



## How Celestial Polarization Changes due to Reflection from the Deflector Panels Used in Deflector Loft and Mirror Experiments Studying Avian Orientation

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In bird experiments which investigate the role of optical orientation cues associated with sunset it is a common method to reflect the celestial sunset factors by vertical deflector panels. Similar panels are also used in the deflector loft of homing pigeons that rotate wind and light cues in a clockwise or counterclockwise direction. The responses of test birds in these behavioural experiments often appear to be contradictory, because the deflectors produce a polarized optical stimulus that differs both qualitatively and quantitatively from the natural skylight polarization. This paper gives a quantitative account of the change of celestial polarization in such situations. The polarization pattern of skylight reflected from different vertical deflector panels is computed as a function of the elevation of the sun from the horizon. It is shown that the reflection polarization of a deflector panel composed of transparent glass with or without white or black background cannot simulate the distribution of polarization of light in clear sky. On the other hand, if the deflector consists of a metal plate or metal-glass mirror, it can mimic the celestial polarization pattern well, because it changes the polarization of incident light after reflection only slightly.

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### Introduction

The deflector loft technique utilizes a pinwheel arrangement of stationary deflector panels that rotate wind and light cues in either a clockwise or counterclockwise direction [Fig. 1(a) and (b)]. Such deflector lofts are commonly used in the behavioural experiments studying avian navigation (Schmidt-Koenig, 1979; Helbig, 1991). Homing pigeons (*Columba livia*) raised in normal lofts and then housed in deflector lofts exhibit a deflection in release site orientation which corresponds to the direction of wind and light rotation in their deflector loft. This is called the deflector loft effect, which is frequently claimed to support the olfactory theory of pigeon navigation (e.g. Papi, 1991). However, Phillips & Waldvogel (1988) showed that the biased orientation of short-term deflector loft birds is due to the reflection of visual cues from the glass portions of the

deflector panels, rather than being the result of rotation of wind-borne olfactory cues.

Similar to the deflector loft method, metal or metal-glass mirrors (so-called front surface mirrors or back surface mirrors) are used in some behavioural experiments investigating the role of sunset cues (view of setting sun, sunset glow, skylight polarization) in the migratory orientation of birds (e.g. Kramer, 1950, 1951; Kramer & St. Paul, 1950; Walcott & Michener, 1971; Moore, 1982, 1985; Moore & Phillips, 1988; Phillips & Waldvogel, 1988; Sandberg, 1991). In these experiments the shift of the direction of sunset cues with mirrors produces a predictable shift in the migrant's orientation. This mirror technique was first applied by Santschi (1911), who studied the visual orientation of desert ants. These experiments and others (e.g. Kreithen & Keeton, 1974; Delius *et al.*, 1976; Helbig & Wiltschko, 1989; Able, 1989, 1993; Helbig, 1990; Able & Able, 1993) demonstrated that

