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SOME COMMENT ON THE PURKINJE SHIFT

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In the second volume of his "Beobachtungen und Versuche zur Physiologie der Sinne", dedicated to GOETHE, PURKINJE mentions some experiments with colours in daylight and twilight and says: "Objectiv hat der Grad der Beleuchtung grossen Einfluss auf die Intensität der Farbenqualität. Um sich davon recht lebendig zu überzeugen, nehme man vor Anbruch des Tages, wo es eben schwach zu dämmern beginnt, die Farben vor sich. Anfangs sieht man nur schwarz und grau. Gerade die lebhaftesten Farben, das Roth und das Grün erscheinen am schwärzesten. Das Gelb kann man von Rosenroth lange nicht unterscheiden. Das Blau war mir zuerst bemerkbar. Die rothen Nüancen, die sonst beim Tageslicht am hellsten brennen, nämlich carmin, zinnerber und orange zeigen sich lange am dunkelsten, durchaus nicht im Verhältnisse ihrer mittleren Helligkeit. Das Grün erscheint mehr bläulich, und seine gelbe Tinte entwickelt sich erst mit zunehmendem Tage."

Thus the blue end of the spectrum turns up first in the dark in its right colour, expanding into the green as daylight approaches. In full daylight the red end of the spectrum dominates and this change does not reflect the original brightness distribution. Apparently PURKINJE did not use a spectrum, as is suggested by the quotation, but I have translated the observation into spectral terms. It became known in the early literature as "das PURKINJESCHE Phänomen". I have translated this term as the "PURKINJE shift".

In the experimental development of PURKINJE'S observation the emphasis has fallen on the brightness distribution of spectral lights in the light- and darkadapted states. The early work that led the way came from KÖNIG'S laboratory and will be found in an important classic, his "Gesammelte Abhandlungen" (1903). It is convenient at this point to introduce much later terminology and speak of the daylight or *photopic* and the dimlight or *scotopic* luminosity curves for the two brightness distributions. These two terms were introduced by PARSONS in 1927.

Turning for a moment from psychophysics to the retina, it should be recalled that BOLL discovered visual purple (rhodopsin) in 1876 and Max SCHULTZE'S work on rods and cones, antedating this by some 10 years, was generally known by 1871 from his large review in STRICKER'S Handbuch. On the psychophysical side HERING added a significant observation in 1891 when he found that the totally colour blind only had the scotopic luminosity

curve of normal people. KÖNIG was quick to realize the implications of all this work as well as the need for obtaining the spectral distribution curve of rhodopsin sensitivity. The links were forged by himself (1903) and his pupils KÖTTGEN & ABELSDORFF (1896) when they showed that there was, indeed, good agreement between the scotopic luminosity curve as determined by psychophysical measurements and the distribution of the spectral sensitivity of rhodopsin. Rods, rhodopsin and scotopic luminosity henceforth became connected and a great deal of meticulous experimentation, beginning with LYTHGOE (1937), has gone into establishing with ever-increasing accuracy the interrelations between the components of this triad (see, e. g. GRANIT, 1947, 1962).

Even though next to nothing, was known about cone photochemistry, it seemed reasonably certain that the photopic luminosity curve depended upon cone activity. Thus, by the beginning of this century the spectral shift of brightness or luminosity with the state of adaptation was understood in terms of rods and cones with the active photochemical agent known in principle for the rods. The term PURKINJE shift has often been used as an equivalent for this shift of the luminosity curve with state of adaptation but this does not do the original observation full justice. We have to account also for PURKINJE'S colour transformations. As we have seen, PURKINJE'S own emphasis was on the apparent differential visibility of colours in scotopic and photopic vision. As to luminosity he was content to point out that his effect did not depend on the brightness ("mittlere Helligkeit") which obviously was determined in daylight.

