System analysis in vision

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Introduction

In this, partly historical, survey we shall try to point out some fundamental aspects of system analysis, with special attention to some problems and experimental facts that are still unsolved. Because of our long-standing collaboration with Professor Arden, we thought it appropriate to base this paper mainly on the Amsterdam contribution to system analysis. Looking through our own work and the literature we are impressed anew by the simplicity of the start of (linear) system analysis in vision and the fact that it works so well in such an extremely complex system, in the sense that physico-mathematical relations can be applied to an astonishing degree.

It should be realised that the electrophysiological responses on which this survey is based are the result of a large number of cells acting in co-operation.

Historical background

It can safely be stated that the most important impulse in our field was given by de Lange.[1,2] De Lange, unaware of this when starting his experiments, repeated and extended the experiments 'avant la lettre' of Ives.[3] De Lange simulated with home-made discs, among other things, sinusoidally modulated light and measured with this a spectacular high-frequency attenuation (up to 60 db/oct) as illustrated in Fig. 1, in which are also included observations of Ives[3] and van der Tweel.[4] De Lange used a surround with equal luminance. In fact at low frequencies threshold under such conditions is determined by comparing the flickering field with its surround (spatial contrast). Spatial threshold is comparatively constant at various levels of illumination. Therefore de Lange's curves converge at low frequencies. Without surround, indeed, at low frequencies sensitivity drops as seen in Fig. 1. At higher frequencies temporal contrast becomes the dominating factor.

De Lange's[2] model and that of Ives[3] are shown in Fig. 2; de Lange's research can be considered as the true start of system analysis in vision!

It was realised later (Denier van der Gon, unpublished data) that a cascade of low-pass filters approaches a Gaussian delay distribution which represents the theoretically highest realisable i.e. Gaussian high-frequency cut-off. In reality the steepness of the de Lange curves is less, especially at lower luminances, but the principle seems attractive. Of course in physical reality delay distributions have always to remain in the positive domain.

De Lange was well aware that the power of his method was that near threshold at the stage of discrimination, enough high-frequency attenuation has taken place to ensure linearity in practice. This has a direct parallel in Talbot's law, which states that beyond flicker fusion, brightness is equal to that of a field illuminated with the average (static) luminous flux of the flickering light.

If an approximate logarithmic response/ intensity character (Weber's law) is assumed, three or four stages of high-frequency cut-off with appropriate time constants will suffice for the validity of Talbot's law, i.e. the d.c.-shift due to the curvature of the logarithm becomes smaller than the differential detection threshold.[5] This attenuation is much less than actually found by de Lange. We shall come back to this.

De Lange showed experimentally that Fourier theory proved fully applicable at high frequencies for various waveforms; only the amplitude of the fundamental matters (Fig. 1). Sinusoidal modulation, however, is especially useful at the low-frequency side where any other waveform fails. At low rates of stimulation with square wave modulation, for instance, the subjective threshold becomes rate-independent and will be determined only by the steep transients of the wave shape, according to a kind of differentiation.

Probably the greatest advantage of sinusoidal signals is that, as a consequence of the superposition property of the linear system, any linear filtering leaves the harmonic shape intact. In other words, 'sine wave' remains 'sine wave'. This is due to the simple fact that the sum of two sinusoidal signals of the same period or frequency, but with different phase and amplitude, according to a simple goniometric relation, is again sinusoidal with amplitude and phase depending on the original ones.

Theoretically related to this shape constancy of harmonic functions, is the behaviour of 'Gaussian noise' defined by its Gaussian amplitude distribution. If Gaussian noise is

*Prof. L.H. van der Tweel died on 13 May 1997 H. Spekreijse pays tribute to him in a postscript to this article.