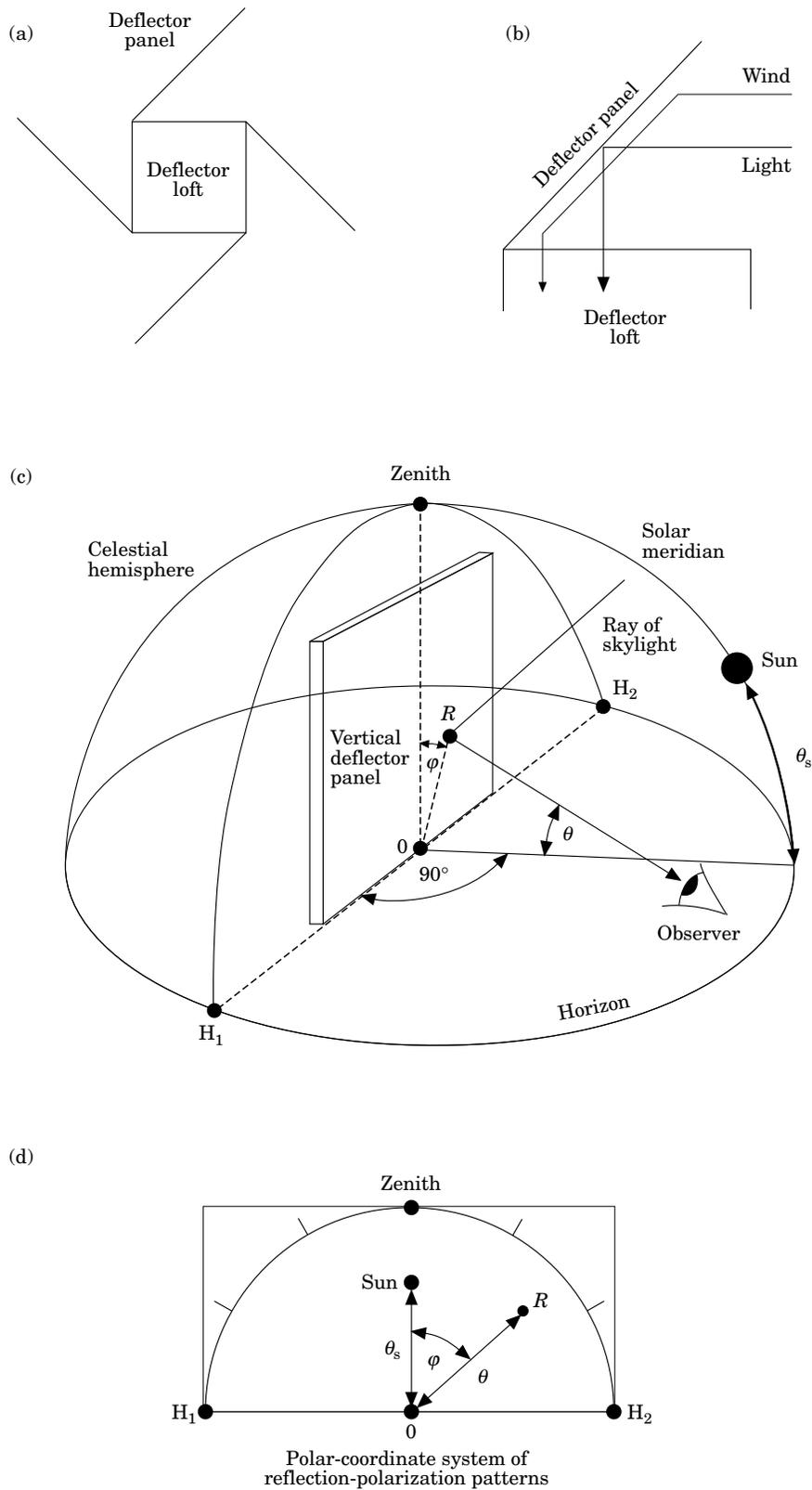


FIG. 1. (a) Top view of a common deflector loft used in the experiments studying the visual and olfactory navigation of birds. The mirroring portion of each deflector panels consists of glass plate (with a brighter or darker background) or glass-metal mirror. (b) The deflector panel rotates both wind and light in the same direction either clockwise or counterclockwise [after Phillips & Waldvogel (1988)]. (c) The geometry in the calculation of polarization patterns of skylight reflected from a vertical deflector panel, which is perpendicular to the plane of the solar meridian. (d) The polar-coordinate system used to represent the reflected celestial polarization patterns.

the celestial polarization pattern is one of the most important visual cues in the orientation of birds, whose visual system is sensitive to polarized light.

Considering the deflector loft and mirror experiments on avian navigation and polarization vision, it would be important to know how the skylight polarization changes due to reflection from these deflector panels and mirrors. Until now only Phillips & Waldvogel (1988) have made an attempt to measure the effect that a plexiglass deflector panel has on the distribution of celestial polarization cues visible in a deflector loft. Since the acceptance angle of the sensor of their polarimeter was too wide (about  $20^\circ$ ), they could not determine the fine details of the reflection-polarization pattern of the deflector panel. To quantify the influence which a deflector panel has on the celestial polarization, we calculate in this work the polarization pattern of skylight reflected from four different deflector panels as a function of the elevation of the sun from the horizon. On the basis of these computations those deflector types can be selected, which modify the celestial polarization pattern only slightly, that is, which can be used without any "reflection-polarization complication" in future experiments with birds.

### Methods

Figure 1(c) shows the geometry in the calculation of the polarization patterns of skylight reflected from a vertical deflector panel, which is perpendicular to the plane of the solar meridian. The two-dimensional reflection-polarization patterns are represented in a polar-coordinate system [Fig. 1(d)], where the viewing angles  $\theta$  and  $\varphi$  of the observer [see Fig. 1(c)] are measured radially and tangentially, respectively. The regions of the patterns with different degrees and directions of polarization are shaded by different grey tones. Since the polarization characteristics of the deflector depend only slightly on the colour of light, all reflection-polarization patterns are computed for wavelengths in the middle of the visible range of the spectrum.

The polarization of the sky is described by the semi-empirical Rayleigh model, which can be considered as a relatively good approximation (Coulson, 1988; Horváth, 1995). Using the Fresnel formulae (Azzam & Bashara, 1989), the reflection-polarization characteristics of the investigated deflector panels are derived in the Appendix. Four different deflector panel types are considered: (i) glass on a white substrate, (ii) glass on a black background, (iii) metal mirror, (iv) metal-glass mirror. The complex index of refraction of the aluminium mirror studied

is  $N_{\text{alu}} = 0.57 - i5.19$ , where  $i \equiv \sqrt{-1}$  is the imaginary unit; the metal-glass mirror investigated consists of a plate glass with a real refractive index of  $n_g = 1.5$  underlied by a thin silver layer, the complex refractive index of which is  $N_s = 0.1194 - i3.144$  (Landolt & Börnstein, 1983). The repolarization of incoherent polarized skylight reflected from a silver-glass mirror and from a glass deflector panel is calculated in Appendices A and B. In Appendix C the degree of polarization of incoherent unpolarized incident light is computed after reflection from the following deflector panels: glass on a black background, aluminium mirror, silver-glass mirror, glass on a white background.

### Results

Figures 2 and 3 show the pattern of the degree  $\delta$  and direction  $\alpha$  of polarization of skylight reflected from a vertical glass deflector panel calculated for four different elevations of the sun. Figures 4 and 5 represent the corresponding differences  $\Delta\delta = \delta_{\text{sky}} - \delta_{\text{deflector}}$  and  $\Delta\alpha = \alpha_{\text{sky}} - \alpha_{\text{deflector}}$  between the degrees and directions of polarization of skylight and reflected skylight. The latter two figures demonstrate well that the glass deflector panel has a considerable influence on the celestial polarization pattern:  $\Delta\delta$  can be as great as  $-100\%$  [Fig. 4(a-c)] and the value of  $\Delta\alpha$  can approximate  $-90^\circ$  [Fig. 5(a-c)].

On the one hand, in the reflected polarization pattern there are several neutral points from which unpolarized light is reflected [Fig. 2(a-c)]. Crossing these neutral points the alignment of the reflected E-vector changes from parallel to perpendicular relative to the panel [Fig. 3(a-c)]. On the other hand, the glass panel possesses a characteristic annular zone, where the reflected skylight is totally polarized (black half rings in Fig. 2) and its E-vector is parallel to the glass surface (black areas in Fig. 3). Although the direction of polarization of the glass-reflected skylight is predominantly more or less parallel to the glass plate (darker areas in Fig. 3), there are also regions where the reflected E-vector is perpendicular to it (brighter areas in Fig. 3). One can see that the difference  $\Delta\alpha = \alpha_{\text{sky}} - \alpha_{\text{deflector}}$  is always negative along the entire deflector panel (Fig. 5), that is, the reflected E-vector becomes more parallel to the panel than the E-vector of incident light. On the basis of Figs 4 and 5 we can establish that a simple glass plate as an optical cue-deflecting panel cannot mimic the real celestial polarization pattern because of its strong reflection polarization.

