

Magnetophosphenes: a quantitative analysis of thresholds

P. Lövsund P. Å. Öberg

Department of Biomedical Engineering, Linköping University, S-581 85 Linköping, Sweden

S. E. G. Nilsson

Department of Ophthalmology, Linköping University, S-581 85 Linköping, Sweden

T. Reuter

Department of Zoology, Division of Physiology, University of Helsinki, Helsinki 10, Finland

Abstract—*Low-frequency and transient magnetic fields of moderate flux densities are known to generate visual phenomena, so-called magnetophosphenes. In the present study, time-variable very low frequency (10–50 Hz) electromagnetic fields of moderate flux density (0–40 mT) were used to induce magnetophosphenes. The threshold values for these phosphenes were determined as a function of the frequency of the magnetic field both in normal subjects and colour defective ones. Maximum sensitivity occurred at a frequency of approximately 20–30 Hz, and with broad-spectrum light the threshold flux density was 10–12 mT. The threshold values were found to be dependent upon the intensity and the spectral distribution of the background light. Sensitivity decreased during dark adaptation. In certain respects deuterans differed from subjects with normal colour vision. Possible mechanisms for generation of magnetophosphenes are discussed. The present magnetic threshold curves show a close resemblance to corresponding curves obtained by electric stimulation at various frequencies provided the electric thresholds are divided by the a.c. frequency. These problems are under current investigation in our laboratory. This is in full agreement with the assumption that the fluctuating magnetic field affects retinal neurons by inducing currents which polarise synaptic terminals.*

Keywords—*Biological effects, Electromagnetic fields, Magnetophosphenes, Occupational medicine*

1 Introduction

FOR many years studies have been made within various scientific disciplines of the biological effects of electric and magnetic fields. These effects have been documented at all levels from the cell to the fully exposed human body. The results of almost 100 years' research are documented both in a number of general monographs (BARNOTHY, 1964 and 1969; PRESMAN, 1970; MILBURN, 1971; LLURADO *et al.*, 1974; PERSINGER, 1974; BATTOCLETTI, 1976; Royal Swedish Academy of Engineering Sciences, 1976; SHEPPARD and EISENBUD, 1977) and in bibliographies (SPIEGLER, 1962; CABANES, 1976; FORMANEK, 1976; GLASER *et al.*, 1977). The emphasis in this research has clearly been placed on the way in which electromagnetic radiation of very short wavelengths (microwaves, millimetre waves) influences biological systems. The studies have often been initiated following the introduction of new technical apparatus such as radar systems, communication systems and microwave ovens, which can generate radiation dangerous to human beings.

The increasing knowledge of the effects of these very high frequency fields has led many countries to set threshold limit values for exposure to them. The earliest research, however, was directed at the effects, primarily upon human beings, of both static and very low frequency fields. Of particular interest was the observation by experimental physicists that time-variable magnetic fields could cause a special visual phenomenon, a so-called phosphene. A phosphene is defined as a visual sensation generated by stimuli other than photons, such as pressure upon the eye, mechanical shock, chemical agents, sudden fright, electric currents and magnetic fields, and often appears as a faint flickering light in the peripheral parts of the visual field.

Phenomena of this type caused by magnetic fields are called magnetophosphenes. They occur in conjunction with both transient and periodic magnetic fields (MAGNUSSON and STEVENS, 1911–12) and their extent and nature depend partly on the intensity and frequency of the magnetic field (MAGNUSSON and STEVENS, 1911–12) and partly on purely photic factors, such as the intensity and spectral characteristics of the background light.

Magnetophosphenes were first investigated by D'ARSONVAL (1896). Using subjective terms he described the light sensations observed by volun-

teers when their heads were placed within a time-variable magnetic field. BEER (1902) reported certain light sensations at the edge of the visual field when the heads of volunteers were placed within a coil supplied with alternating current.

THOMPSON (1910) exposed the heads of volunteers to magnetic fields with flux densities of 100–140 mT at a frequency of 50 Hz. The exposure took place in the dark or with closed eyes. The magnetophosphenes were described as a weak, flickering light, colourless or slightly blue, and which was clearer at the periphery of the visual field than in the central parts. Light sensations superimposed upon the normal visual impressions were obtained with open eyes in daylight. Thompson noted no after-images.

DUNLAP (1911) was able to confirm Thompson's results. Dunlap also conducted experiments with both positive and negative after-images but could not find that they were influenced by phosphenes.

MAGNUSSON and STEVENS (1911–12) were the first to study threshold values for magnetophosphenes. Their experiments were conducted with air-wound coils supplied with direct and alternating current. Among other things, strong visual sensations were obtained when switching current through the coils. Using a.c. stimulation the strongest phosphenes were obtained at 20–30 Hz. BARLOW *et al.* (1947a) carried out experiments by placing a coil over the necks of volunteers but no phosphenes were obtained even at very high flux densities. The same authors concentrated the highest field strength on a small part of the retina. The sensations were then experienced in the corresponding quadrant of the visual field. From these results the conclusion was drawn that the phosphenes were generated through a stimulation of the retina and not in the visual pathways or visual cortex.

On the basis of electrodynamic field equations VALENTINUZZI (1962) attempted to explain the mechanism that generates magnetophosphenes. He postulated that each retinal receptor functions as a microscopic circuit which is influenced by the magnetic flux density. Because his model is not based on empirical data relating to the electrical characteristics of nerve cells, it is very general and difficult to interpret in physiological terms.