The existence of a PURKINJE shift also in the electroretinogram was first demonstrated by HIMSTEDT & NAGEL in 1901 with the frog eye and put on a quantitative basis in our laboratory (GRANIT & MUNSTERHJELM, 1937; GRANIT & WREDE, 1937). I do not intend to review the extensive electroretinographic literature on the spectral distribution of sensitivity in light- and dark-adapted eyes of man and the many animals whose eyes have since been studied from this point of view at our laboratory and DODT'S laboratory. For a long time we have been on safe ground when such shifts of luminosity curves with state of adaptation have been ascribed to the dominance of cones or rods respectively. At the receptor end the problem ultimately is one of photochemistry and it is not of much interest to summarize once more what has been summarized so many times before. Another matter is how the dominance of either type of receptor, rods or cones, is organized within the retina.

The questions of light and colour raised by PURKINJE'S original discovery suggest problems of transformations within the retina and transfer of information which still cannot be regarded as finally solved at that level. When in 1939 the problem of specific sensitivities to wavelength became, for a while, the leading interest in my laboratory (summarized GRANIT, 1945, 1947) it soon became clear that in dark-adapted eyes of frogs and mammals, isolated spikes representing the information for upper stations tended to reproduce the spectral sensitivity of rhodopsin. There was thus a scotopic luminosity message in single fibres whose destination in mammals would be cells or aggregates of cell in the colliculi, the lateral geniculate bodies and the cortex and at these stations it would be interpreted

as luminosity. All wavelengths would influence this message in the same manner, their effects being proportional to the ordinates by which they were represented in the rhodopsin spectrum.

These same nerve fibres, after light adaptation were then found to transmit a spectral distribution like that of rhodopsin but shifted towards the red end of the spectrum to produce the photopic luminosity curve, provided one studied an eye with a sufficient number of cones. I called this single-fibre response, in so-called mixed eyes the dominator, photopic or scotopic, dependent upon the adaptive state of the retina. It seemed to me that these particular ganglion cells in the retina were the carriers of the information embodied in the photopic and scotopic luminosity curves. Furthermore, since the stations to which this optic-nerve fibre delivered its message produced luminosity in the scotopic state it could not very well produce something else after light adaptation. The photopic dominator was shown to be dependent on cones. It was, for instance, the only one obtained in a pure cone eye. Analysis of its composition showed that cones of different spectral sensitivity were combined in the dominator type of response. In the frog's eye this problem was studied by DONNER & RUSHTON (1959a, b) and DONNER (1959) who also utilized the Stiles-Crawford effect to separate rods and cones. It is interesting to note that in this eye during recovery from dark adaptation there is an intermediate stage of maximal sensitivity to blue light (GRANIT, 1941 and Figs. 143 and 144 in GRANIT, 1947) reminiscent of PURKINJE'S observation that blue is the first colour to turn up in the dark in its right hue. This effect I had (1941) tentatively ascribed to the 'green rods' of SCHWALBE. The contributions of DENTON & WYLLIE (1955) and of DONNER & RUSHTON (1959a, b) left no doubt about this being the correct interpretation. Another matter is then if PURKINJE'S observation can be similarly explained. These rods have not been found in man.

The change-over from light adaptation to dark adaptation and vice versa *within the retina*, was found not to be explicable on a simple photochemical basis (GRANIT & RIDDELL, 1934). If I may quote (GRANIT, 1947): "What might, perhaps, be called 'the resetting of the visual instrument' by light adaptation is obviously largely due to a change-over from rod to cone dominance, but light adaptation must clearly have done more than simply remove the rods from the scene of activity. . . . in the dark-adapted retina, the rods must in some way be capable of damping cone activity . . ." Discussing various possibilities it was concluded that "somehow PIII seems to be an essential factor in these processes" (p. 141). This last remark was based on the increased speed of return of PIII to the baseline in the state of light adaptation.

The light adapted retina was proved to be a very much faster instrument than the dark adapted one, indicating that faster elements had come to the fore. In the thirties (GRANIT, 1938) I used to refer to the resetting of the retina by light adaptation under the term 'electro-adaptation' (since dropped) and asked "how are we to explain that these [fast] elements refrained from participating in the reactions of the dark adapted eye . . . , intensity of stimulation has been constant; in most experiments the same light even has been used as the adapting light. Why and where have the fast elements

been 'in hiding' during dark adaptation?" (p. 65). This question still seems to me relevant. It was concluded that in the dark the rods had inhibited the cones and suggestions were made as to various possibilities for such inhibitions. The analogy with 'auditory masking' was pointed out. At the time the nature of post-synaptic inhibition was still unknown.

