polar-coordinate system, Stockhammer (1959) reversed the E-vector directions. As a result, all E-vectors appeared mirrored about the radii corresponding to the meridians through the zenith (Fig. 24.2A). Although Wehner presented the sky polarization patterns correctly in three-dimensional representation (e.g. Wehner 1982, fig. 13, p. 34; 1989a fig. 1a, p. 354; 1989b fig. 1a, p. 67), all of his earlier two-dimensional E-vector patterns mentioned above have the same error as the Stockhammer's (1959) pattern. Here the error was that the E-vector directions were determined by looking up at the skydome, but then plotted in a polar-coordinate system viewing the sky vault from above. Again, the result is a mirroring of the E-vector directions at the local meridian. The aim of these figures was to represent the E-vector distribution of the single-scattered Rayleigh skylight. However, in this case the E-vectors should always be aligned perpendicularly to the great circle passing through the sun and the investigated celestial point, irrespectively of whether the map displays the skydome from the point of view of an airborne or a ground-based observer. The mentioned figures are erroneous and/or misleading, because the E-vectors are not perpendicular to the scattering plane due to the incorrect mirroring relative to the local meridian.

Fortunately, inferences regarding the orientation mechanism of honeybees and desert ants have been not affected by this misleading plotting in any way, because the bee's and ant's internal representation of the celestial E-vector pattern has been represented in the same erroneous way (e.g. Wehner and Rossel 1985, fig. 2b on p. 19, fig. 6 on p. 28 and fig. 16 on p. 47; Wehner 1989a, fig. 3B on p. 355 and fig. 9 on p. 358; 1989b, fig. 8, p. 75; 1991, fig. 4B, p. 94; 1992, fig. 3.24c, p. 88).

There are two problems with these E-vector maps: (i) It has not been defined either in the text or in the figure legend whether the E-vector pattern displayed on the two-dimensional representation of the skydome is seen by a ground-based observer or by an observer who looks from above toward the skydome like an astronaut. Only from the figure legend of Duelli (1975, fig. 1, p. 45) was clear that his E-vector map, taken over simply from Frisch (1965), is seen by an ant from the ground. However, also in this case the E-vector map is erroneous. (ii) It has never been mentioned that the E-vectors are displayed in such a strange way that they are mirrored with respect to the local meridian.

Although Wehner (1994b, p. 36) did not acknowledge his mistake, all his two-dimensional representations of the celestial E-vector pattern as well as the honeybee's and desert ant's simplified internal representations of this pattern published after 1993 in a plethora of review articles (e.g. Wehner 1994a, fig. 3, p. 108; 1997, fig. 1b on p. 147 and fig. 9a,b on p. 160; 1998, inserted figs., p. 60 and fig. 7a on p. 66; 1999, fig. 9, p. 11; 2001, fig. 4 on p. 2593 and figs. 5A,B on p. 2594) follow already the correct scheme of Schwind and Horváth (1993) (see Fig. 24.1B). But henceforward the exact position of the observer has not been defined in these figures.

24.3 Misleading Nomenclatures

24.3.1 "Perception of Polarized Light" versus "Perception of Light Polarization"

In numerous publications dealing with polarization sensitivity the misleading terms 'perception/detection of polarized light' or 'sensitive to polarized light' are used, when the authors want to express that a visual system is able to perceive the E-vector direction. Wehner and Strasser (1985, p. 337), for example, wrote: "The photoreceptors of these ommatidia are characterized by a number of anatomical and physiological peculiarities which suggest that they have functional significance for the *detection of polarized skylight*". And the next sentence sounds "Here, we show by painting out different parts of the eye and recording the bee's behavioural responses that the specialized photoreceptors at the dorsal margin of the eye are indeed necessary for *detecting polarized skylight*", or "The ultraviolet receptors of the DORS MARG ommatidia are highly *sensitive to polarized light*". I would like to emphasize that these careless terms are misleading, because any visual system

is sensitive to polarized light, even if it cannot perceive the direction of the E-vector. The correct formulation would be e.g. 'perception/detection of light polarization', or 'sensitive to polarization of light'.

24.3.2 "Linear Polarization" versus "Totally Linear Polarization" and "Partial Polarization" versus "Partial Linear Polarization"

It is a common misleading nomenclature that 'linearly polarized light' is used to describe 'totally/completely linearly polarized light', and 'partially polarized light' instead of 'partially linearly polarized light' (e.g. Bernard and Wehner 1977, pp. 1019-1020). Note, however, that linearly polarized light is either partially ($p < 100\%$) or totally/completely ($p = 100\%$) polarized. Furthermore, partially polarized light can be either linearly (Stokes parameter $V = 0$) or elliptical ($V \neq 0$).