SEIDEL *et al.* (1968) studied and systematised the visual patterns described by volunteers exposed to magnetic fields. About 30 different patterns appeared frequently and were similar to those generated by KNOLL *et al.* (1958, 1962) using electric current. OSTER (1970) attempted to illustrate the phosphene sensation in colour.

Although a number of investigations have been made to determine and explain the mechanism generating magnetophosphenes there are still no systematic studies of threshold values, influence of background light, etc. Furthermore, the phenomenon is an interesting and well-established bio-

magnetic effect which can provide a useful model for the influence of magnetic fields on the nervous tissue.

The aim of this work was to describe quantitatively the nature of magnetophosphenes. Particular interest has been paid to threshold values and the way in which they are affected by background light.

2 Material and methods

In order to generate magnetophosphenes in volunteers a special apparatus was constructed. A U-shaped electromagnet as in Fig. 1 was built of laminated iron plates. Each arm was fitted with a coil of 115 turns of insulated copper wire with a cross-section of 14.5 mm². The coils were connected in series. This gave a total resistance of 0.08Ω and an inductance of 14.5 mH. The distance between the poles of the magnet was made adjustable to allow for differing widths of the heads of the volunteers. The flux density in the airgap between the poles of the magnet was inhomogenous (Fig. 1). The shaded parts in Fig. 1 show the levels within which the flux density varied over each retina. Since the electromagnet was individually adapted the same field gradient over the retina was obtained in each experiment. The flux density in the airgap was varied between 0–40 mT (r.m.s.) and was measured in the vicinity of the retina (2 cm from the pole).

The sinusoidal voltage in the particular frequency range of 10–50 Hz was obtained from a function generator (Wavetek 134 Sweep Generator, USA). The signal was amplified in a power amplifier (Brüel & Kjaer, type 2708, Denmark) connected to the electromagnet. An accurate determination of the frequency of the field was obtained using a frequency meter (Advance Electronics Timer Counter TC6, England). The flux density in the airgap was

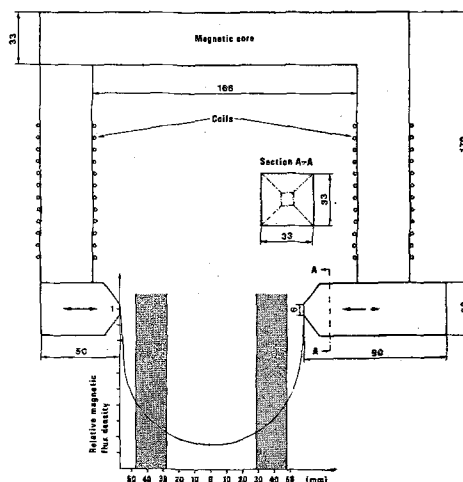


Fig. 1 The electromagnet and the specified relative flux density in the pole gap. The shadowed columns indicate the approximate position of the eyes in the pole gap (all dimensions in mm)

measured with a gauss meter (F. W. Bell 610Z, USA).

The experiments were carried out with the volunteer in the supine position. The U-shaped magnet was placed with each pole near the temporal area and in such a way that the same position relative to the head could be obtained in repeated experiments. Above the volunteer's head was placed at a distance of approximately one metre a hemisphere 0.9 m in diameter with its inside facing the volunteer. The inside of the hemisphere was painted white and could be illuminated with broad-spectrum light from a normal light bulb with variable luminance. The hemisphere was necessary in order to obtain a uniform neutral background when studying the phosphenes under the influence of background light. The study also covered the dependence of phosphenes upon three different colours of monochromatic background light. The colours were generated with the aid of special spectacles with interference filters. The spectacles were completely

sealed against stray light. To avoid condensation on the inside of the interference filters an imperceptible air current was passed over them. The filters were Schott interference filters with centre wavelengths of 443, 531 and 572 nm and half bandwidths of 10–14 nm. The filter wavelengths were selected to correspond with the wavelengths at which the human cone pigments show maximum absorption (445, 535 and 570 nm, MARKS *et al.* (1964) or 450, 525 and 555 nm, BROWN and WALD (1964)).

Before beginning the experiment the volunteers were informed on how magnetophosphenes are experienced and how they probably arise. The volunteers were also allowed to see the test programme. After adjusting the electromagnet over the temples to obtain the smallest possible airgap between the head and the magnet, the experiments were begun with a dark-adaptation period of 30 minutes. The threshold values for magnetophosphenes in darkness were then determined. The frequency of the field was increased from 10 Hz to 50 Hz in steps of 5 Hz and was then decreased in a similar way. For each frequency the flux density of the field was increased until the test subject was able to say that he clearly saw phosphenes. The flux density was then decreased until the phosphene effect completely disappeared and this threshold value was recorded. The mean value was calculated from the two readings at each frequency. For each change in the background luminance/colour the experiment started with a luminance/colour adaptation period of ten minutes. After each experiment the volunteer's qualitative observations were recorded by filling in a special form.

The study comprised four different test groups. Group I consisted of eleven healthy volunteers (five women, six men), ten of them aged 20–30 and one 40 years. In this group threshold values were determined for magnetophosphenes in darkness as well as against background light with luminance values of 0.1, 1.2 and 130 cd/cm².

Group II consisted of eight healthy volunteers (three women, five men), aged 20–26. In this group threshold values for magnetophosphenes were recorded at frequencies of 20, 30 and 35 Hz during dark-adaptation.