The idea that one receptor could inhibit another did not appeal in the least to my learned successors in retinology and I would hardly, after so many years, have dared mention the old results and ideas, had they not been revived in recent experiments concerned with today's subject, the PURKINJE shift. My own contributions (in GRANIT & RIDDELL, 1934), after all, are now 35 years old. Some still older psychophysical work suggesting inhibition of the cones by the rods were mentioned in "Sensory Mechanisms of the Retina" (GRANIT, 1947, p. 146-147).

In a paper on the neural mechanism of the PURKINJE shift, LIPETZ (1962) has shown that when two small light spots in different parts of the receptive field of the bullfrog's retina are tested in terms of relative sensitivity to flashes of 558 m μ versus 505 m μ , light adaptation of either spot produces a PURKINJE shift in both of them. The effect was recorded from a single ganglion cell whose receptive field was studied. Thus, within a receptive field something happens that carries the change in relative sensitivity to long and short wavelengths across the field, from light adapted to non-light adapted receptors. "The results of this experiment," says LIPETZ, "while providing evidence for a neural mechanism of the PURKINJE shift, do not provide evidence for or against the existence of non-neural mechanisms of the shift" (p. 7).

More information about interaction between receptors including suggestions as to the precise location of such a process has recently been produced by BROWN & MURAKAMI (1969), who have taken up a modern version of the problem of the fast return to the baseline of PIII after light adaptation. In the intervening years terminology has undergone some changes, based on advanced experimentation, but "plus ça change, plus c'est la même chose". PIII, or at least the part of it that now concerns us, is called the late receptor potential (late RP) and its return to the baseline after illumination is called the decay of the late RP. This decay we had found to be fast in light adaptation and slow in dark adaptation. The alterations took place within a few minutes and thus could not represent variations in the amount of rhodopsin (GRANIT, 1947, p. 134 whose figures are from GRANIT & RIDDELL, 1934). These rapid transformations BROWN & MURAKAMI now find reflected also in the so-called S-potentials that after the analysis of McNICHOL & SVAETICHIN (1958) are held to be events in the horizontal cells below the bases of the receptors. [The review by BROWN (1968) and the paper of BROWN & MURAKAMI (1968) should be consulted for information on recent developments in retinology which cannot be included here.]

BROWN & MURAKAMI recorded both the local receptor potential [part of the IERG in the terminology of TOMITA & TORIHAMA (1956), LERG in BROWN's terminology] and the S-potential with intraretinal microelectrodes. Experimental animals were cat and monkey. The phase of decay in both these changes of potential was studied, because it was in this part of the responses that the striking changes occurred with the state of adaptation.

It turned out that a light adapted S-potential with the characteristic fast decay, as obtained with a stimulus area of 2.18 mm, changed into one with an almost exclusively slow decay within a few minutes of dark adaptation but that this change was not demonstrable with a small spot of 0.18 mm in diameter. Provided that the stimulus area was large enough the slow decay set in very rapidly in the dark while the rapid phase continually decreased. In the dark the receptive field of the S-potential is reorganized to include peripheral summation with rod dominance, in the light adapted state the receptive field is homogeneous in this respect, possessing only an S-potential with fast decay. The hypothesis of BROWN & MURAKAMI, for which further evidence will be given below, is that "the S-potential elicited by a large stimulus is dominated by cones in the light adapted state and by rods in the dark adapted state" (p. 1153). In the light adapted state cone activity summates over the entire receptive field but after some dark adaptation the cone response from the centre of the field is suppressed by peripheral rod activity provided that centre and periphery are stimulated at the same time (the large stimulus spot).

The authors find that rhodopsin regeneration is too slow for these changes because with the large stimulus spot the alternation of the S-potential from one with fast to one with slow decay would be 88 per cent complete after only 2 mins of dark adaptation. One could, however, imagine some kind of feedback by photoproducts in the manner of the negative feedback depressing rod sensitivity that DONNER & REUTER (1967) have reported for the frog's eye. But this, too, would have to be carried neurally.