24.4 The Celestial Hemisphere Rotates Around the Pole-Point Rather than Around the Zenith

A wide-spread misbelief is that the celestial hemisphere together with the sun and the polarization pattern of skylight rotates around the zenith. For instance, according to Wehner (1989b, pp. 66-67), "... due to the westward movement of the sun, the symmetry plane, and with it the whole e-vector pattern, rotates about the zenith", or "Since the sun changes its azimuth position during the day, the symmetry axis of the pattern in Fig. 4A and with it the distribution of all skylight parameter rotates around the zenith" (Wehner 1991, p. 97)¹. An example for a misleading formulation is: "Owing to the daily westward movement of the sun across the sky (by some 15 degrees per hour), the entire e-vector pattern rotates about the zenith, thus changing its orientation with respect to geography" (Lambrinos et al. 1997, p. 134, 135). A somewhat less misleading description of the rotation of the celestial pattern sounds: "In a horizon system of coordinates, the pattern of polarization rotates about the zenith, due to the westward movement of the sun. Note, however, that the whole pattern does not merely rotate. Due to the sun's change in elevation mentioned above the pattern changes its intrinsic properties as it rotates about the zenith" (Wehner and Rossel 1985, p. 17).

However, the fact is that the sky rotates around the pole-point (Brines 1980). A ground-based observer can see the pole-point at the zenith only on the geographic north- and south-pole, thus the skydome can rotate around the zenith only at the geographic poles.

¹ Translated from the German original: "Da die Sonne im Tagesgang ihre Azimuthposition verändert, rotiert die Symmetrielinie des in Abb. 4A gezeigten Musters und mit ihr die Verteilung aller Himmelslichtparameter um den Zenit."

24.5 The Light Reflected by the Water Surface is not Always Horizontally Polarized

In the biological literature a common naive and too simplified conception is that the light reflected from the flat water surface is always horizontally polarized. For example, according to Wehner (1983, p. 361), "As light reflected from water surfaces is polarised horizontally ...", or "The e-vector direction of reflected light is always oriented parallel to the reflecting surface" (Wehner 1994a, p. 111). Another example is the statement of Kelber et al. (2001, p. 2469): "Generally speaking, the polarisation angle is parallel to the reflecting surface and perpendicular to the plane of incidence of the light. Horizontal surfaces therefore reflect horizontally polarised light."

However, these statements are not always true. As Schwind and Horváth (1993), Horváth (1995a,b), Horváth and Zeil (1996), Horváth and Varjú (1997), Horváth et al. (1997), Gál et al. (2001b) and Bernáth et al. (2002, 2003) have shown both theoretically and experimentally, if the incident light is partially linearly polarized with approximately vertical E-vector, as is the case for skylight from the celestial band of maximum degree of polarization when the sun is near the horizon, for example, then also the water-surface-reflected light is approximately vertically polarized outside and inside the strongly and horizontally polarized annular Brewster zone. Consequently, during sunset and sunrise vertically polarized skylight is reflected from a considerable area of the flat water surface, even for perfectly black waters, from the subsurface region of which no light is returned (see e.g. Figs. 10.2E-H, 11.3, 11.7, 11.10, 11.12, 12.7, 23.4, 23.5). The light returned by the subsurface regions influences significantly the reflected E-vector pattern in such a way, that the relative proportion of the water surface reflecting approximately vertically polarized light is remarkably enhanced (see Figs. 12.1, 12.4, 17.3, 17.5, 18.3) depending on the solar elevation and the amount of subsurface-reflected light, which varies with the wavelength. Bernáth et al. (2003) measured the proportion of the area reflecting nearly vertically polarized light from horizontal glass panes underlain by a black or a light grey cloth as a function of the solar elevation. They obtained that at higher solar elevations the vertically polarizing regions of the grey reflecting surface, mimicking bright water bodies, was dominant (Fig. 23.3). This demonstrates well that the light reflected from the water is not always horizontally polarized.

24.6 Arago has Discovered the Skylight Polarization Rather than Malus

In the literature dealing with polarization sensitivity the discoverer of skylight polarization, Dominique Francois Jean Arago (1786-1853) is frequently confused with another French physicist, Etienne Louis Malus (1775-1812), who has also provided discoveries about light polarization. We mention here only four examples demonstrating this confusion:

- "... the French physicist E. Malus (1809) looking through a cordierite crystal accidentally observed ... the polarization pattern of the sky ..." (Wehner 1982, p. 25).
- "Owing to the scattering of light within the earth's atmosphere sky-light is partially linearly polarized. In 1809 this phenomenon was discovered accidentally by the French physicist Etienne Malus when he was looking at the sky through a dichroic crystal ..." (Wehner 1989a, p. 353).
- "There is, however, an order to the light in the sky that the human eye fails to perceive. It is a phenomenon that was discovered accidentally by the French physicist Etienne Malus in 1809. Malus had looked up at the sky through a special type of crystal and noticed that the light was polarized. Although he did not fully appreciate what he saw, the phenomenon is now well understood" (Hawryshyn 1992, p. 164).
- "This phenomenon was accidentally discovered by the French physicist Etienne Malus in 1809; while looking at the sky through a crystal, Malus recognized that the light was polarized" (Wolken 1995, p. 183).