Each experiment began with two minutes of darkness followed by a five-minute pre-adaptation period in light (130 cd/m²). The threshold values for magnetophosphenes at the three frequencies were measured before and immediately after the light was extinguished and then every second minute during dark-adaptation. The mean value was calculated from the readings at the three frequencies. The conventional dark-adaptation curve—i.e. with photic instead of magnetic stimuli—was determined following the same pre-adaptation luminance and using a Goldmann-Weekers adaptometer.

Group III comprised six healthy volunteers with normal colour vision (five women, one man) aged

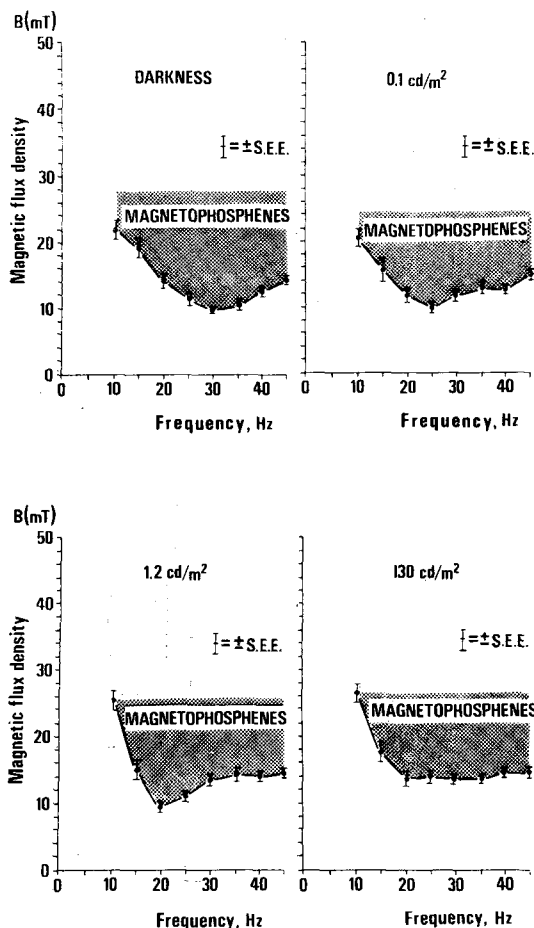


Fig. 2 Threshold values for group I (11 volunteers) with broad-spectrum light at luminance levels darkness and 0.1, 1.2 and 130 cd/m²

20-26 years. In this group the threshold values for phosphenes were recorded with three discrete background colours (443, 531 and 572 nm) and a luminance of 3 cd/m².

Group IV comprised nine healthy but colour defective volunteers (green-deficiencies: four deuteranopic, five deuteranomalous, all men) aged 19-25. In deuteranomalous subjects the absorption maximum of the green-sensitive photopigment is displaced towards that of the red-sensitive photo-

pigment so that the basis of normal colour vision is affected (PIANTANIDA and SPERLING, 1973 and RUSHTON *et al.*, 1973). Deuteranopic subjects probably lack the green-sensitive photopigment, even if it cannot be wholly excluded that its absorption maximum is located so near that of the red-sensitive one that the two cannot be distinguished from each other (ALPERN and WAKE, 1977). It therefore appears that the deuteranomalous and deuteranopic cases are similar enough to be placed in the same group, deutans. The threshold values in this group were recorded under the same conditions as for group III.

3 Results

The mean values for the threshold flux density as a function of the frequency of the magnetic field are given in Fig. 2. They were obtained for the eleven volunteers in group I and for the following four luminance levels: darkness and 0.1, 1.2 and 130 cd/m². For each level of background light a more or less marked sensitivity maximum was obtained on the curve. In darkness the sensitivity to the magnetic field was maximal at 30 Hz. With increased luminance of the background light this sensitivity maximum was displaced towards lower frequencies. At the highest luminance (130 cd/m²) this effect was less clear. In certain volunteers a sensitivity maximum was obtained at 20 Hz while in other subjects the maximum was recorded at higher frequencies. This explains the flat section of the 130 cd/m² curve at higher frequencies.

The results show that magnetophosphenes occur even at relatively moderate flux densities. Many industrial processes, for example, various welding applications, generate magnetic fields of the same flux densities as those used to arouse phosphenes (LÖVSUND *et al.*, 1978).

The results of the dark-adaptation experiments are given in Fig. 3a which shows the mean values for eight volunteers. The mean values for threshold determinations at frequencies of 20, 30 and 35 Hz has been used for each subject.

The sensitivity curve for magnetophosphenes during dark-adaptation assumed the asymptote's value after approximately 16 minutes. The adaptation curve for magnetophosphenes shows a very small sensitivity decrease whose progress is reminiscent of the inverse of the normal dark-adaptation curve for light stimuli. With the weak pre-adaptation light used here, the latter curve approached the asymptote after approximately 15 minutes as shown in Fig. 3b (cf. also RUSHTON and POWELL, 1972).

In order to confirm that the change in the threshold values during dark-adaptation were in fact a result of this and not of the iterated magnetic stimulations, the experiment was repeated but against a continuous background light. No change in the threshold values as a function of time was found.