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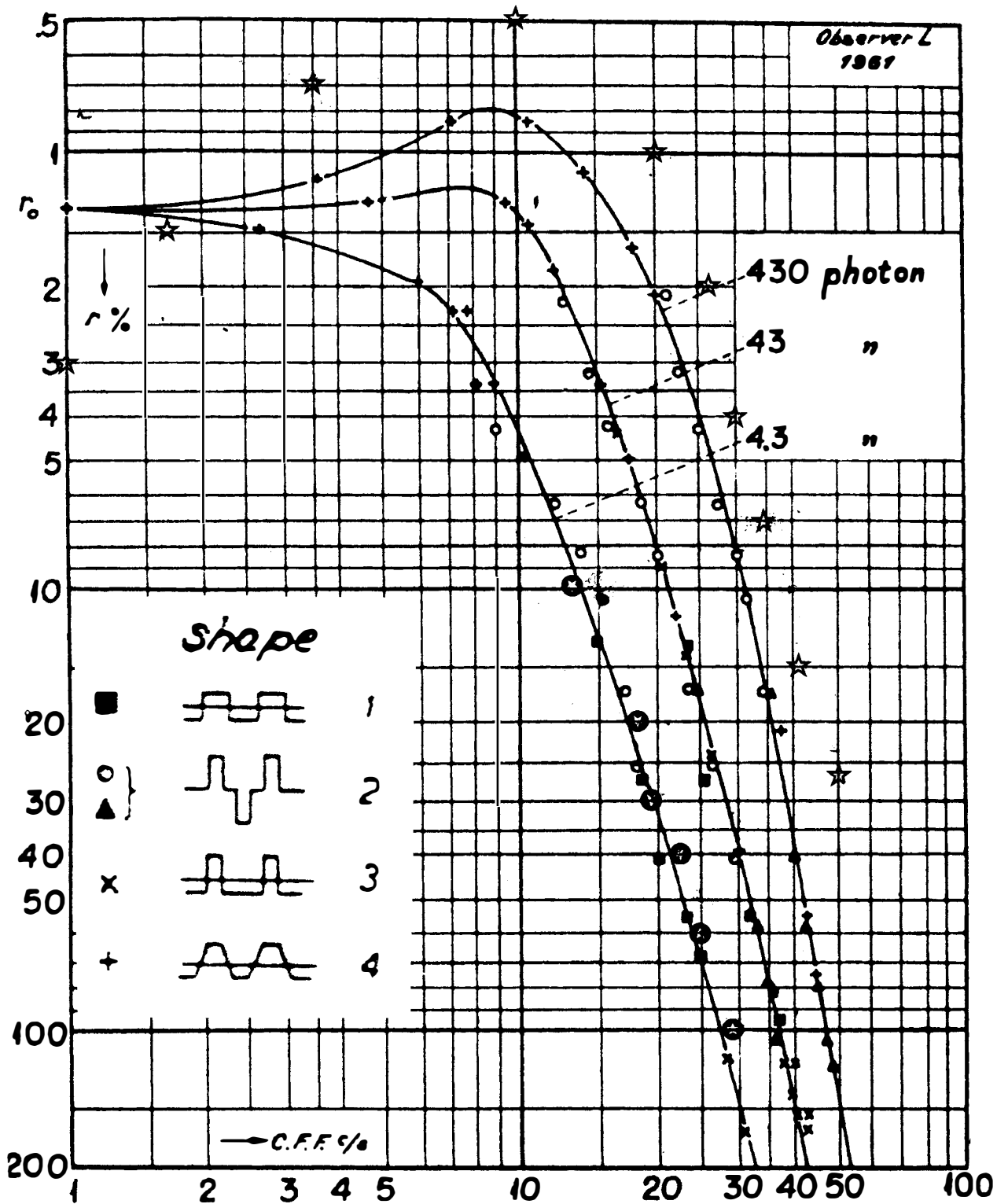Amsterdam-Zuidoost
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Fig. 1. *Original curves from de Lange[2] of human flicker sensitivity (equal surround). Several waveforms were employed; the curves show that at high frequencies the threshold is exclusively determined by the amplitude of the fundamental (as indicated by the symbols). Modulation percentages > 100% are virtual ones, but fit into the general curve. The convergence with all illumination levels at low frequencies is due to the steady surround which causes a switch in the threshold mechanism from temporal to spatial. White stars in black circles: adapted from Ives[3] at low (unknown) luminance; stars: from van der Tweel,[4] measured at 60 000 td, 60°; no surround.*

passed through a linear filter, it keeps its Gaussian amplitude distribution, although its frequency spectrum may change dramatically. Approximated Gaussian noise (there is no negative light) has been fruitfully employed by Denier van der Gon and in his thesis by Reits[6] with respect to essential non-linearities (see also Lopes da Silva[7] and Spekreijse et al.[8]). Parallel to this, also in the

spatial domain (where in geometrical optics Fourier methods have already been in use for a long time), visual research was directed to the use of sinusoidal grids by Schade,[9] which later became a main theme of Fergus Campbell and the Cambridge group. We shall devote some attention to the principal problems concerning analysis in time and space.

