10 How the Polarization of Skylight Changes due to Reflection from the Deflector Panels in Deflector Loft and Mirror Experiments Studying Avian Orientation

The deflector loft technique utilizes a pinwheel arrangement of glass panels that deflect wind and light in either a clockwise or counter-clockwise direction (Figs. 10.1A,B). Such deflector lofts are commonly used in behavioural experiments to investigate avian navigation (e.g. Schmidt-Koenig 1979; Helbig 1991). Homing pigeons *Columba livia* raised in normal lofts and then housed in deflector lofts change their site orientation corresponding to the direction of wind and light deflection. This is called the "deflector loft effect" (e.g. Papi 1991). Phillips and Waldvogel (1988) showed that the biased orientation of short-term deflector loft birds is due to the reflection of light from the glass portions of the deflector panels, rather than being the result of rotation of wind-borne olfactory cues.

Also metal or metal-glass mirrors have been used in some behavioural experiments to investigate the role of the view of setting sun, sunset glow, skylight polarization in the migratory orientation of birds (e.g. Kramer 1950a,b, 1951; Kramer and St. Paul 1950; Walcott and Michener 1971; Moore 1982, 1985; Moore and Phillips 1988; Phillips and 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. Helbig and Wiltschko 1989; Able 1989, 1993; Helbig 1990; Able and Able 1993) demonstrated that the celestial polarization pattern is one of the most important visual information in the orientation of certain birds, whose visual system is sensitive to polarization.

Considering the deflector loft and mirror experiments on avian navigation and polarization sensitivity, it is important to know how the skylight polarization changes due to reflection from these deflector panels and mirrors. Phillips and Waldvogel (1988) have made an attempt to investigate the effect that a Plexiglas deflector panel has on the distribution of celestial polarization cues visible at a deflector loft. Since the acceptance angle of the sensor of their polarimeter was too wide, about 20^o, they could not determine the fine structure of the reflection-polarization pattern induced by the deflector panel.

To quantify the influence of a deflector panel on the celestial polarization, Horváth and Pomozi (1997) calculated the polarization pattern of skylight reflected from four different deflector panels as a function of the solar elevation. 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 significant "reflection-polarization complication" in behavioural experiments with polarization-sensitive birds. Figures 10.1C,D show the geometry of reflection of polarized skylight from a vertical deflector panel, which is perpendicular to the plane of the solar meridian. Since the polarizational characteristics of the deflector depend only slightly on the colour of light, all reflection-polarization patterns were computed for wavelengths in the middle of the visible range of the spectrum. The polarization of skylight was described by the single-scattering Rayleigh model. Using the Fresnel formulae (Azzam and Bashara 1992), the reflection-polarizational characteristics were derived for the following four different types of deflector panel: (i) glass on a white substratum, (ii) glass on a black background, (iii) metal mirror, (iv) metal-glass mirror.

Figure 10.2 shows the pattern of the degree p and angle α of linear polarization of skylight reflected from a vertical glass deflector panel calculated for four different solar elevations. Figure 10.3 displays the corresponding differences $\Delta p = p_{sky} - p_{deflector}$ and $\Delta\alpha = \alpha_{sky} - \alpha_{deflector}$ between the degrees and angles of linear polarization of skylight and reflected skylight. These figures demonstrate well that the glass deflector panel has a considerable influence on the celestial polarization pattern: Δp can be as large as -100%, and $\Delta\alpha$ can approximate -90°.

On the one hand, in the mirrored celestial polarization pattern there are several neutral points from which unpolarized light is reflected (Figs. 10.2A-D). Crossing these neutral points, the alignment of the reflected E-vector changes from parallel to perpendicular relative to the panel surface (Figs. 10.2E-G). On the other hand, the glass panel possesses a characteristic annular zone, where the reflected skylight is totally linearly polarized (black half rings in Fig. 10.2A-D) and its E-vector is parallel to the glass surface (black areas in Fig. 10.2E-H). Although the direction of polarization of the glass-reflected skylight is predominantly more or less parallel to the glass plate (dark areas in Fig. 10.2E-H), there are also regions where the reflected E-vector is perpendicular to it (brighter areas). One can see that the difference $\Delta\alpha = \alpha_{sky} - \alpha_{deflector}$ is always negative along the entire deflector panel (Fig. 10.3E-H), that is, the reflected E-vector becomes more parallel to the panel than the E-vector of incident light. On the basis of Fig. 10.3 we can establish that a simple glass plate cannot mimic the real celestial polarization pattern because of the strong reflection polarization.