Fig. 4 shows the threshold value curves for test

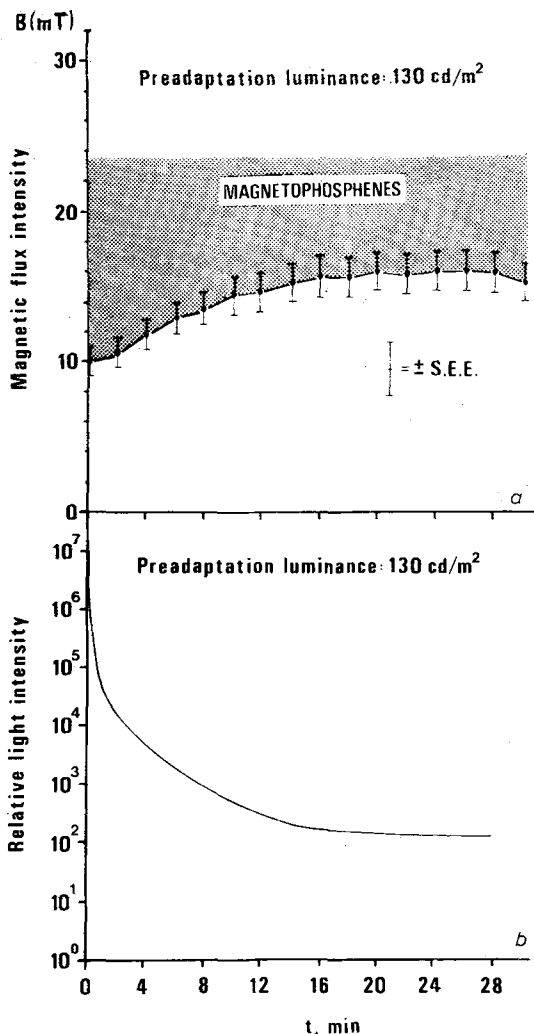


Fig. 3 Comparison of dark-adaptation curves
(a) The dark-adaptation curve for magnetophosphenes. The mean value of the thresholds at frequencies of 20, 30 and 35 Hz for each person were first calculated. The curve represents the mean values for eight volunteers
(b) Example of a normal dark-adaptation curve (photic stimuli) following a preadaptation luminance of 130 cd/m². Mean value of two experiments on two subjects

group III with background light of three discrete wavelengths. For each of the three colours there were sensitivity maxima both at 20-25 Hz and above 40 Hz.

The results from test group IV are shown in Fig. 5. No principal difference in the threshold curves for the two subgroups of colour defective volunteers could be detected, and they were therefore combined into a single group. A sensitivity maximum at 20 Hz occurred for all background colours. Only at 443 nm was there a development of a further maximum from approximately 40 Hz, but also with this background light the sensitivities at 25-40 Hz were lower than the corresponding values for test group III (significant differences ($p < 0.05$) at 25 and 30 Hz and also at 15 Hz).

Against the 572 and 531 nm backgrounds the sensitivities at 35 and 40 Hz were significantly lower in group IV than in group III ($p < 0.05$). When the threshold values for all three wavelengths were

combined, significant differences ($p < 0.05$) between the two groups were likewise obtained at the 35 and 40 Hz frequencies.

Virtually all the volunteers noted tiredness and some reported headaches after the experiment. Some experienced after-images which were generally of only of short duration following exposure to the magnetic field. In one case, however, they persisted up to ten minutes after the experiment. Individual volunteers reported spasms of the eye muscles, probably arising from stimulation by the field.

4 Discussion

Possible anatomical locations for the neuronal stimulation leading to phosphenes have long been discussed in the literature relating to this subject. DUNLAP (1911) and FLEISCHMANN (1922) suggested the optic nerve or visual cortex. BARLOW *et al.* (1947a), however, conducted experiments whose

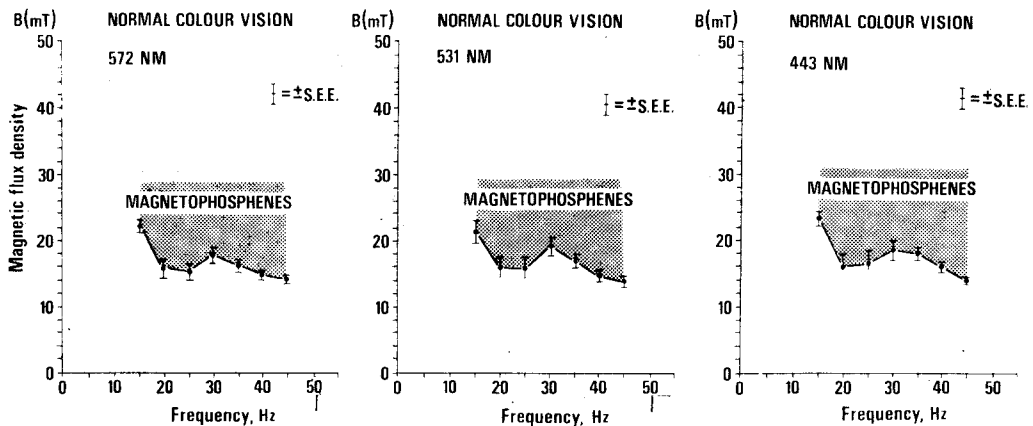


Fig. 4 Threshold values for group III (six volunteers with normal colour vision) at a luminance of 3 cd/m^2 and wavelengths 443, 531 and 572 nm