Though we calculated the celestial reflection-polarization patterns only for such a vertical deflector

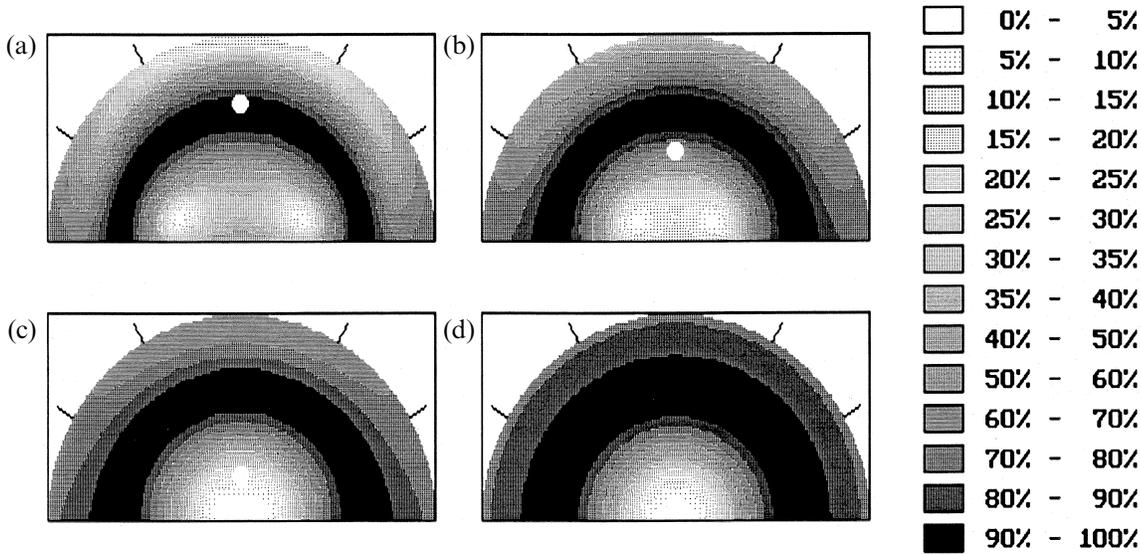


FIG. 2. The pattern of the degree of polarization  $\delta$  of skylight reflected from a vertical glass deflector panel calculated for four different elevations  $\theta_s$  of the sun: (a)  $\theta_s = 60^\circ$ , (b)  $\theta_s = 40^\circ$ , (c)  $\theta_s = 20^\circ$ , (d)  $\theta_s = 0^\circ$  (sun on the horizon). The mirror image of the sun is represented by a dot. The different intervals of  $\delta$  (measured in %) are shaded by different grey tones: the darker the tone, the greater is  $\delta$ .

panel, which is perpendicular to the plane of the solar meridian, this restriction does not concern at all our conclusions. In the bird experiments also other alignments of the deflectors and mirrors occur, but in these cases, at a given elevation of the sun, the reflection-polarization pattern visible in the panel can be obtained by a corresponding rotation of the pattern computed for the panel perpendicular to the solar meridian.

Similar to Figs. 2–5, we calculated the polarization pattern of skylight reflected from a silver-glass mirror. Contrary to the glass deflector, we learned that such a mirror has practically no influence on the polarization characteristics of incident light: the differences between the degrees and directions of polarization of skylight and reflected skylight were smaller than 2% and 2 degrees ( $\Delta\delta < 2\%$ ,  $\Delta\alpha < 2^\circ$ ). Thus, the reflected celestial polarization pattern

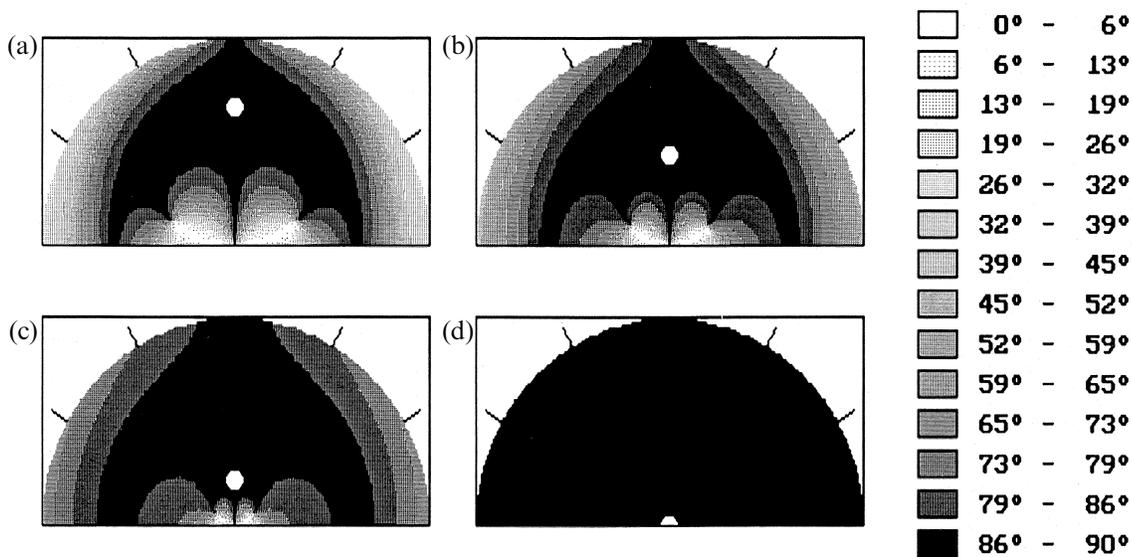


FIG. 3. The pattern of the direction of polarization  $\alpha$  of skylight reflected from a vertical glass deflector panel calculated for four different elevations  $\theta_s$  of the sun: (a)  $\theta_s = 60^\circ$ , (b)  $\theta_s = 40^\circ$ , (c)  $\theta_s = 20^\circ$ , (d)  $\theta_s = 0^\circ$ . The mirror image of the sun is represented by a dot.  $\alpha$  is measured from the normal of the panel and its different intervals are shaded by different grey tones: brighter shades represent regions where the E-vector is more or less perpendicular to the panel, while darker tones mean E-vectors are more or less parallel to it.