However, the fact is that the linear polarization of skylight was discovered by the French astronomer, physicist and politician D. F. J. Arago rather than by E. L. Malus. In 1809 Arago observed first that the light from the blue sky is partially polarized. Then he established the general distribution of skylight polarization, observed the maximum of the degree of polarization of skylight at about 90° from the sun and antisun, as well as discovered the first neutral point, which nowadays bears his name (Coulson 1988, p. 2). On the other hand, in 1808 the Institute of France announced a contest for papers to give a mathematical theory, verified by experiments, of the double refraction of light when transmitted through different crystallized bodies. The prize was awarded in 1810 to E. L. Malus, who was a colonel of the French Imperial Corps of Engineers. During his experiments on the specified subject, Malus looked through a calcite crystal at the light of the setting sun reflected by the windows of a building in Paris, and was surprised to observe the disappearance of one of the two images of the windows as he rotated the crystal. This observation led to his discovery of the laws of reflection by which his

² Translated from the German original: "... der französische Physiker E. Malus (1809) beim Blick durch einen Cordierit-Kristall zufällig am Himmel beobachtet hatte ... das Polarisationsmuster des Himmels".

name is immortalized. In fact, Malus was the first to use the term "polarization" as applied to light. He hypothesized that the corpuscles, which made up light were aligned by the process of reflection in a manner similar to the way magnetic bodies are aligned by the poles of a magnet (Coulson 1988, p. 2).

Note, however, that Wehner (1997, p. 150) corrected his earlier misinformation mentioned above: "... it was only in 1809 that the French physicist Etienne-Louis Malus, while looking at a glass through a calcite crystal, discovered and correctly interpreted the phenomenon of the polarization of light. However, the polarization he observed by looking at a glossy surface was produced by the reflection rather than the scattering of light. The first to describe the latter phenomenon was Dominique Arago (1811). Looking at the sky through a rotating dichroic (polarization) filter, he perceived the alternating appearance and disappearance of an impressive dark band extending across the sky at a distance of 90° from the sun."

24.7 The E-vector Patterns of Real Skies Differ from those of Rayleigh Skies

In the literature dealing with polarization sensitivity, the E-vector patterns of skies are always considered to be the same as those predicted by the single-scattering Rayleigh model. Only seven citations are listed here to demonstrate this widespread simplification:

- "The sunlight is polarized linearly by scattering in a direction perpendicular to the plane through the incident solar ray in a celestial point P (with good approximation equivalent to the direction of the sun from the observatory) and the direction of P from the observatory" (Glas 1977, p. 132).
- "In addition to the well-established relationship between the E-vector of sky polarization and the position of the sun (i.e., the E-vector in a given region of the sky is perpendicular to a line drawn by the observer between that point in the sky and sun), ..." (Phillips and Waldvogel 1982, p. 197).
- "... the skylight polarization pattern in the natural sky where the E-vector is everywhere perpendicular to the plane containing the sun, the point in the sky being observed and the observer ..." (Able and Able 1990, p. 1190).
- "The e vector of the polarized light of the sky is perpendicular to the sun, with the band of maximal polarization at 90° from the sun's position" (Schmidt-Koenig et al. 1991, p. 5).
- "The only E-vector orientations that reach the surface are those that are perpendicular to both the path of the light from the sun to the atmospheric particle, and also perpendicular to the path of the light from the particle to the earth's surface" (Hawryshyn 1992, p. 166).
- "The natural distribution of linearly polarized light in the sky, ..., is closely related to the position of the sun. The orientation of polarization is perpendicular to the direction of the sun, ..." (Shashar et al. 1998, p. 276).

- "As light passes through the atmosphere, it is partially polarised, depending on the scattering angle. The electrical (e) vector of each scattered ray exhibits a predominant vibration direction, which is perpendicular to the plane in which the ray was deflected (Rayleigh scattering)" (Freake 1999, p. 1159).

However, there exist relatively great areas in the sky, around the sun, antisolar point and the Arago, Babinet and Brewster neutral points, where the E-vector pattern of real skies differ from those of Rayleigh skies. In these celestial regions the E-vectors are parallel to the plane of scattering (negative polarization) or are neither perpendicular nor parallel to it. In these celestial areas of "anomalous polarization"³, the degree of polarization is usually lower than the threshold of polarization sensitivity in animals. Thus the skylight from these regions are perceived as unpolarized. Although the polarization patterns of Rayleigh skies are rather a gross approximation of the real ones, they can be considered as a good model for biological purposes. It could be an important task of future research to measure the portion of the sky where the deviation of the E-vector direction from that predicted by the single-scattering Rayleigh model is below a given threshold as a function of the solar elevation and the meteorological conditions.