The receptor potential (the late RP), which is part of PIII of the electroretinogram (ERG) and in BROWN & MURAKAMI'S experiments was recorded locally, has a fast decay in the light adapted state and up to a point increases with spot size, apparently because of the increase in the number of receptors. In dark adaptation it also alters its form, the increasing spot size bringing a slow decay into prominence. The parallelism with the behaviour of the S-potentials is obvious. The increasing spot size draws surrounding rods into the sphere of activity and their effect is to increase the slow decay phase and decrease the fast one. This reorganization of the response does not take place in barbiturate anaesthesia. The surrounding rods gain control because of their greater convergence, a process which BROWN & MURAKAMI assume to be at the site of generation of the S-potential, in other words, at the horizontal cells. These are held to work as interneurons mediating reciprocal lateral inhibition between rods and cones.

Here then is a mechanism capable of taking care of the relative dominance of rods or cones depending upon the state of adaptation and thus of performing the operations demanded by the existence of a PURKINJE shift in the dominator response from a single ganglion cell. It has the interesting property of dealing with the receptor potential itself so that rods, for instance, inhibit cones in dark adaptation by a neural mechanism.

An essential aspect of the experimental work of BROWN & MURAKAMI is the rapid alteration of the retina by this mechanism from fast to slow or vice versa. It is interesting in retrospect to note that much of the retinal evidence for rods inhibiting cones in our old work was obtained by studying

the response to flickering lights and a whole chapter of "Sensory Mechanisms of the Retina" (Ch. VIII) was devoted to a study of "differentiation velocity", slow in rods, fast in cones.

It would carry too far to take up these questions. Our subject is the PURKINJE shift and the separation it produces of rod effects from cone effects in a dominator response from a single ganglion cell. Evidently it also presupposes regeneration of rhodopsin in order to make the rods come out with their proper distribution of sensitivity, that in sensory terms is the scotopic luminosity curve.

Returning to PURKINJE'S old work we recall that the first colour to turn up in its right hue in twilight was the blue. Indeed, PURKINJE was more concerned with colour than with luminosity. Now, why is it that blue turns up as blue before red turns up as red? Rods and cones have about the same absolute thresholds with small spots (ARDEN & WEALE, 1954) and the rest is a matter of differences in convergence. Blue-sensitive and red-sensitive cones should be suppressed to the same degree by a non-discriminative rod inhibition of the cones. An observer tends to use perifoveal vision in twilight, thereby also avoiding the blue-blind fovea, but this does not change our problem; it merely emphasizes it. Why should it matter if a cone happens to be 'red' or 'blue'? Thinking in terms of rod inhibition of cones, the luminosity curve of the rods gives them a far more powerful action on the blue than on the red end of the spectrum and so, if anything, the blue cones should be more strongly inhibited by rods when these have been sensitized by rhodopsin.

This problem has been overlooked in recent work and there is no solution of it at hand. One hesitates a little to assume that the inhibition of rods upon cones is a function of wavelength of the inhibiting partner. This idea would imply that one of the photoproducts of rod decomposition would be given a new specific function. My old standpoint was that the blue-sensitive receptors are more rod-like in character and thus with a synaptic organization likely to be less markedly of cone type, say, with several blue cones lumped together by convergence. Alternatively, the response of the blue cones could be assumed to receive an injection of excitation from the rods at some point in the path through the retina. Then, of course, there is the possibility that the human eye, like the frog's eye, has a blue-sensitive receptor which actually is a rod. Something 'rod-like' certainly is inherent in the blue-sensitive retinal organization, regarded as a totality. Thus, for instance, in the rabbit it is so prominent in photopic vision that this animal has a reversed PURKINJE shift (KSINSIK, 1967). Yet the fusion frequency to blue-violet light is characteristically low per unit luminance, as in the cat (GRANIT & WIRTH, 1958).

These suggestions need not be taken too seriously. They have to be tested by experimentation. In this connexion they merely serve to draw attention to an unexplained aspect of the PURKINJE shift.

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