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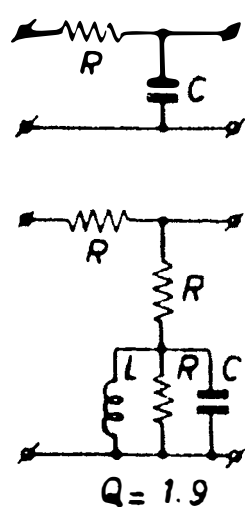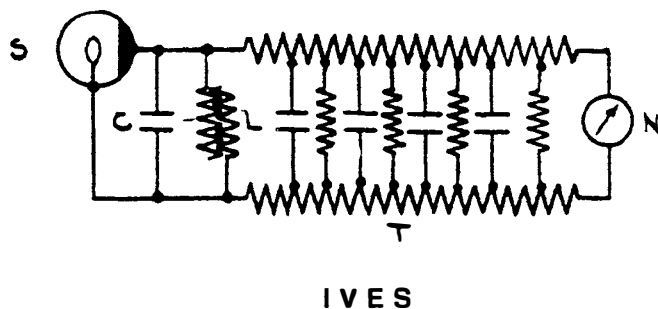
Fig. 2. *De Lange's model.[2] Ten RC stages in series simulating the steep high-frequency attenuation are in series with two second-order filters simulating the pseudo-resonance at c. 10 Hz (see text). For curiosity's sake Ives' model[3] is also shown.*

How should 'system analysis in vision' be defined and specified?

One of the first system biophysicists was certainly the neurologist Larry Stark[10] who, among other things, employed sinusoidal stimuli on crayfish photoreceptors and on the pupillary reflex, which remained for a long time his study subject. The latter was also studied by van der Tweel,[4,11] and Stegemann.[12] Frequency response curves were recorded with a high-frequency slope that was estimated to be around 12–18 db. Fig. 3 shows one of the first (if not *the* first) physiological Bode plots by Stegemann. From the amplitude and phase of this figure a step-function was calculated that exhibited a latency of c. 200 ms, fitting the experimental one.

Modern visual (electro-)physiology and physiology in general, are much interested in systems: the term 'visual system', however, has a wider meaning than that covered by the methodology of system analysis as treated in the present paper.

Following the example of de Lange, our studies were originally directed along filter-analytical concepts, which actually were based on linear functioning. Originally we were enthusiastic that so often linear operations were applicable objectively in electrophysiology, giving the feeling that a certain problem under study has been solved; for example in the electroretinogram one could estimate step response from amplitude and phase characteristics at sinusoidal modulation. Later we realised, however, that linear system theory dictates that no sequence of linear filter processes can be established. Therefore one of the aims of our research, i.e. to localise the various processes in the visual pathway, can not be achieved in this way.

This changes dramatically, however, as soon as non-linearities are involved. It should be realised, though, that for non-linear systems no standard solutions exist,

but that for certain classes of non-linearities there are feasible experimental and theoretical procedures that allow sequence determination and localisation of the various processes acting on the signal transport.

Early experiments from the Amsterdam group

After our research on the pupil and extending de Lange's work, a next step was to apply sinusoidal modulation to human electrophysiology. One of our first studies was with depth electrodes in patients of Sem Jacobsen in Olso.[13,14]

With two primitive frequency analysers (high-Q resonance circuits) and a modulated light source with a TV-projection tube it was shown that intracortical
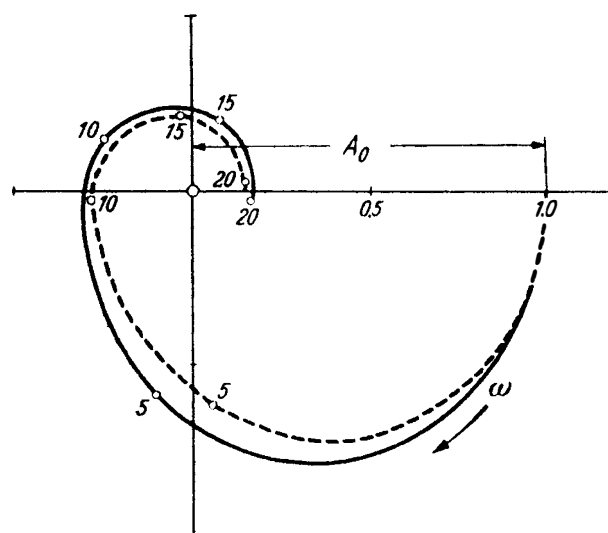