24.8 Four Measurements are not Enough to Determine the Spectral and Polarizational Characteristics of Linearly Polarized Multichromatic Light

According to Wehner (1989b, p. 65), "How does the insect unambiguously detect particular e-vectors in the sky? ... solving the first problem was considered to be analogous to solving a set of four equations with four unknowns (with the four unknowns being intensity, spectral composition, degree of polarization and direction of polarization). To acquire the necessary input data the insect could perform four measurements: either simultaneously by using four different receptors, or successively by employing only one receptor."

However, this formulation is misleading, since the "spectral composition" cannot be simply considered as one of the unknown variables. The spectral composition is actually nothing else as the wavelength-dependent intensity $I(\lambda)$ of light. On the one hand, one can consider the intensity I , degree of linear polarization p and direction of polarization α as unknowns at a given wavelength λ . Then there are only 3 unknowns and only 3 independent measurements should be performed to determine them, if the light is elliptically unpolarized, that is, if the fourth component of the Stokes parameter $V = 0$. On the other hand, one can consider the wavelength-dependent functions $I(\lambda)$, $p(\lambda)$ and $\alpha(\lambda)$ in a given range of λ , and $3n$ ($n = 1, 2, 3, \dots$) independent measurements are necessary to determine

³ Anomalous in the sense that the E-vector directions of skylight differ from those predicted by the single-scattering Rayleigh model.

the values of these functions at $3n$ different wavelengths. By means of 4 measurements one cannot unambiguously determine the values of $I(\lambda)$, $p(\lambda)$ and $\alpha(\lambda)$ at different wavelengths. With 4 measurements one can at the very most obtain all four components of the Stokes vector of elliptically and linearly polarized light at a given λ .

24.9 A Common Methodological Error: Brightness Patterns Induced by Selective Reflection of Linearly Polarized Light from Black Surfaces

In behavioural laboratory experiments studying animal orientation, black surfaces are traditionally used to minimize the influence of light reflected from the surfaces surrounding the animal. The same tradition has been adopted by the majority of researchers investigating the polarization sensitivity of animals. However, in these cases the use of black surfaces is the worst choice. The reasons for this are briefly discussed here in a typical case, in which the polarization sensitivity of the rainbow trout (*Oncorhynchus mykiss*) was tested (Hawryshyn et al. 1990; Hawryshyn and Bolger 1990). Although later electrophysiological experiments revealed that juvenile rainbow trouts indeed perceive the linear polarization of light, it is worth criticizing the methodological shortcomings of the experimental technique, which are wide-spread in similar behavioural experiments. Coemans and Vos (1989), Coemans et al. (1990, 1994a) and Vos et al. (1995) called the attention of the scientific community to the need of elimination of such strongly polarizing black surfaces. This has led to the change of paradigm in behavioural experiments on animal polarization sensitivity.

The forerunners of this subject are Baylor and Smith (1958), Kalmus (1958, 1959) and Waterman (1981). Baylor and Smith (1958) suggested an extra-ocular mechanism of polarization sensitivity in honeybees. According to their hypothesis, an appropriate substratum, serving as dancing place for bees, can function as a polarization analyzer, since vertical beams of linearly polarized light illuminating the substratum give rise to reflections with minimum and maximum intensities parallel and perpendicular to the E-vector direction, respectively. On the other hand, vertical rays of unpolarized light illuminating the substratum give rise to reflections of light with uniform intensities in all directions. Although later anatomical, electrophysiological, behavioural and theoretical studies (e.g. Autrum and Stumpf 1950; Stockhammer 1956; Shaw 1967; Seitz 1969; Skrzipek and Skrzipek 1974) have proven that the rhabdomeres are responsible for polarization sensitivity in bees and many other arthropods, the merit of the hypothesis of Baylor and Smith (1958) was that they as first called the attention of researchers dealing with animal polarization sensitivity to the possibility that spurious unwanted intensity patterns induced by selective reflection of linearly polarized light from the surfaces surrounding the animal can also serve as a cue for orientation. The same was emphasized by Kalmus (1958, 1959), who investigated the responses of insects to linearly polarized light in the presence of dark

reflecting surfaces. He observed that certain optomotor reactions to plane polarized light disappeared when the experimental situation was redesigned so that the unwanted scattering- and reflection-induced intensity patterns could not arise. Waterman (1981) is also one of the few researchers who has taken this problem seriously and pointed out the necessity of testing whether a reaction of an animal to linearly polarized light is not elicited by such unwanted brightness patterns. In spite of these warnings, many experimentators studying the responses of animals to polarized light have left them out of consideration. In these cases the polarization sensitivity of the investigated animals cannot be considered as proven.