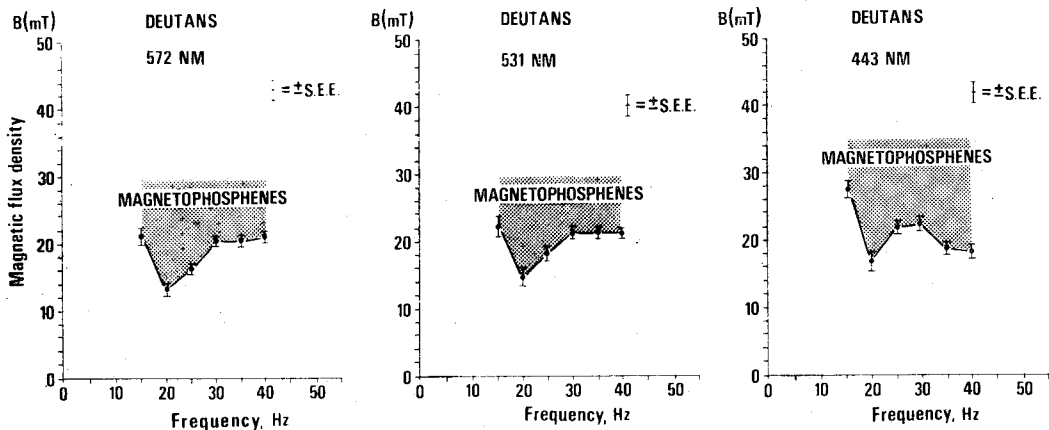


Fig. 5 Threshold values for group IV (nine colour defective volunteers, deuterans) at a luminance of 3 cd/m^2 and wavelengths 443, 531 and 572 nm

results strongly indicated that the phosphenes were generated through a stimulation of the retina.

In order to clarify further the problem of phosphene generation two totally blind subjects were also examined. One was blind as a result of *retinitis pigmentosa*, a disease in which retinal changes primarily affect the photoreceptors and pigment epithelium. This patient may therefore have had at least partially conserved bipolar and ganglion cell layers in the retina. The patient experienced phosphenes but no threshold value curve could be determined since the patient had pronounced and persistent after-images. The fact that the patient experienced phosphenes may indicate that these were not generated in the receptors. The other blind person had had both eyes removed as a consequence of glaucoma. This person experienced no phosphenes, which supports the view that these are generated through a stimulation of the retina and not through a direct stimulation of the visual centres of the brain.

Another visual phenomenon of the same principal type as magnetophosphenes is that known as electrophosphenes, i.e. phosphenes aroused by an electric current. These can be generated easily by an electric current passed between two electrodes placed on the skin near the eye. Electrophosphenes occur at fairly low currents and within approximately the same frequency range (10-100 Hz) as in generation of magnetophosphenes. Electrophosphenes have been studied by a number of authors (for a survey see e.g. CLAUSEN, 1955; SEIDEL, 1968; MOTOKAWA, 1970). Threshold values for the relationship between frequency and current strength have also been given by various authors (ROHRACHER, 1935; SCHWARZ, 1947; MOTOKAWA and IWAMA, 1950; ABE, 1951).

BARLOW *et al.* (1947a) have pointed out several similarities between the phosphenes produced by electric and magnetic stimulation and suggest that both forms of stimulation activate the same retinal elements. Probably the fluctuating magnetic field induces intra- and extracellular currents polarising synaptic membranes and causing changes in synaptic transmission similar to those caused by electric stimulation and by light. It seems probable that the induced currents in the first place affect populations of elongated and regularly oriented cells normally responding with graded potentials of relatively low amplitude. The receptors and the horizontal and bipolar cells of the retina fulfil these requirements (WERBLIN and DOWLING, 1969; KANEKO, 1970). The retinal amacrine and ganglion cells are structurally and functionally similar to the neurons of the visual cortex of the brain (SHEPHERD, 1974), where no magnetophosphenes can be aroused even when high field strengths are used (BARLOW *et al.*, 1947a). Thus a direct magnetic stimulation of them seems less probable.

Studying electrically evoked potentials in the frog's eye KNIGHTON (1975) concluded that in that

preparation electrical stimuli act primarily on the synaptic terminals of the photoreceptor cells. The observation in this study of magnetophosphenes perceived by a blind person suffering from *retinitis pigmentosa* suggests, however, that the receptors are not the only retinal structures affected. POTTS and INOUE (1970), studying cortical potentials evoked by photic and electric stimulation of the rat eye, have reported a similar finding: rats with a congenital retinal dystrophy which destroyed the photoreceptor cells had no visually evoked response but still had a normal electrically evoked response.

The sensitivity maxima for phosphenes which appeared when the threshold flux density was plotted as a function of the frequency of the magnetic field (Fig. 2) can probably be explained on the basis of the law of induction, whence it follows that the current density is proportional to the magnetic flux density multiplied by the frequency. For the magnetic flux density this gives a curve showing a falling threshold forwards higher frequencies, if it is assumed that a constant current density is necessary for the generation of phosphenes. If we further assume that the synaptic processes need a certain summation time it is obvious that the threshold will rise again when the summation time with increasing frequency becomes very short. This interpretation of the magnetic threshold curves is supported by an inspection of published data giving thresholds for sinusoidal (electric) a.c. currents as a function of frequencies (SCHWARZ, 1947). In contrast to our magnetic thresholds these electric threshold curves show a maximum sensitivity for dark-adapted eyes at or below 10 Hz and for light-adapted eyes (149 cd/m²) the sensitivity is much lower at 40 Hz than at 20 Hz (Fig. 6a). When these threshold values for electric current are divided by the a.c. frequency, however, we obtain curves which are very similar to the magnetic threshold curves obtained in this study (compare Fig. 6b with Fig. 2, darkness and 130 cd/m²).

The above presentation (Fig. 6a) further shows that, in the light-adapted eye, there is a mechanism which also decreases the electro-sensitivity towards very low frequencies (< 20 Hz). In the magnetic experiments this effect appears as a very rapid sensitivity loss when going from 20 to 10 Hz.