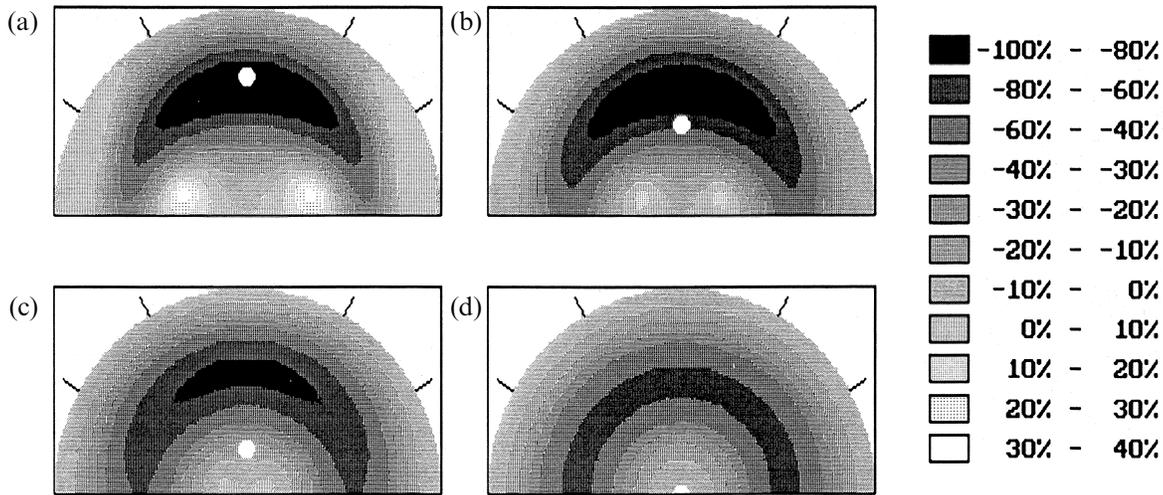


FIG. 4. The difference  $\Delta\delta = \delta_{sky} - \delta_{deflector}$  between the degree of polarization  $\delta_{sky}$  of skylight and  $\delta_{deflector}$  of skylight reflected from a vertical glass deflector panel calculated for four different elevations  $\theta_s$  of the sun: (a)  $\theta_s = 60^\circ$ , (b)  $\theta_s = 40^\circ$ , (c)  $\theta_s = 20^\circ$ , (d)  $\theta_s = 0^\circ$ . The mirror image of the sun is represented by a dot. The different intervals of  $\Delta\delta$  are shaded by different grey tones.

deflected by a common metal-glass mirror can be considered realistic in the deflector loft or mirror experiments investigating avian orientation.

The latter two conclusions are also supported by Fig. 6 that shows the degree of polarization  $\delta$  of unpolarized incident light after reflection from different deflector panels as a function of the incident angle  $\theta$  measured from the normal of the panel. Curves (b) and (c) in Fig. 6 represent the change of  $\delta$  vs  $\theta$  for a deflector panel composed of an aluminium plate or a silver-glass mirror. We can see that the maximum of  $\delta$  reaches only a few per cent, that is, the unpolarized incident light remains almost unpolarized

after reflection from these mirrors. The light reflected from the aluminium mirror is slightly more polarized than the light deflected by the silver-glass mirror. Contrary to this, a deflector panel made of glass on a black substrate [curve (a) in Fig. 6] or on a white background [curve (d) in Fig. 6] alters significantly the polarization of unpolarized incident light.

We can read from curve (a) in Fig. 6 that as  $\theta$  increases from zero to  $90^\circ$  the degree of polarization of the deflector panel consisting of glass on a black background increases from zero to 100% up to the Brewster angle ( $\theta_B \approx 56^\circ$  measured from the vertical), then  $\delta$  decreases to zero, but it remains always

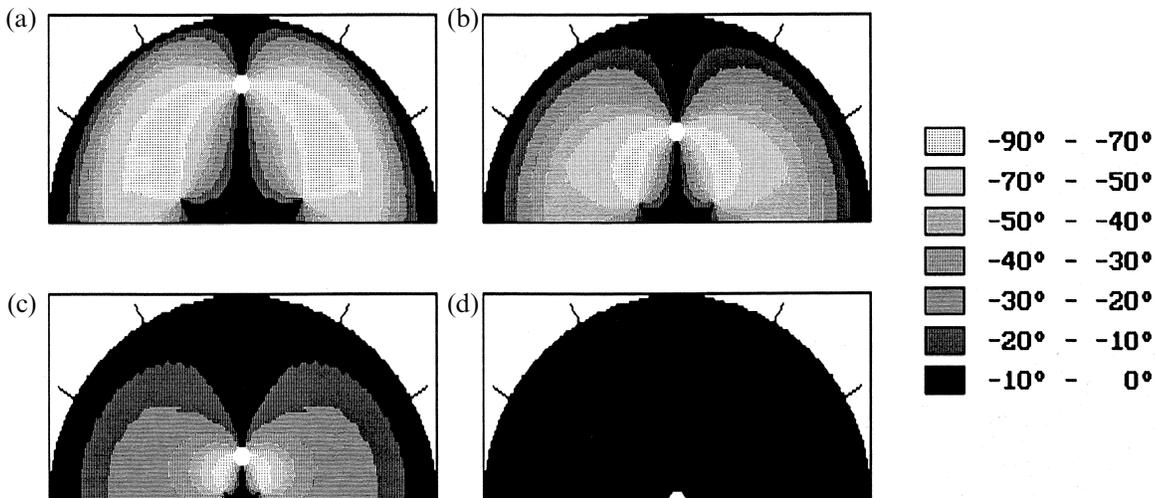


FIG. 5. The difference  $\Delta\alpha = \alpha_{sky} - \alpha_{deflector}$  between the direction of polarization  $\alpha_{sky}$  of skylight and  $\alpha_{deflector}$  of skylight reflected from a vertical glass deflector panel calculated for four different elevations  $\theta_s$  of the sun: (a)  $\theta_s = 60^\circ$ , (b)  $\theta_s = 40^\circ$ , (c)  $\theta_s = 20^\circ$ , (d)  $\theta_s = 0^\circ$ . The mirror image of the sun is represented by a dot. The different intervals of  $\Delta\alpha$  are shaded by different grey tones. Since  $\alpha_{sky}$  is always smaller than  $\alpha_{deflector}$ ,  $\Delta\alpha$  is smaller than zero in every point of the deflector.