Now let us consider the criticism of such an experimental technique. During their experiments, Hawryshyn et al. (1990) and Hawryshyn and Bolger (1990) made the following typical methodical mistakes (written in bold face):

- All experiments were conducted in a room (Fig. 24.3A) with vertical walls **painted flat black** "in order to minimize spurious brightness cues".
- The training tank consisted of **black Plexiglas** with vertical walls (Fig. 24.3A).
- All observations during the test experiments were made from behind a vertical **black curtain** positioned in the immediate vicinity of the test tank (Fig. 24.3B).
- The test tank was a circular plastic pool **painted with flat grey marine paint** with an elevated floor and an approximately vertical, slightly tilted wall (Figs. 24.3A,B) "in order to limit intensity patterns as a potential cue". The fishes could see the curtain as well as the walls of the room, the training tank and the test tank.
- Although the irradiance of the polarized light field was measured along 8 arms in three positions in the test tank at the water surface with a radiometer, it was not mentioned in which range(s) of the spectrum this measurement happened. The **spatial distribution of the UV irradiance** available to the fishes in the training and test tank **was not measured**. Only this measurement could have convincingly excluded the possibility that the fishes oriented to the **brightness cues induced by selective reflection of UV polarized light from the flat black walls** of the experimental room, and/or **from the black curtain**, and/or **from the flat grey Plexiglas wall** of the testing tank, and/or **from the black Plexiglas wall** of the training tank.

In the experiments of Hawryshyn et al. (1990) the training tank was placed on two boards situated on top of the test tank. Above the training and test tanks was an overhead light source fitted with a filter tray for neutral density and cut-off filters and a UV-grade linear polarizer. The fish was placed under the release box (cover: white Plexiglas, sides: **black Plexiglas**) for 20 min prior to every experiment. A trial was initiated by lifting the release box. If a fish did not respond within 5 min the release box was pulled from the test tank completely. The fish was allowed 1-3 min in the release box between trials.

The light reflected from a non-metallic partially transparent material with a flat surface has two components. The first is reflected directly from the surface, the second one originates from the subsurface, that is, from the inner layers of the

material. When a partially linearly polarized light with a given degree of polarization and angle of incidence is reflected from a flat dielectric material, its amount depends on the angle of polarization α measured from the plane of reflection. The smaller the α , the less the amount of reflected light. Thus, more light is reflected from the surface if the E-vector is perpendicular to the plane of reflection than when it is parallel to this plane (Fig. 24.3C). This selective reflection depends only slightly on the wavelength in the near-UV and visible ranges of the spectrum, because the index of refraction of dielectric materials is usually only slightly dependent on the wavelength in these spectral ranges. The light penetrating into the material is randomly, diffusely scattered and absorbed, the consequence of which is depolarisation and decrease of intensity. Both the absorption and the diffuse scattering-induced depolarisation may strongly depend on the wavelength, which results in that the subsurface-returned component will be more or less depolarised and will possess more or less changed spectral composition.

In the case of dark partially transparent materials with smooth surfaces the surface-reflected component dominates in those regions of the spectrum, in which the subsurface-returned component is reduced by strong absorption. If a dark material strongly absorbs UV light, for example, the surface-reflected component will dominate in the UV, where the amount of reflected light will vary with the change of the E-vector direction relative to the plane of reflection. The higher the degree of polarization, the stronger this variation. Then in the UV the dark surface is seen apparently darker or brighter if the E-vector of incident light is perpendicular or parallel to the surface, respectively (Fig. 24.3C). Such reflection-polarization-induced UV-brightness differences can occur in all dark chambers, rooms or tanks, for instance, the walls of which are covered by black or grey UV-absorbing paint, or composed of black UV-absorbing Plexiglas or black UV-absorbing cloth curtain. The walls receiving more or less perpendicularly polarized light reflect less light in the UV than the walls receiving more or less parallel polarized light (Fig. 24.3C). If the E-vector of ambient light in these chambers, rooms or tanks is rotated, the reflection-induced UV-brightness pattern will follow this rotation (Figs. 24.3D,E).

Unfortunately, it cannot be excluded that the rainbow trouts in the experiments described above perceived reflection-polarization-induced UV-brightness cues for orientation, like the homing pigeons in the methodologically erroneous experiments of Delius et al. (1976) and Kreithen and Keeton (1974), because in the UV the spatial distribution of the irradiance of light reflected from the black or grey walls of the room, curtain and training as well as test tanks was not measured. This was admitted also by Hawryshyn et al. (1990, p. 570): "However, this does not fully rule out the possibility that polarization-induced brightness patterns are being utilized...". All results of Hawryshyn et al. (1990) and Hawryshyn and Bolger (1990) can be explained also by these possible UV-brightness differences induced by reflection polarization:

- "Two groups of fishes were trained under a polarized light field with the E-vector parallel and perpendicular to the training tank. During testing, both groups showed orientation consistent with the trained direction". The two groups of fishes could also be trained at a non-homogeneous UV-brightness pattern induced by a polarized light field with the E-vector parallel and perpendicular to the training tank. During testing, both groups would orient consistently with the trained direction (Figs. 24.3D,E).
- "Trouts which were tested at one E-vector orientation performed equally well at an E-vector orientation shifted by 90°". Trouts tested with one non-homogeneous UV-brightness pattern induced by one E-vector orientation could also perform equally well at a shifted non-homogeneous UV-brightness pattern induced by an E-vector orientation shifted by 90°.
- "Trouts which were tested under a polarized light field lacking UV radiation did not orient to the predicted direction". Trouts which would be tested under a polarized light field lacking UV radiation would not orient to the predicted direction, because reflection-polarization-induced brightness differences would occur only in the UV.
- "Trouts at the developmental stage when UV-sensitive cones disappear were not capable of orienting to the polarized light field". Trouts at the developmental stage when UV-sensitive cones disappear would not be capable of orienting to non-homogeneous UV-brightness patterns, because these UV patterns could not be perceived by the photoreceptors sensitive only to longer wavelengths.
- "The lower the degree of polarization p of UV+white light, the smaller the accuracy of the polarotactic orientation of trouts. If p is smaller than a threshold, trouts cannot detect the E-vector and orient polarotactically". The lower the p , the smaller would be the accuracy of the phototactic orientation of trouts, because the weaker would be the UV-brightness differences induced by reflection polarization. If p is lower than a threshold, trouts could not detect these UV-brightness differences and could not orient phototactically.

All these problems could have been avoided if white materials with as rough surfaces as possible would have been used in the above-mentioned experiments with rainbow trouts instead of black or grey materials with flat shiny surfaces. In the case of bright, UV+white-reflective materials with rough surfaces the polarized surface-reflected component, causing all the troubles, would have been strongly depolarised and suppressed by the intense and unpolarized subsurface-returned component, which would have drastically reduced or even eliminated any brightness differences induced by reflection polarization.

24.10 The Alleged Viking Navigation by Skylight Polarization

It has been mentioned in the Icelandic sagas that the Vikings sailed to Greenland by steering a course due west after leaving Bergen on the west coast of Norway. The sun would have been an obvious reference source for keeping a true westerly course during the long daylight of the polar summer (Veback and Thirlund 1992). Since the weather at these high latitudes is strongly variable, there have been periods during which the sun was consistently hidden behind clouds. The Danish archaeologist Thorkild Ramskou (1967, 1969) suggested that the Vikings might have used a certain crystal, called "sunstone" as a polarization analyser of skylight for finding the location of the overcast sun. Sunstones are mentioned in the sagas, but without enough detail for a decisive identification (Foote 1956; Schnall 1975). It has been speculated that these enigmatic sunstones might have been composed of calcite or cordierite or tourmaline, since these birefringent or dichroic or pleochroic crystals are common in the areas where the Vikings have lived. However, the fact is that presently it is completely unknown what sort of stone the sunstones were. Furthermore, sunstones are nowhere mentioned in connection with navigation or sailing, nor has any archaeological record of an object with the optical properties of an analyser been discovered (Roslund and Beckman 1994).

Since Ramskou knew that sunlight scattered by clouds is practically unpolarized, he always stressed the importance of a cloudfree sky at the zenith for the successful application of polarimetry as an aid to navigation. In spite of this severe limit to its usefulness at sea and the lack of literary and archaeological evidence for it, Viking navigation by polarimetry has largely been reported in favourable terms as an established fact of Viking achievements. It is so described in text-books (e.g. Barfoed 1967), in scientific essays (e.g. Wehner 1982) and in popular scientific journals such as *National Geographic* (LaFay 1970) or *Scientific American* (Wehner 1976). Experienced deep-sea navigators have considered the sunstone as a remarkably accurate instrument and an essential aid to Viking navigation (Britton 1972; McGrath 1991). All these have led to the widespread misbelief that navigation by skylight polarization is possible under any conditions, from clear to completely overcast skies (Roslund and Beckman 1994). The theory that the Vikings utilized polarized skylight for finding their way across the Atlantic has been uncritically accepted also by many biologists dealing with animal polarization sensitivity. We mention here only five examples:

- Kreithen and Keeton (1974, p. 83): "Instruments that measure the axis of sky polarization are presently used in circumpolar navigation where the magnetic compass is of limited use; for the same reason, early Viking ship captains may have carried polarizing crystals."
- Wehner (1976, pp. 106-107): "It has recently learned, however, that about the year 1000 the Vikings were taking advantage of the polarization of skylight in their voyages west from Iceland and Greenland to Newfoundland. The Danish archaeologist Thorkild Ramskou has pointed out that the 'sunstones' described

in the old sagas were nothing other than birefringent and dichroic crystals that could serve as polarization analysers. As I write this article I have on my table a small crystal of cordierite. When I look through it at any point in the sky, I can determine the direction of polarization by observing the changes of color and brightness as I rotate the crystal around the line of sight. Some years ago an airplane was steered with fair precision from Norway to Sondre Storm Fjord airfield in Greenland with a cordierite crystal as the only navigational aid. These crystals can be found as pebbles on the coast of Norway. Although it is unlikely that the Vikings knew anything about polarized light, they apparently perceived the relation between what they saw through a sunstone and the position of the sun (which was often hidden by clouds in those northern latitudes)."