The two-humped curves which appeared when the threshold experiments were conducted with background light of varying wavelengths (Fig. 4) can be interpreted as the result of a combination of two basic curves with different current density thresholds and different requirements on summation time. In this case the two basic curves would represent two different mechanisms or 'channels' in the retina, one sensitive and slow and the other less sensitive but faster and thus able to follow higher frequencies.

In fact, some psychological investigations and a large number of electrophysiological studies of the retinal ganglion cells in cats and monkeys suggest

that there are two sets of channels in the mammalian visual system. One is sustained and slow and signals the colour of a stimulus when stimulated with coloured lights. The other gives transient responses at the onset of light and responds to higher temporal frequencies (KING-SMITH, 1975; TOLHURST, 1977). On the ganglion cell level the first class probably is represented by the *X* and the second by the *Y* cells (DE MONASTERIO, 1978). Further, it is obvious that the *X* and *Y* ganglion cells receive their signals from different sets of presynaptic elements (HOCHSTEIN and SHAPLEY, 1976; DE MONASTERIO, 1978). It is thus tempting to think that the maximum at 20-25 Hz is due to a stimulation of a set of retinal cells, possibly bipolars, feeding into *X* ganglion cells, while the maximum above 40 Hz is due to elements feeding into *Y* cells. One can also speculate about the possibility that the two maxima could be related to the fact that the scotopic rod system and the blue-sensitive cone mechanism have their fusion frequencies at 10-20 Hz, when stimulated with flickering light, while the green- and red-sensitive cone mechanisms fuse at 50-60 Hz (HECHT and SHLAER, 1936; BRINDLEY *et al.*, 1966; the same

mechanisms could have somewhat higher fusion frequencies when stimulated magnetically as they are then freed from delays caused by visual pigment processes). This hypothesis obtains some support from the observation that (against certain backgrounds) deuteranopic and deuteranomalous observers show somewhat lower sensitivities at 35 and 40 Hz than normal observers (Figs. 4 and 5). Combining the above hypotheses we suggest that the maximum above 40 Hz could reflect the activation of *Y* ganglion cells through the synaptic endings of green- and red-sensitive cones.

Since electric and magnetic stimuli bypass the photochemical machinery of the receptor outer segment, they provide a useful tool for studying possible neural changes during light- and dark-adaptation of the retina. Some authors have stressed the importance of receptor and visual pigment processes for the intermediate and slow phases of the dark-adaptation curve (DONNER and REUTER, 1968; RUSHTON and POWELL, 1972; DONNER and HEMILÄ, 1979), while others have pointed out that in addition to pigment processes in the receptors there are, in the skate retina, indications of slow adaptive processes located within the neural network of the inner retina (DOWLING and RIPPES, 1977).

BARLOW *et al.* (1947b) who studied the electric and light thresholds of the human eye during dark-adaptation, found that when a strong background illumination is turned off, the electric threshold suddenly decreases, i.e. the sensitivity increases. After that, however, they observed a slow fourfold rise of threshold resulting in a sensitivity slightly lower than that found in the presence of the strong background illumination. Thus the sensitivity to electric stimulation *decreased* while the sensitivity to light increased by more than two logarithmic units (the authors review a number of earlier studies reporting similar observations).

Measuring magnetic (and light) thresholds we obtained very similar results. In the presence of a 130 cd/m² background the thresholds at 20-35 Hz were 11 mT. Immediately after turning off this light the threshold was found to be 10 mT after which it slowly rose to 15-16 mT (Fig. 3a). Thus the threshold for magnetic stimulation increased by a factor of about 1.5 while the light threshold measured in the same conditions decreased by a factor of more than 10 000.

We can conclude that the elements responsible for the slow dark-adaptation processes seem to lie before the 'magnetoreceptors' in the optic pathway. Thus our results give no evidence for a slow increase of sensitivity within the neural network of the human retina.

The slight decrease in sensitivity (0.2 log units) to magnetic stimuli, which has been observed during the slow dark-adaptation process, roughly follows the progress of the regeneration of rhodopsin in the retinal rods (see ALPERN, 1971). This decrease could

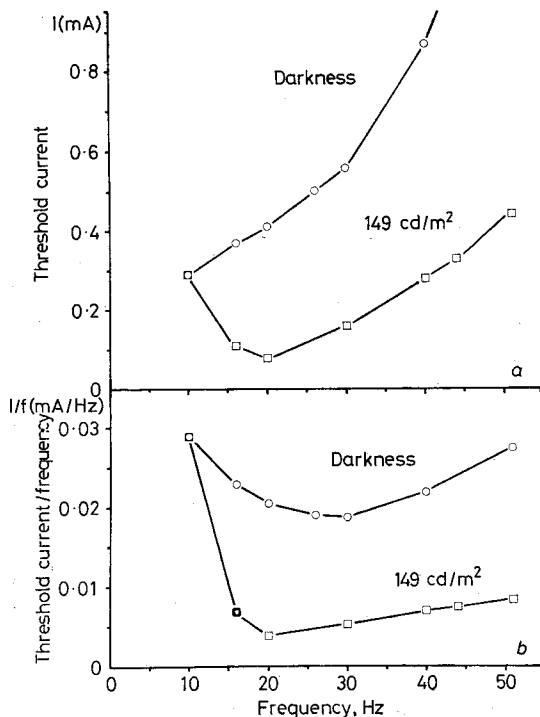


Fig. 6 Threshold values

(a) Threshold values for electrophospheres at luminance 149 cd/m² and in darkness. (Data from Schwarz (1947) 'Tabelle' 1, 469 asb and 'Tabelle' 2, 500 min)

(b) Threshold values as in (a) but divided by frequency

be due simply to slight changes in rod dimensions affecting the flow of the induced currents, or possibly to an increase of the noise level of the receptors and the bipolar cells (cf. SIMON *et al.*, 1975; ASHMORE and FALK, 1976).