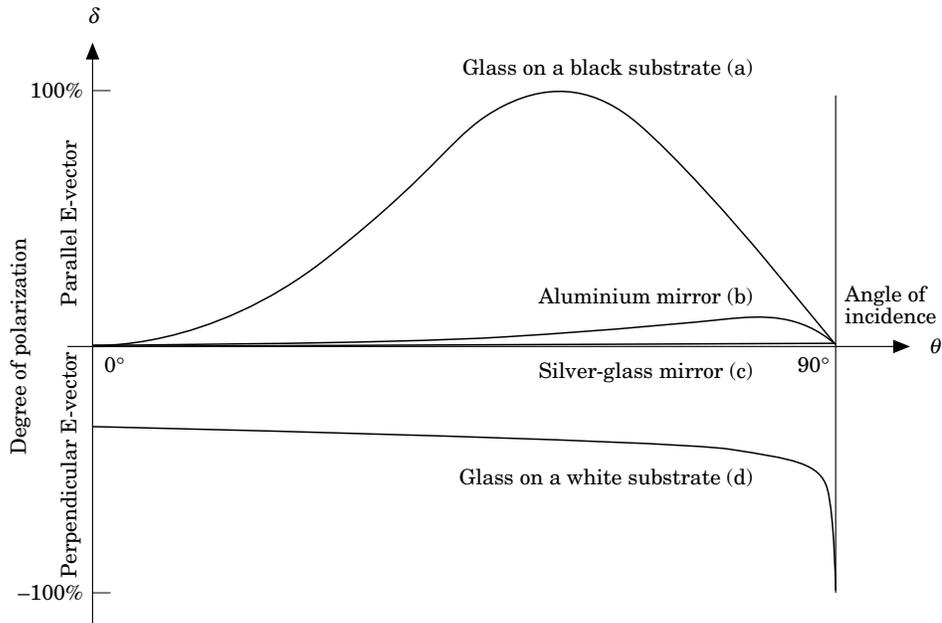


FIG. 6. The degree of polarization  $\delta$  of unpolarized incident light after reflection from different deflector panels as a function of the incident angle  $\theta$  measured from the normal of the panel composed of (a) glass on a black background, (b) aluminium plate, (c) silver-glass mirror, (d) glass on a white substrate with an albedo of  $A = 0.8$ . Positive or negative  $\delta$ 's mean E-vectors parallel or perpendicular to the panel, respectively.

positive, that is, the reflected E-vector is always parallel to the panel.

The situation is quite different in the case of a deflector made of glass on a white substrate. Here the light component penetrating into the glass is diffusely scattered backwards by the white background, then it is refracted at the upper glass surface. The light emanating from the glass is always perpendicularly polarized to the surface due to refraction at the glass-air interface (Horváth & Varjú, 1995). This perpendicularly polarized light is superimposed with the light component that is specularly reflected from and parallel polarized to the upper glass surface. Apart from quite grazing angles ( $\theta \approx 90^\circ$ ) the former component dominates, thus the net E-vector is perpendicular ( $\delta < 0$ ) to the panel. If  $\theta \approx 90^\circ$  the parallel polarized ( $\delta > 0$ ), specularly reflected light controls the net degree of polarization, as we can see on curve (d) in Fig. 6. Figure 7 shows the change of  $\delta$  vs  $\theta$  as a function of the albedo  $A$  of the white background. We can see that the albedo has a considerable influence on the reflection-polarization characteristics of the panel. Increasing  $A$ , the E-vector of reflected light becomes more and more perpendicular to the panel, that is, the region of the incident angle characterized by parallel polarized reflected light becomes gradually narrower. The larger the  $A$ , the weaker polarized is the reflected light with perpendicular E-vector.

## Discussion and Conclusions

We have seen above that a glass deflector panel modifies considerably the distribution of polarization in the deflector loft or mirror experiments studying avian orientation. In our opinion such deflector panels might induce a visual cue-conflict situation for the test birds in such a way that the intensity and spectral features of the reflected skylight contradict its polarization characteristics: a glass plate modifies the colour and intensity of incident skylight only slightly, however, it changes significantly the celestial polarization pattern after reflection. Hence, a polarization-sensitive test bird in this case is confronted with such a deflected view of the sky, where the spatial distribution of intensity and colour is similar to the real one but the polarization pattern is quite different from the expected pattern. Since many birds prefer the celestial polarization pattern against other optical cues of the sky (e.g. Able, 1993), they may solve this cue-conflict in such a way, that they begin to orient not by means of skylight polarization, but on the basis of other cues (for example, stars or Earth magnetism), or they orient randomly or ambiguously. This might be one of the reasons for the frequently observed ambivalent responses of test birds during the deflector loft or mirror experiments using such deflector panels, that change significantly the polarization of skylight.

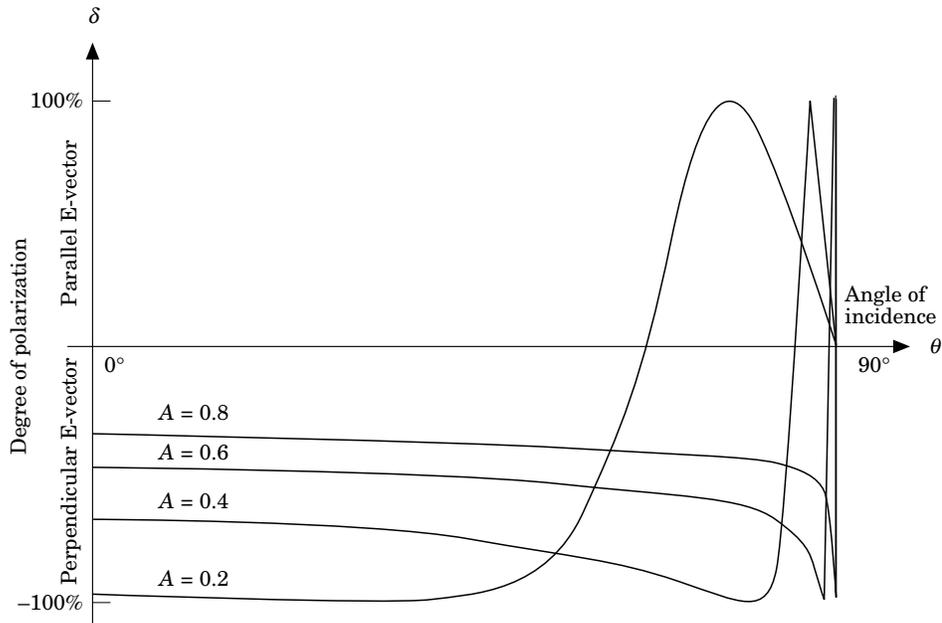


FIG. 7. The degree of polarization  $\delta$  of unpolarized incident light after reflection from a glass deflector panel as a function of the incident angle  $\theta$  (measured from the normal of the panel) calculated for four different values of the albedo  $A$  of the underlying white substrate:  $A = 0.2, 0.4, 0.6, 0.8$ .