- Können (1985, p. 18): "About 1000 the Vikings discovered the dichroic properties of crystals like cordierite. With these crystals they observed the polarization of the blue sky and were thus able to navigate in the absence of the sun."
- Wehner (1997, pp. 148, 150): "... humans have only one way to visualize celestial E-vector patterns, namely by using polarization filters as optical aids. This kind of visualization might date back to the times of the Vikings, who used cordierite crystals as polarization filters."
- Shashar et al. (1998a, p. 276): "The natural distribution of linearly polarized light in the sky, ..., is closely related to the position of the sun. ... This close association between the orientation of polarization and the location of the sun was utilized by the Vikings, who used 'sun stones', probably calcite crystals, as navigational aids."

However, in the opinion of Roslund and Beckman (1994), on most overcast days the Vikings could most certainly not have used the polarization of skylight to determine the location of the sun, since cloudlight is practically unpolarized. Although the Vikings might have been able to do so on partly cloudy days, there would have been no need to. A navigational method that requires patches of blue sky would have been of little interest to the Vikings. Even, when the sun is hidden by clouds, its location can often be found quite accurately for most navigational needs from the pattern of the solar illumination of clouds, from the bright lining of cloud tops and the crepuscular rays emanating from the sun. On overcast days careful observations of the sky may reveal the faint disk of the sun if the cloud cover is not too dense. Nor does polarimetry give clues to the solar position when the sun is below the horizon. The colour and intensity distribution during twilight appears distinct enough for the naked eye to guess the direction of the sun.

On the other hand, according to Roslund and Beckman (1994), simple sun sightings do not directly give meaningful information for steering. The solar positions should have been converted by a Viking navigator into azimuths with reference to geographical north. Today this is done by lengthy calculations with tables of data or by computers. But it is known that the Norsemen possessed a fair amount of knowledge concerning the sun's daily and seasonal movements (Roslund 1989). To convert data from the state of polarization of skylight into

directions for holding the ship's course is a vastly more complicated process. Until compelling new evidence comes forth, the notion that Vikings could have used polarimetry for finding their way across the Atlantic has little scientific basis. The use of skylight polarization for Viking navigation under partly cloudy skies should be treated with extreme caution and scepticism.

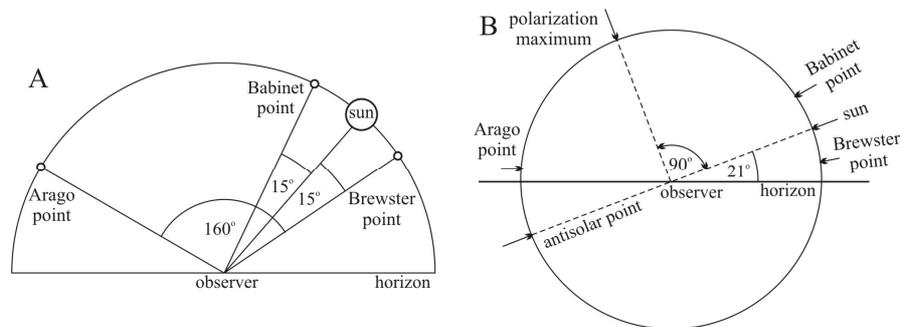


Fig. 24.1. Two erroneous representations of the relative positions of the Arago, Babinet and Brewster neutral points of skylight polarization along the solar-antisolar meridian. In these figures the positions of all three neutral points are shown as if they were observable simultaneously in the sky above the horizon. A: Budó and Mátrai (1980, Fig. 296,3, p. 250). B: Czelnai (1979, Fig. 118, p. 218).