Similarly to Figs. 10.2 and 10.3, Horváth and Pomozi (1997) calculated the polarization pattern of skylight reflected from a silver-glass mirror. Contrary to the glass deflector, they established that such a mirror has practically no influence on the linear polarizational characteristics of incident light. The differences Δp and $\Delta\alpha$ between skylight and reflected skylight were lower than 2% and 2°. Thus, the reflected celestial polarization pattern of light deflected by a common metal-glass mirror can be considered realistic in the deflector loft or mirror experiments investigating avian orientation.

The latter conclusion is also supported by Fig. 10.4A which shows p of light reflected from different deflector panels as a function of the incident angle θ measured from the normal vector of the panel calculated for unpolarized incident light. In the case of a deflector panel composed of an aluminium plate or a silver-glass mirror the maximum of p reaches only a few %, that is, the unpolarized incident light remains almost unpolarized after reflection. The light reflected from the aluminium mirror is slightly more polarized than the light reflected by the silver-glass mirror. Contrary to this, a deflector panel made of glass on a black substratum or on a white background polarizes significantly the reflected light. As θ increases from 0^o to 90^o, p increases from 0% to 100% up to the Brewster angle $\theta_B \approx 56^o$ from the vertical, then it decreases to 0%, but remains always positive, that is, the E-vector of reflected light is always parallel to the panel.

The situation is quite different in the case of a deflector made of glass on a white substratum. 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. This perpendicularly polarized light is superimposed with the parallelly polarized light reflected from the upper glass surface. Apart from quite grazing angles ($\theta \approx 90^o$) the former component dominates, thus the net E-vector is perpendicular to the panel. If $\theta \approx 90^o$ the parallel polarized reflected light controls the net p, as we can see on the corresponding curve in Fig. 10.4A. Figure 10.4B shows the change of p versus θ as a function of the albedo A of the white background. The albedo has a considerable influence on the reflection-polarizational 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 albedo A, the weaker is the reflected light polarized with perpendicular E-vector.

Hence, a glass deflector panel modifies considerably the polarization pattern of reflected skylight in the deflector loft or mirror experiments studying avian orientation. Thus, such deflector panels might induce a conflict situation for the test birds in such a way, that the intensity and spectral features of reflected skylight contradict to its polarizational characteristics. A glass plate modifies the colour and intensity of incident skylight only slightly. However, it changes significantly the polarization of reflected skylight. Thus, in this case a polarization-sensitive test bird 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 from the sky (e.g. Able 1993), they may solve this conflict in such a way, that they begin to orient not by means of skylight polarization, but on the basis of other cues, e.g. stars or geomagnetism, 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 deflector panels, which change significantly the polarization of skylight.