Interestingly, the reflection-polarization characteristics of the deflector panels made of glass with or without a black background is qualitatively quite similar to those of the flat water surface. This water surface-reflected polarization pattern plays an important role in the water detection by water-seeking insects (Schwind, 1991, 1995; Schwind & Horváth, 1993; Horváth, 1995; Horváth & Zeil, 1996).

On the basis of the above we conclude the following:

(I) A deflector panel consisting of a back surface (metal-glass) mirror or front surface (pure metal plate) mirror changes the polarization of incident light slightly independently of the incident angle. Thus, such a deflector can mimic the celestial polarization pattern well in the deflector loft or mirror experiments studying the role of skylight polarization in the orientation of birds possessing polarization vision.

(II) A deflector panel made of a translucent glass plate changes the polarization of incident light after reflection considerably. Such a deflector in the deflector loft or mirror experiments cannot simulate the distribution of polarization in the sky at all due to its strong reflection polarization. This might be one of the reasons why birds frequently respond ambivalently to the deflected optical cues in these behavioural experiments.

(III) A deflector panel made of glass on a black substrate significantly alters the polarization features

of incident light due to reflection. The degree of polarization of reflected light is 100% at the Brewster angle (about  $56^\circ$  from the normal of the panel) and decreases farther away from this direction; the reflected E-vector is always parallel to the panel.

(IV) A deflector panel consisting of glass on a white background considerably modifies the polarization characteristics of incident light after reflection. If the incident light is unpolarized, the reflected light possesses an E-vector, which is perpendicular to the panel for smaller angles of incidence. For larger incident angles the E-vector becomes parallel to the panel. The region of perpendicular E-vector increases with increasing albedo of the underlying white substrate. The degree of polarization of reflected light with perpendicular E-vector is gradually reduced as the albedo increases.

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## REFERENCES

- ABLE, K. P. (1989). Skylight polarization patterns and the orientation of migratory birds. *J. Exp. Biol.* **141**, 241–256.  
 ABLE, K. P. (1993). Orientation cues used by migratory birds: a review of cue-conflict experiments. *Trends Ecol. Evol.* **8**, 367–371.

- ABLE, K. P. & ABLE, M. A. (1993). Daytime calibration of magnetic orientation in a migratory bird requires a view of skylight polarization. *Nature* **364**, 523–525.
- AZZAM, R. M. A. & BASHARA, N. M. (1989). *Ellipsometry and Polarized Light*. Amsterdam: North-Holland.
- COULSON, K. L. (1988). *Polarization and Intensity of Light in the Atmosphere*. Hampton, VA: A. Deepak Publishing.
- DELIUS, J. D., PERCHARD, R. J. & EMMERTON, J. (1976). Polarized light detection by pigeons and an electrophysiological correlate. *J. Comp. Physiol. Psychol.* **90**, 560–571.
- HELBIG, A. J. (1990). Depolarization of natural skylight disrupts orientation of an avian nocturnal migrant. *Experientia* **46**, 755–758.
- HELBIG, A. J. (1991). Experimental and analytical techniques used in bird orientation research. pp. 270–306. In *Orientation in Birds*. (Berthold, P., ed.) Berlin: Birkhäuser Verlag.
- HELBIG, A. J. & WILTSCHKO, W. (1989). The skylight polarization at dusk affects the orientation behavior of Blackcaps, *Sylvia atricapilla*. *Naturwissenschaften* **76**, 227–229.
- HORVÁTH, G. (1995). Reflection-polarization patterns at flat water surfaces and their relevance for insect polarization vision. *J. theor. Biol.* **175**, 27–37.
- HORVÁTH, G. & VARJÚ, D. (1995). Underwater refraction-polarization patterns of skylight perceived by aquatic animals through Snell's window of the flat water surface. *Vision Research*, **35**, 1651–1666.
- HORVÁTH, G. & ZEIL, J. (1996). Kuwait oil lakes as insect traps. *Nature* **379**, 303–304.
- KRAMER, G. (1950). Orientierte Zugaktivität gekäfigter Singvögel. *Naturwissenschaften* **37**, 188.
- KRAMER, G. (1951). Eine neue Methode zur Erforschung der Zugorientierung und die bisher damit erzielten Ergebnisse. *Proceeding of the 10th Ornithology Congress*, Uppsala, pp. 269–280.
- KRAMER, G. & v. ST. PAUL, U. (1950). Stare (*Sturnus vulgaris* L.) lassen sich auf Himmelsrichtung dressieren. *Naturwissenschaften* **37**, 526–527.
- KREITHEN, M. L. & KEETON, W. T. (1974). Detection of polarized light by the homing pigeon, *Columba livia*. *J. Comp. Physiol.* **89**, 83–92.
- LANDOLT, H. & BÖRNSTEIN, R. (1983). Zahlenwerte und Funktionen aus Naturwissenschaften und Technik. Berlin: Springer Verlag.
- MOORE, F. R. (1982). Sunset and the orientation of nocturnal bird migrant: a mirror experiment. *Behav. Ecol. Sociobiol.* **10**, 153–155.
- MOORE, F. R. (1985). Integration of environmental stimuli in the migratory orientation of the savannah sparrow (*Passerculus sandwichensis*). *Anim. Behav.* **33**, 657–663.
- MOORE, F. R. & PHILLIPS, J. B. (1988). Sunset, skylight polarization and the migratory orientation of yellow-rumped warblers, *Dendroica coronata*. *Anim. Behav.* **36**, 1770–1778.
- PAPI, F. (1991). Olfactory navigation. pp. 52–85. In: *Orientation in Birds*. (Berthold, P. ed.) Berlin: Birkhäuser Verlag.
- PHILLIPS, J. B. & WALDVOGEL, J. A. (1988). Celestial polarized light patterns as a calibration reference for sun compass of homing pigeons. *J. theor. Biol.* **131**, 55–67.
- SANDBERG, R. (1991). Sunset orientation of robins, *Erithacus rubecula*, with different fields of sky vision. *Behav. Ecol. Sociobiol.* **28**, 77–83.
- SANTSCHI, F. (1911). Observations et remarques critiques sur le mecanisme de l'orientation chez les fourmis. *Revue Suisse Zoolog.* **19**, 303–338.
- SCHMIDT-KOENIG, K. (1979). *Avian Orientation and Navigation*. London: Academic Press.
- SCHWIND, R. (1991). Polarization vision in water insects and insects living on a moist substrate. *J. Comp. Physiol. A* **169**, 531–540.
- SCHWIND, R. (1995). Spectral regions in which aquatic insects see reflected polarized light. *J. Comp. Physiol. A* **177**, 439–448.
- SCHWIND, R. & HORVÁTH, G. (1993). Reflection-polarization pattern at water surfaces and correction of a common representation of the polarization pattern of the sky. *Naturwissenschaften* **80**, 82–83.