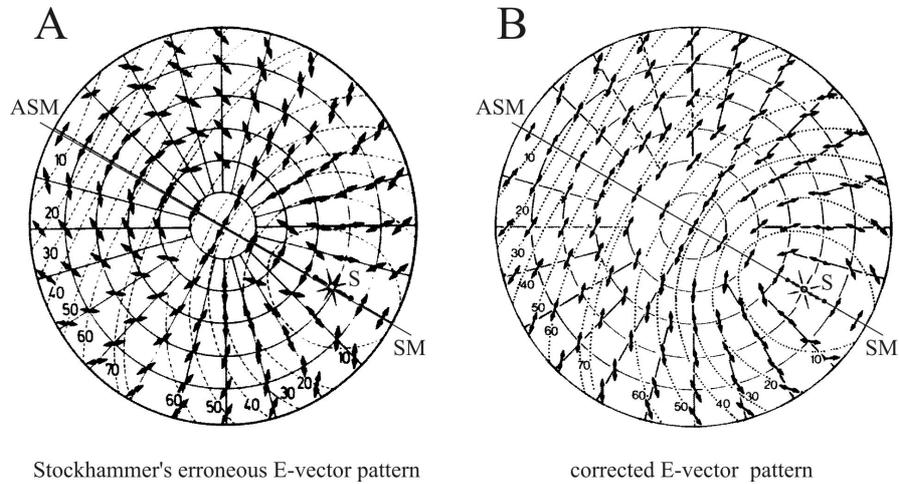


Fig. 24.2. A: The erroneous celestial polarization pattern of Stockhammer (1959) with the E-vector directions mirrored about the local meridians. B: Correct polarization pattern of the sky, with the sun at 30° elevation from the horizon. Circles: elevations at 15° intervals. Dotted: lines of equal degree of linear polarization p . Lines of equal p pass across the sky approximately concentrically around the sun, and the E-vectors are approximately tangential to these circles. In the two-dimensional representation, therefore, the E-vectors must be approximately parallel to the dotted lines and cannot in some cases lie nearly perpendicular to them, as in the Stockhammer's pattern. S: sun, SM: solar meridian, ASM: antisolar meridian. (After Fig. 2 of Schwind and Horváth, 1993, p. 83).

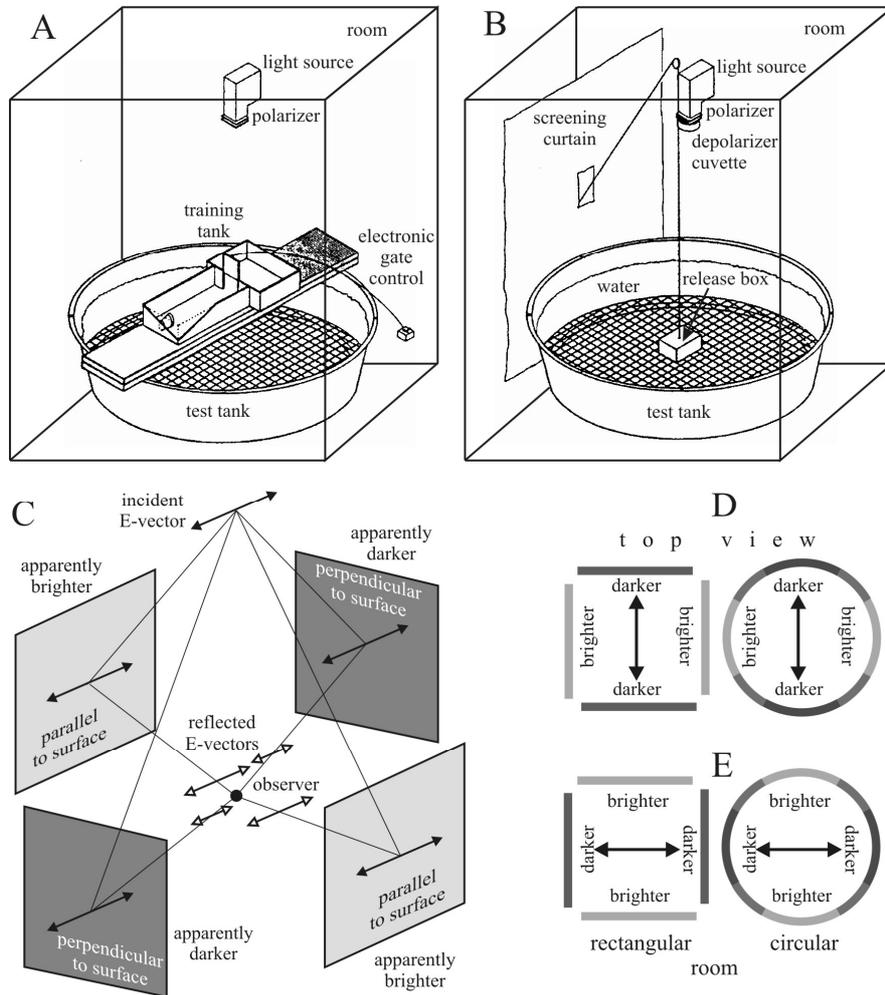


Fig. 24.3. A, B: Arrangements of training (A) and testing (B) of rainbow trout in the behavioural laboratory experiments of Hawryshyn et al. (1990) and Hawryshyn and Bolger (1990). C: Selective reflection of linearly polarized light from the vertical walls surrounding an imaginary observer. The E-vectors are represented by double-headed arrows, the length of which is proportional to the intensity. The differences in the grey shades demonstrate qualitatively the brightness differences perceived by the observer. D, E: The relative positions of the brighter and darker regions of the walls of a rectangular (left) and circular (right) room as perceived by an observer in the centre for two orthogonal directions of the E-vector of linearly polarized light illuminating the scene from above.