Acknowledgments—We thank S. Hemilä for valuable discussions and suggestions and B. Svensson for her skilful assistance. This work was financially supported by the Swedish Work Environment Fund (Grant 74/138, 77/172) and the Swedish Medical Research Council (Project No. 12X-734).

References

- ABE, Z. (1951) Influence of adaptation on the strength-frequency curve of human eyes, as determined with electrically produced flickering phosphenes. *Tohoku Journal of Experimental Medicine*, **54**, 37–44.
- ALPERN, M. (1971) Rhodopsin kinetics in the human eye. *J. Physiol.*, **217**, 447–471.
- ALPERN, M. and WAKE, T. (1977) Cone pigments in human deutan colour vision defects. *J. Physiol.*, **266**, 595–612.
- ASHMORE, J. F. and FALK, G. (1976) Absolute sensitivity of rod bipolar cells in a dark-adapted retina. *Nature*, **263**, 248–249.
- BARLOW, H. B., KOHN, H. I. and WALSH, E. G. (1947a) Visual sensations aroused by magnetic fields. *Am. J. Physiol.*, **148**, 372–375.
- BARLOW, H. B., KOHN, H. I. and WALSH, E. G. (1947b) The effect of dark adaptation and of light upon the electric threshold of the human eye. *Am. J. Physiol.*, **148**, 376–381.
- BARNOTHY, M. F. (ed.) (1964) *Biological effects of magnetic fields* vol. 1, Plenum Press, New York.
- BARNOTHY, M. F. (ed.) (1969) *Biological effects of magnetic fields* vol. 2, Plenum Press, New York–London.
- BATTOCLETTI, J. H. (1976) *Electromagnetism, man and the environment*, Westview Press, Boulder.
- BEER, B. (1902) Über das Auftreten einer subjectiven Lichtempfindung im magnetischen Felde. *Wien. Klin. Wchschr.*, **15**, 108–109.
- BRINDLEY, G. S., DU CROZ, J. J., and RUSHTON, W. A. H. (1966) The flicker fusion frequency of the blue-sensitive mechanism of colour vision. *J. Physiol.*, **183**, 497–500.
- BROWN, P. K. and WALD, G. (1964) Visual pigments in single rods and cones of the human retina. *Science*, **144**, 45–52.
- CABANES, J. (1976) Bibliographic study on the electric and magnetic field effect on living organisms. *RGE—special issue*, 27–30.
- CLAUSEN, J. (1955) Visual sensations (phosphenes) produced by a.c. sine wave stimulation. *Acta Psychiatrica et Neurologica Scand.*, **94**, 1–101.
- D'ARSONVAL, A. (1896) Dispositifs pour la mesure des courants alternatifs de toutes fréquences. *Compt. Rend. Soc. Biol.*, **3**, 450–451.
- DE MONASTERIO, F. M. (1978) Properties of concentrically organized X and Y ganglion cells of macaque retina. *J. Neurophysiol.*, **41**, 1394–1417.
- DONNER, K. O. and HEMILÄ, S. O. (1979) Dark-adaptation of the aspartate-isolated rod receptor potential of the frog retina: threshold measurements. *J. Physiol.*, **287**, 93–106.
- DONNER, K. O. and REUTER, T. (1968) Visual adaptation of the rhodopsin rods in the frog's retina. *J. Physiol.*, **199**, 59–87.
- DOWLING, J. E. and RIPPS, H. (1977) The proximal negative response and visual adaptation in the skate retina. *J. Gen. Physiol.*, **69**, 57–74.
- DUNLAP, K. (1911) Visual sensations from the alternating magnetic field. *Science*, **33**, 68–71.
- FLEISCHMANN, L. (1922) Gesundheitsschädlichkeit der magnetwechselfelder. *Naturwissenschaften*, **10**, 434.
- FORMANEK, V. C. (1976) *ELF electromagnetic field effects on life forms—bibliography*. Technical Report 2, IITRI Project E6249 Contract N 00039-73-C-0030 for US Naval Electronic Systems Command, Washington, D.C., IIT Research Institute, Chicago, Ill.
- GLASER, Z. R., BROWN, P. F., ALLAMONG, J. M., and NEWTON, R. C. (1977) *Bibliography of reported biological phenomena ('effects') and clinical manifestations attributed to microwave and radio-frequency radiation*. Ninth supplement to Bibliography of Microwave and RF Biologic Effects, US Department of Health, Education and Welfare, National Institute for Occupational Safety and Health, Cincinnati, Ohio.
- HECHT, S. and SHLAER, S. (1936) Intermittent stimulation by light. V. The relation between intensity and critical frequency for different parts of the spectrum. *J. Gen. Physiol.*, **19**, 965–977.
- HOCHSTEIN, S. and SHAPLEY, R. M. (1976) Linear and nonlinear spatial subunits in Y cat retinal ganglion cells. *J. Physiol.*, **262**, 265–284.
- KANEKO, A. (1970) Physiological and morphological identification of horizontal, bipolar and amacrine cells in goldfish retina. *J. Physiol.*, **207**, 623–633.
- KING-SMITH, P. E. (1975) Visual detection analysed in terms of luminance and chromatic signals. *Nature*, **255**, 69–70.
- KNIGHTON, R. W. (1975) An electrically evoked slow potential of the frog's retina. I. Properties of response. *J. Neurophysiol.*, **38**, 185–197.
- KNOLL, M. (1958) Anregung geometrischer figuren und anderer subjektiver lichtmuster in elektrischen feldern. *Schweizerische Zeitschrift für Psychologie*, **17**, 110–126.
- KNOLL, M., KUGLER, J., EICHMEIER, J. and HÜFER, O. (1962) Note on the spectroscopy of subjective light patterns. *J. Analytical Psychology*, **7**, 55–69.
- L LAURADO, J. G., SANCES JR., A. and BATTOCLETTI, J. H. (eds.) (1974) *Biologic and clinical effects of low-frequency magnetic and electric fields*, Charles C. Thomas, Springfield.
- LÖVSUND, P., ÖBERG, P. Å. and NILSSON, S. E. G. (1978) ELF magnetic fields in electro-steel and welding industries. *Open symposium on the biological effects of electromagnetic waves held at the XIX general assembly of the international union of radio science*. August 1–8, 1978, Helsinki, Finland, p. 22.
- MAGNUSSON, C. E. and STEVENS, H. C. (1911–12) Visual sensations caused by changes in the strength of a magnetic field. *Am. J. Physiol.*, **29**, 124–136.
- MARKS, W. B., DOBELLE, W. H. and MACNICHOL, JR. E. F. (1964) Visual pigments of single primate cones. *Science*, **143**, 1181–1183.