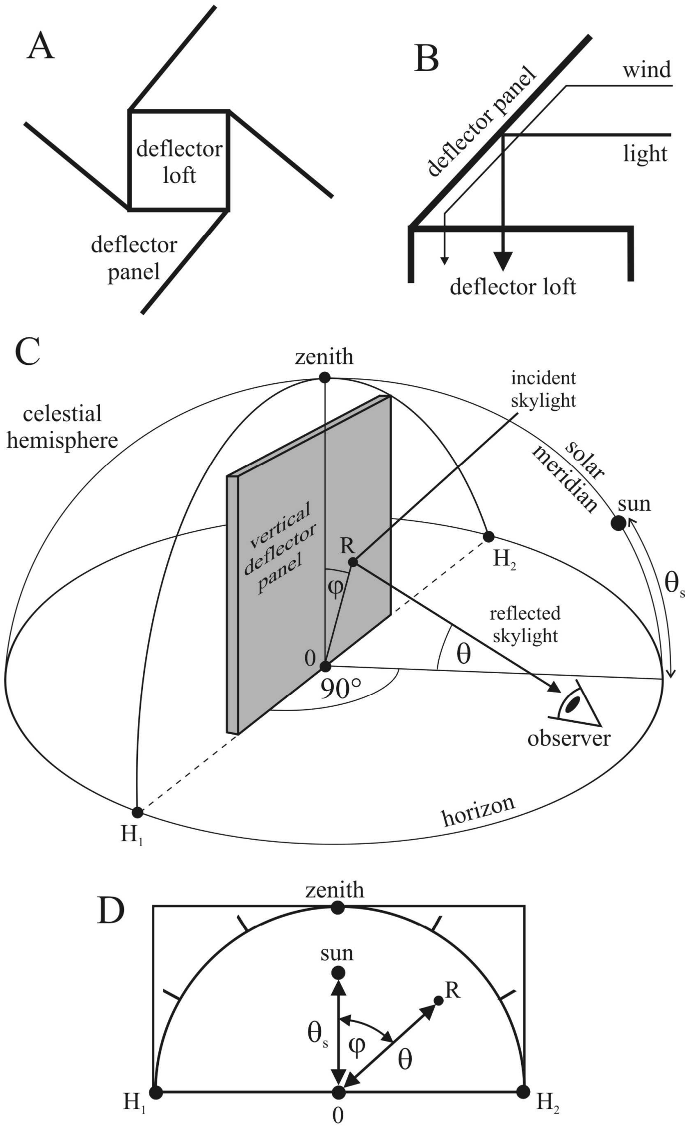


Fig. 10.1. A: Top view of a common deflector loft used in the experiments to investigate the visual and olfactory navigation of birds. The mirroring portion of each deflector panels consists of a glass-metal mirror or a glass plate with a bright or dark background. B: The deflector panel changes both wind and light in the same direction either clockwise or counter-clockwise. C: The geometry of reflection of polarized skylight 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. (After Fig. 1 of Horváth and Pomozi 1997, p. 292).