Fig. 3. *Stegemann's[12] Bode plot of the pupil response to modulated light for low and high intensities (continuous and dashed curves respectively). Numbers indicate circular frequency. A_0 is a quasi-dc amplitude. Because all amplitudes remain smaller than A_0, the pupil forms a stable control system.*
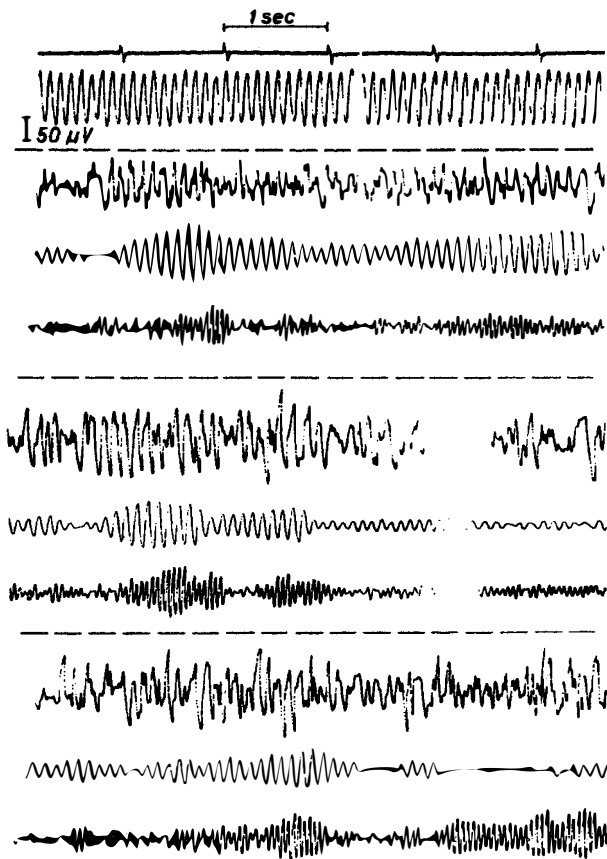
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Fig. 4. *Depth electrode recordings from the visual cortex by means of stainless steel electrodes at three locations at a distance of 10 mm. Two selective amplifiers were used, tuned at the stimulation frequency of 10 Hz and its second harmonic; modulation depth (MD) 50%. The responses within and between the channels are poorly correlated for the fundamental and the second harmonic. Reproduced from Kamp et al.[14]*

responses could be obtained around 10 Hz at as low as 5% modulation depth (MD). Fig. 4 shows that at 50% MD nearby sites were poorly correlated in their fundamental and second harmonic responses. The main results were confirmed as soon as sophisticated averagers etc. became available. It was realised already at that time that rectification must be an important phenomenon in visual electrophysiology.

The electroretinogram

The electroretinogram (ERG) was also subjected to the novel technique of modulated light. Van der Tweel and Visser[15] recorded the ERG to sine wave modulated light. Fig. 5 shows the results of conventional ERG recording in the cat with modulated light as a stimulus. The responses were linear enough to allow application of the Laplace transform, such that a step response was adequately reconstructed from the amplitude and phase characteristics. It soon became apparent that in the human photopic ERG above 1 Hz three systems or structures can be discerned that exhibit quite different properties. The main tools used were sinusoidally modulated light and simultaneous stimulation with two different frequencies. At a luminance of 600 cd/m^2

amplitude and phase of the first harmonic in the response to sinusoidally modulated light is plotted in Fig. 6 for a field size of 180°.

At frequencies below about 6 Hz the responses show a larger phase delay, i.e. a steeper slope of the phase plot against linear frequency, than at frequencies above 20 Hz. By varying luminance levels and field sizes the three systems are differently influenced (Fig. 7). The low-frequency structure behaves as a low-pass filter with a cut-off frequency of 5 Hz at 18 db/oct. This system seems to be related to the b-wave in the flash ERG, which has a comparable latency. The second system has a peak near 20 Hz and a low-frequency cut-off of c. 6 db/oct and a high-frequency attentuation of 18 db/oct. It exhibits an essentially non-linear character and has a short latency (<3 ms) estimated from the phase curve if corrected for the minimum phase shift due to the amplitude characteristic. The system behaves as the so-called scotopic a-wave in the flash ERG. The third system has a peak near 40 Hz, a low-frequency cut-off of 6 db/oct and a high-frequency cut-off of 24 db/oct. Non-linearity is not prominent and occurs mainly as saturation. Its latency is below 4 ms. It behaves as the 'photopic' a-wave in the flash ERG. The higher harmonics of the 20 Hz structure show a latency (after correction for minimum-phase shift) of c. 20 ms.