- WALCOTT, C. & MICHENER, M. (1971). Sun navigation in homing pigeons: attempts to shift sun coordinates. *J. Exp. Biol.* **54**, 291–316.

## Appendix A

### Repolarization of Incoherent Polarized Light Reflected from a Silver-Glass Mirror

The electric field vector  $E_0$  of an incoherent, partially linearly polarized light can be composed of two components  $E_0^{\parallel}$  and  $E_0^{\perp}$ , where the former and latter is parallel and perpendicular to the plane of incidence. The amplitudes  $E_r^{\parallel}$ ,  $E_r^{\perp}$  and the complex conjugates  $E_r^{\parallel*}$ ,  $E_r^{\perp*}$  of the electric field vector components of light reflected from a metal-glass mirror can be obtained as a sum of an infinite geometrical series, as we can see in Fig. A1.

$$E_r = E_0 \left( \rho_{a,g} + \sigma_{a,g} \sigma_{g,a} \rho_{g,s} \sum_{n=0}^{\infty} \rho_{g,a}^n \rho_{g,s}^n e^{-i\beta_n} \right),$$

$$E_r^* = E_0 \left( \rho_{a,g} + \sigma_{a,g} \sigma_{g,a} \rho_{g,s}^* \sum_{m=0}^{\infty} \rho_{g,a}^m \rho_{g,s}^{*m} e^{i\beta_m} \right), \quad (\text{A.1})$$

where  $\beta_n$  is the random phase of the  $n$ -th reflected E-vector component,  $\rho$  and  $\sigma$  are the amplitude reflection and transmission coefficients; subscripts  $a$ ,  $g$  and  $s$  refer to air, glass and silver. In the derivation of the complex conjugate in (A.1) we took into consideration that in the mirror only the silver layer possesses a complex refractive index, that is, among the amplitude reflection and transmission coefficients only  $\rho_{g,s}$  is complex. For the sake of clarity, in (A.1) we omitted the superscripts  $\parallel$  and  $\perp$ , however, we shall use them later again. On the basis of the Fresnel formulae (Azzam & Bashara, 1989)

$$\rho_{a,g}^{\parallel} = \frac{n_g^2 \cos \phi_0 - \sqrt{n_g^2 - \sin^2 \phi_0}}{n_g^2 \cos \phi_0 + \sqrt{n_g^2 - \sin^2 \phi_0}}, \quad (\text{A.2})$$

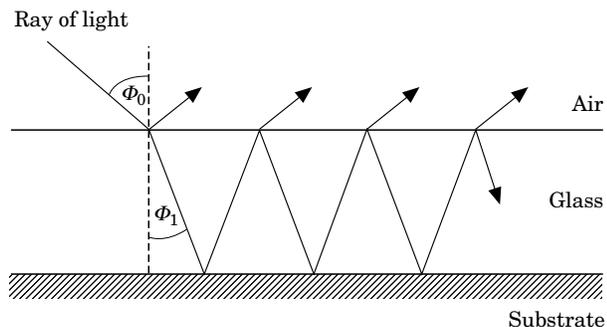


FIG. A1. Ray tracing of an incident ray of light reflected by a glass-metal mirror.

$$\rho_{a,g}^{\perp} = \frac{\cos \phi_0 - \sqrt{n_g^2 - \sin^2 \phi_0}}{\cos \phi_0 + \sqrt{n_g^2 - \sin^2 \phi_0}}, \quad (\text{A.3})$$

$$\rho_{g,s}^{\parallel} = \frac{N_s^2 \sqrt{n_g^2 - \sin^2 \phi_0} - n_g^2 \sqrt{N_s^2 - \sin^2 \phi_0}}{N_s^2 \sqrt{n_g^2 - \sin^2 \phi_0} + n_g^2 \sqrt{N_s^2 - \sin^2 \phi_0}}, \quad (\text{A.4})$$

$$\rho_{g,s}^{\perp} = \frac{\sqrt{n_g^2 - \sin^2 \phi_0} - \sqrt{N_s^2 - \sin^2 \phi_0}}{\sqrt{n_g^2 - \sin^2 \phi_0} + \sqrt{N_s^2 - \sin^2 \phi_0}}, \quad (\text{A.5})$$

where  $n_g$  is the real refractive index of glass,  $N_s$  is the complex index of refraction of silver, and  $\phi_0$  is the incident angle measured from the normal of the mirror. The intensity of light reflected from the mirror is proportional to the time average of the quantity  $\mathbf{E}_r \mathbf{E}_r^*$ . We must take into consideration that the time average of the terms is zero, which contain the quantities  $e^{-i\beta_n}$  and  $e^{-i(\beta_n - \beta_m)}$  due to the randomness of phases  $\beta_n$ . Thus, the time average is

$$\langle \mathbf{E}_r \mathbf{E}_r^* \rangle = E_0^2 \left[ \rho_{a,g}^2 + \sigma_{a,g}^2 \sigma_{g,a}^2 \rho_{g,s} \rho_{g,s}^* \times \sum_{n=0}^{\infty} (\rho_{g,a}^2 \rho_{g,s} \rho_{g,s}^*)^n \right]. \quad (\text{A.6})$$