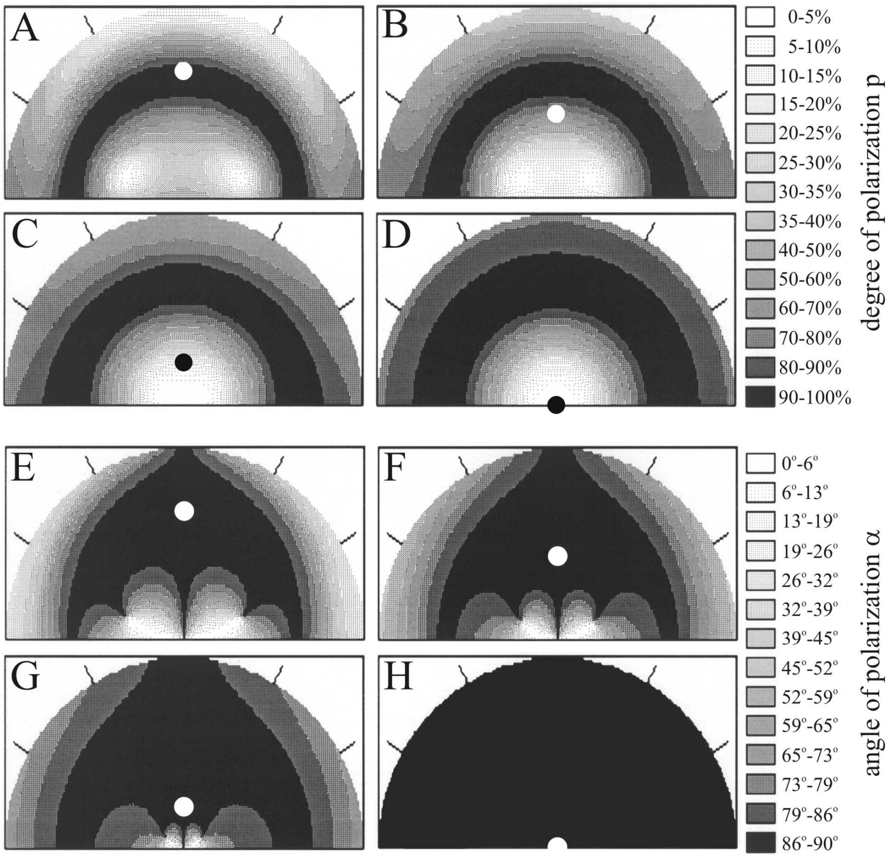


Fig. 10.2. A-D: The pattern of the degree of linear polarization p of skylight reflected from a vertical glass deflector panel calculated for four different solar elevations θ_s. The mirror image of the sun is represented by a dot. (After Fig. 2 of Horváth and Pomozi 1997, p. 294). E-H: The angle of polarization α of reflected skylight measured from the normal vector of the panel. Brighter shades represent regions where the E-vector is more or less perpendicular to the panel, while darker tones mean E-vectors more or less parallel to it. (After Fig. 3 of Horváth and Pomozi 1997, p. 294).

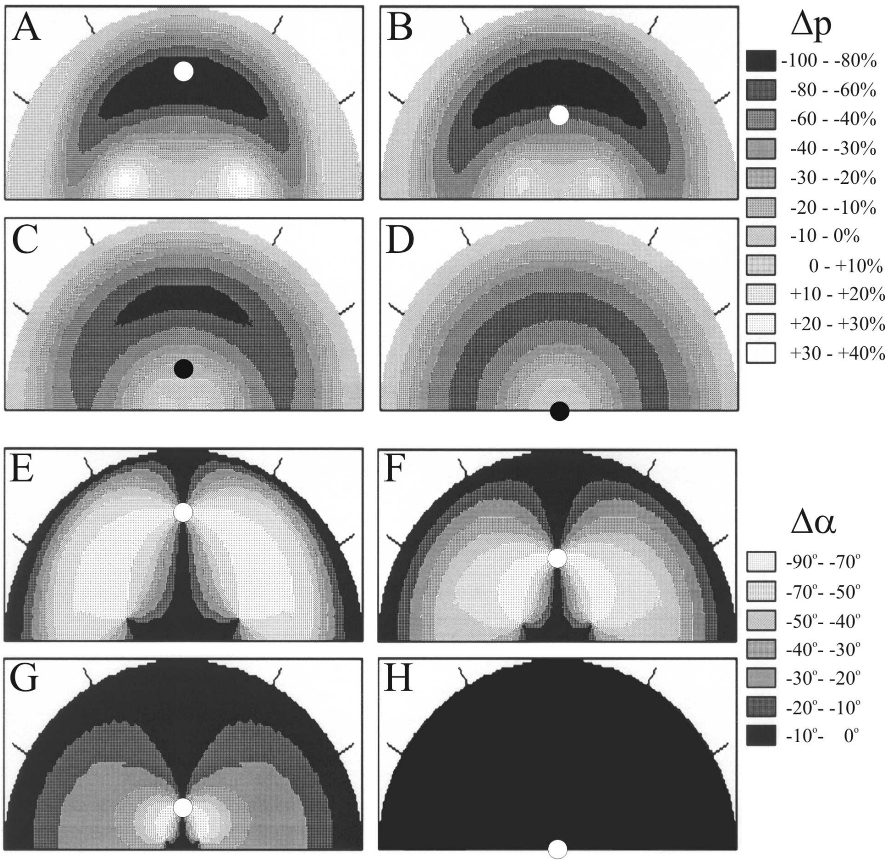
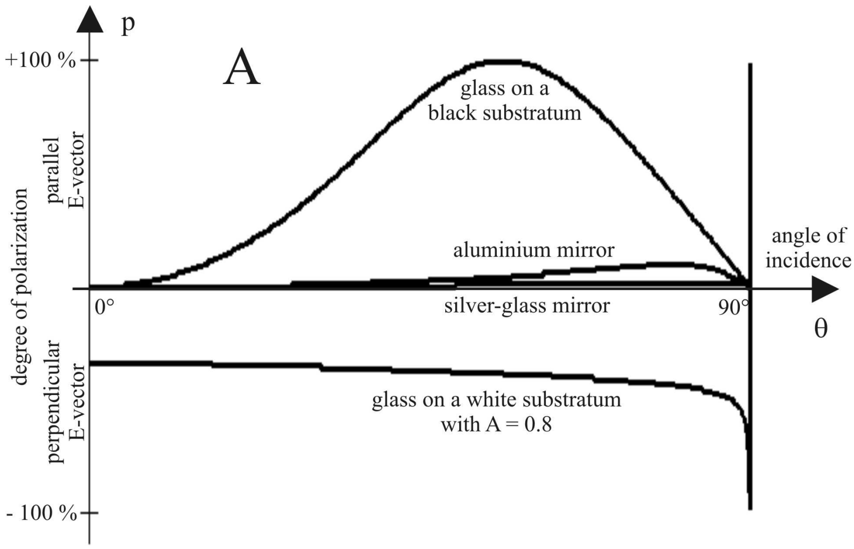