The results indicate that in the photopic ERG there are responses in two higher-frequency regions with almost no latency, and (linear) rectification at c. 20 ms from stimulus onset (cone activity?), which may suggest a ganglion cell origin. There is one phenomenon that behaves to a certain extent similarly in eye and ear, i.e. the existence of combination frequencies. In hearing sum and difference frequencies have been well known for a long time. They can easily be demonstrated by increasing the loudness of two separately presented pitches. Combination frequencies in vision have been employed to advantage by, for example, Spekreijse and Reits[16] and Regan.[17] There is a difference, however, between combination frequencies in the case of linear rectification as mainly found in vision and of saturation. For linear rectification their relative amplitudes are independent of stimulation strength, whereas e.g. in hearing and other types of non-essential distortion, the relative amplitudes grow approximately with the square of the stimulation amplitudes.

Although subsequently in the retina-cortex pathways a division will be made regarding frequency preference, including differences in latency and non-linearities, the combination frequency method is in principle independent of central properties. Stimulation is performed with two frequencies, F_1 and F_2, with a constant difference, in the present case being 18 Hz. Visual evoked potential (VEP) recordings are then made looking only at the amplitude of the difference frequency; in this way the influence of central selectivities etc. will be absent (Fig. 8). Therefore we may consider the results as relevant for the filtering processes in the retina distal to the non-linearities. The peak
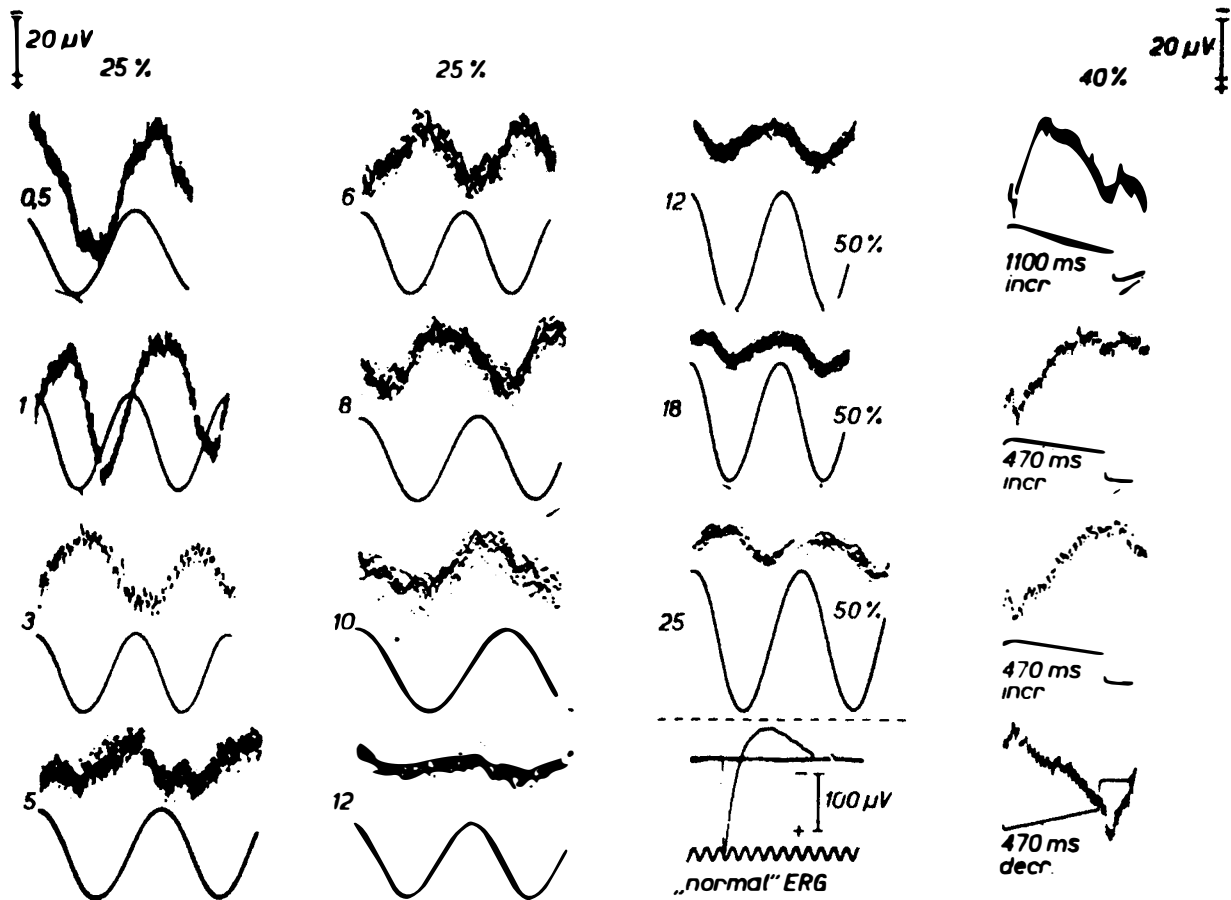
Fig. 5. ERG responses in the anaesthetised cat (pentobarbitol). High retinal illumination (c. 50 000 td); field size c. 60°. The large phase shifts at low frequencies are caused by stray light that produces larger low-frequency ERGs than high intensities, at opposite polarity. Right-hand column: incremental and decremental step responses in good accordance with the sinusoidal ones. Reproduced from van der Tweel and Visser.[15]