- MILBURN, B. (1971) *Very low frequency electromagnetic fields and behavior*. Doctoral Dissertation, Univ. of California, Los Angeles.
- MOTOKAWA, K. (1970) *Physiology of color and pattern vision*, Igaku Shoin Ltd., Tokyo, Springer-Verlag, Berlin, Heidelberg, New York, 161-173.
- MOTOKAWA, K. and IWAMA, K. (1950) Resonance in electrical stimulation of the eye. *Tohoku Journal of Experimental Medicine*, **53**, 201-206.
- OSTER, G. (1970) Phosphenes. *Sci. Am.*, **222**:2, 82-87.
- PERSINGER, M. A. (ed.) (1964) *E.L.F. and V.L.F. electromagnetic field effects*, Plenum Press, New York and London.
- PIANTANIDA, T. P. and SPERLING, H. G. (1973) Isolation of a third chromatic mechanism in the deuteranomalous observer. *Vision Res.*, **13**, 2049-2058.
- POTTS, A. M. and INOUE, J. (1970) The electrically evoked response of the visual system (*E.E.R.*). III. Further contribution to the origin of the *E.E.R.* *Invest. Ophthalmol.*, **9**, 814-819.
- PRESMAN, A. S. (1970) *Electromagnetic fields and life*, Plenum Press, New York and London.
- ROHRACHER, H. (1935) Ueber subjektive Lichterscheinungen bei reizung mit wechselströmen. *Zeitschrift für Sinnesphysiologie*, **66**, 164-181.
- Royal Swedish Academy of Engineering Sciences (1976) *Biological effects of electromagnetic fields*. Royal Swedish Academy of Engineering Sciences, IVA-meddelande 210. Stockholm.
- RUSHTON, W. A. H. and POWELL, D. S. (1972) The early phase of dark adaptation. *Vision Res.*, **12**, 1083-1093.
- RUSHTON, W. A. H., POWELL, D. S. and WHITE, K. D. (1973) Pigments in anomalous trichromats. *Vision Res.*, **13**, 2017-2031.
- SCHWARZ, F. (1947) Über die elektrische reizbarkeit des auges bei hell- und dunkeladaptation. *Pflügers Arch.*, **249**, 76-86.
- SEIDEL, D. (1968) Der existenzbereich elektrisch und magnetischinduktiv angeregter subjektiver lichterscheinungen (phosphene) in abhängigkeit von äusseren reizparametern. *Elektromedizin*, **13**, 194-211.
- SEIDEL, D., KNOLL, M. and EICHMEIER, J. (1968) Anregung von subjektiven lichterscheinungen (phosphenen) beim menschen durch magnetische sinusfelder. *Pflügers Archiv*, **299**, 11-18.
- SHEPHERD, G. M. (1974) *The synaptic organization of the brain*, Oxford University Press, New York.
- SHEPPARD, A. R. and EISENBUD, M. (1977) *Biological effects of electric and magnetic fields of extremely low frequency*, New York University Press, New York.
- SIMON, E. J., LAMB, T. D. and HODGKIN, A. L. (1975) Spontaneous voltage fluctuations in retinal cones and bipolar cells. *Nature*, **256**, 661-662.
- SPIEGLER, P. E. (ed.) (1962) *Bibliography of the biological effects of magnetic fields*, Federation Proceedings 21, Supplement 12. Federation of American Societies for Experimental Biology, Washington, D.C.
- THOMPSON, S. P. (1910) A physiological effect of an alternating magnetic field. *Proc. of the Royal Society. Ser. B.*, **82**, 396-398.
- TOLHURST, D. J. (1977) Colour-coding properties of sustained and transient channels in human vision. *Nature*, **266**, 266-268.
- VALENTINUZZI, M. (1962) Theory of magnetophosphenes. *Am. J. Med. Electr.*, **1**, 112-121.
- WERBLIN, F. S. and DOWLING, J. E. (1969) Organization of the retina of the mudpuppy, *Necturus maculosus*. II. Intracellular recording. *J. Neurophysiol.*, **32**, 339-355.