Since  $\rho_{g,a} = -\rho_{a,g}$  and  $\sigma_{a,g} \sigma_{g,a} = 1 - \rho_{a,g}^2$ , the net amplitude reflection coefficients of the mirror for incoherent, partially linearly polarized light are

$$\rho_{mirror}^{(j)} \equiv \frac{\sqrt{\langle \mathbf{E}_r \mathbf{E}_r^* \rangle}}{E_0^{(j)}} = \sqrt{\frac{\rho_{a,g}^{(j)2} + \rho_{g,s}^{(j)} \rho_{g,s}^{(j)*} (1 - 2\rho_{a,g}^{(j)2})}{1 - \rho_{a,g}^{(j)2} \rho_{g,s}^{(j)} \rho_{g,s}^{(j)*}}}, \quad (j) = \parallel, \perp. \quad (\text{A.7})$$

## Appendix B

### Repolarization of Incoherent Polarized Light Reflected from a Glass Deflector Panel

Using (A.2) and (A.3), the net amplitude reflection coefficients of a plate glass in air for incoherent, partially linearly polarized incident light is

$$\rho_{glass} = \rho_{a,g}^{(j)} \sqrt{\frac{2}{1 + \rho_{a,g}^{(j)2}}}, \quad (j) = \parallel, \perp. \quad (\text{B.1})$$

## Appendix C

### Degree of Polarization of Incoherent Unpolarized Incident Light after Reflection from Different Deflector Panels

#### GLASS ON A BLACK BACKGROUND

If the deflector panel consists of a glass plate underlined by a black substrate, then light is reflected only from the upper glass surface, because the penetrating light component is totally absorbed by the black background. Thus, the amplitude reflection coefficients of this black panel are

$$\rho_{black}^{\parallel} = \frac{n_g^2 \cos \phi_0 - \sqrt{n_g^2 - \sin^2 \phi_0}}{n_g^2 \cos \phi_0 + \sqrt{n_g^2 - \sin^2 \phi_0}},$$

$$\rho_{black}^{\perp} = \frac{\cos \phi_0 - \sqrt{n_g^2 - \sin^2 \phi_0}}{\cos \phi_0 + \sqrt{n_g^2 - \sin^2 \phi_0}}, \quad (\text{C.1})$$

and the degree of polarization of unpolarized incident light after reflection from this deflector is

$$\delta_{black} = \frac{\rho_{black}^{\perp 2} - \rho_{black}^{\parallel 2}}{\rho_{black}^{\perp 2} + \rho_{black}^{\parallel 2}}. \quad (\text{C.2})$$

#### ALUMINIUM MIRROR

In the case of an aluminium plate light is reflected only from the upper surface, because the penetrating light is totally absorbed by the metal. If the complex refractive index of aluminium is  $N_{alu}$ , then its amplitude reflection coefficients are

$$\rho_{alu}^{\parallel} = \frac{N_{alu}^2 \cos \phi_0 - \sqrt{N_{alu}^2 - \sin^2 \phi_0}}{N_{alu}^2 \cos \phi_0 + \sqrt{N_{alu}^2 - \sin^2 \phi_0}},$$

$$\rho_{alu}^{\perp} = \frac{\cos \phi_0 - \sqrt{N_{alu}^2 - \sin^2 \phi_0}}{\cos \phi_0 + \sqrt{N_{alu}^2 - \sin^2 \phi_0}}, \quad (\text{C.3})$$

and the degree of polarization of unpolarized incident light after reflection from a deflector panel composed of pure aluminium plate is

$$\delta_{alu} = \frac{\rho_{alu}^{\perp} \rho_{alu}^{\perp*} - \rho_{alu}^{\parallel} \rho_{alu}^{\parallel*}}{\rho_{alu}^{\perp} \rho_{alu}^{\perp*} + \rho_{alu}^{\parallel} \rho_{alu}^{\parallel*}}. \quad (\text{C.4})$$

#### SILVER-GLASS MIRROR

A silver-glass mirror consists of a plate glass underlined by a highly reflecting, thin silver layer. Using (A.2–A.5) and (A.7), the degree of polarization of unpolarized incident light after reflection from a deflector panel made of silver-glass mirror is

$$\delta_{mirror} = \frac{\rho_{mirror}^{\perp 2} - \rho_{mirror}^{\parallel 2}}{\rho_{mirror}^{\perp 2} + \rho_{mirror}^{\parallel 2}}. \quad (\text{C.5})$$

## GLASS ON A WHITE BACKGROUND

When the deflector panel is composed of a plate glass on a white substrate, one component of the incident light is directly reflected by the upper glass surface, and the penetrating component is infinite times diffusely backscattered by the white underlying layer and reflected from and refracted at the glass–air interface. If the albedo of the white substrate is  $A$ , then the net amplitude reflection coefficients are

$$\rho_{white}^{(j)} = \rho_{black}^{(j)} + A\sqrt{1-R}\sigma_{black}^{(j)} \sum_{n=0}^{\infty} A^n \sqrt{R}^n, \quad (j) = \parallel, \perp, \quad (\text{C.6})$$

where

$$R = \frac{\rho_{black}^{\parallel 2} + \rho_{black}^{\perp 2}}{2} \quad (\text{C.7})$$

is the reflectivity of the upper glass surface for unpolarized incident light, and

$$\sigma_{black}^{\parallel} = \frac{2n_g \sqrt{n_g^2 - \sin^2 \phi_0}}{\sqrt{n_g^2 - \sin^2 \phi_0 + n_g^2 \cos \phi_0}},$$

$$\sigma_{black}^{\perp} = \frac{2\sqrt{n_g^2 - \sin^2 \phi_0}}{\sqrt{n_g^2 - \sin^2 \phi_0 + \cos \phi_0}} \quad (\text{C.8})$$

are its amplitude transmission coefficients. From here

$$\rho_{white}^{(j)} = \rho_{black}^{(j)} + A \frac{\sigma_{black}^{(j)} \sqrt{1-R}}{1 - A\sqrt{R}}, \quad (j) = \perp, \parallel. \quad (\text{C.9})$$

Finally, the degree of polarization of unpolarized incident light after reflection from a plate glass underlined by a white substrate with albedo  $A$  is

$$\delta_{white} = \frac{\rho_{white}^{\perp 2} - \rho_{white}^{\parallel 2}}{\rho_{white}^{\perp 2} + \rho_{white}^{\parallel 2}}. \quad (\text{C.10})$$