Fig. 10.3. A-D: Difference $\Delta p = p_{sky} - p_{deflector}$ between p_{sky} of skylight and $p_{deflector}$ of skylight reflected from a vertical glass deflector panel calculated for four different solar elevations θ_s. The mirror image of the sun is represented by a dot. (After Fig. 4 of Horváth and Pomozi 1997, p. 295). E-H: Difference $\Delta\alpha = \alpha_{sky} - \alpha_{deflector}$ between α_{sky} of skylight and $\alpha_{deflector}$ of skylight reflected from a vertical glass deflector panel. Since $\alpha_{sky} < \alpha_{deflector}$, $\Delta\alpha < 0$ in every point of the deflector. (After Fig. 5 of Horváth and Pomozi 1997, p. 295).



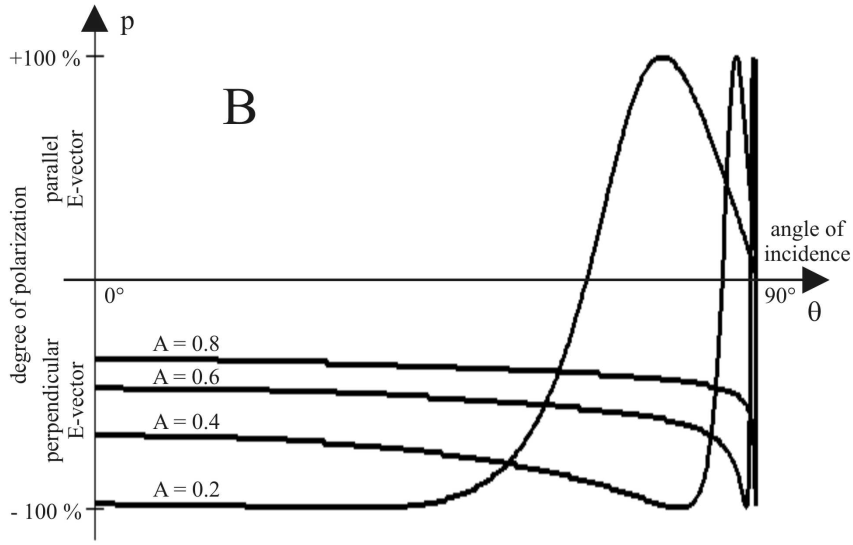


Fig. 10.4. A: The degree of linear polarization *p* of light reflected from different deflector panels as a function of the incident angle *θ* measured from the normal vector of the panel calculated for unpolarized incident light. The albedo of the white substratum is *A* = 0.8. Positive or negative *p*-values mean E-vectors parallel or perpendicular to the panel, respectively. (After Fig. 6 of Horváth and Pomozi 1997, p. 296). B: *p* of light reflected from a glass deflector panel as a function of the incident angle *θ* from the normal of the panel calculated for unpolarized incident light in the case of four different values of the albedo *A* of the underlying white substratum. (After Fig. 7 of Horváth and Pomozi 1997, p. 297).