amplitude lies near 28 Hz, which means a distal maximum between 28 and 46 Hz that may be identical to that of the third retinal system of Fig. 7.

With other difference frequencies comparable results are obtained. In the case of dichoptic two-frequency stimulation, however, when only cortical effects can play a role, the responses of the difference frequencies are about 10 times smaller than if both frequencies are presented in the same eye, which means that the studied non-linearities have mainly a monocular origin.

The electro-encephalogram

The ingenious Manfred Clynes,[18] who was also the inventor of the stupendous CAT (Computer of Average Transients), came with his model of unidirectional rate sensitivity, implying differentiation and rectification. A further analysis was developed in Amsterdam with responses to sinusoidally modulated light by van der Tweel and Verduyn Lunel[19,20] and in Spekreijse's thesis.[21]

The use of modulated light soon revealed that there are (at least) two distinct (electrophysiological) systems for transmitting temporal information to the cortex. On the basis of phase-delay curves initially two systems
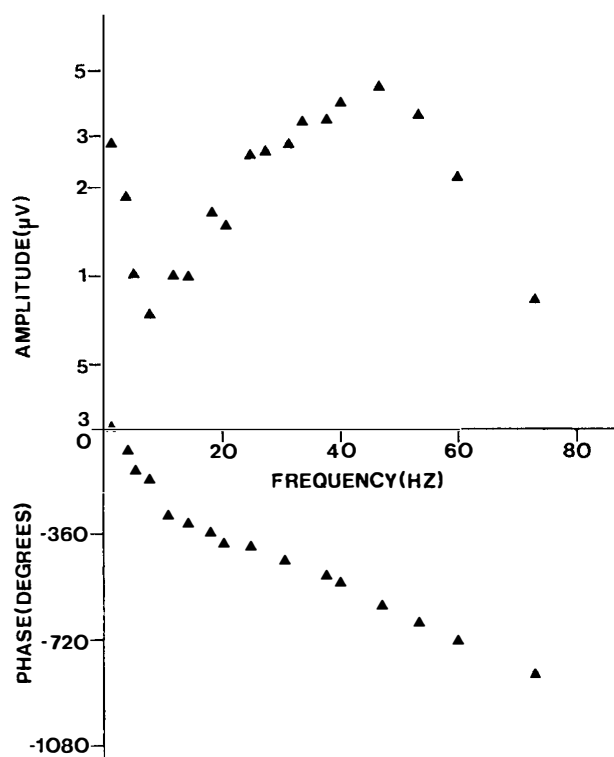

Fig. 6. ERG recordings with skin electrodes in man with sinusoidal stimulation; MD 50%; 600 cd/m²; field 180°. Phase delay at low frequencies is large compared with higher frequencies (see text).
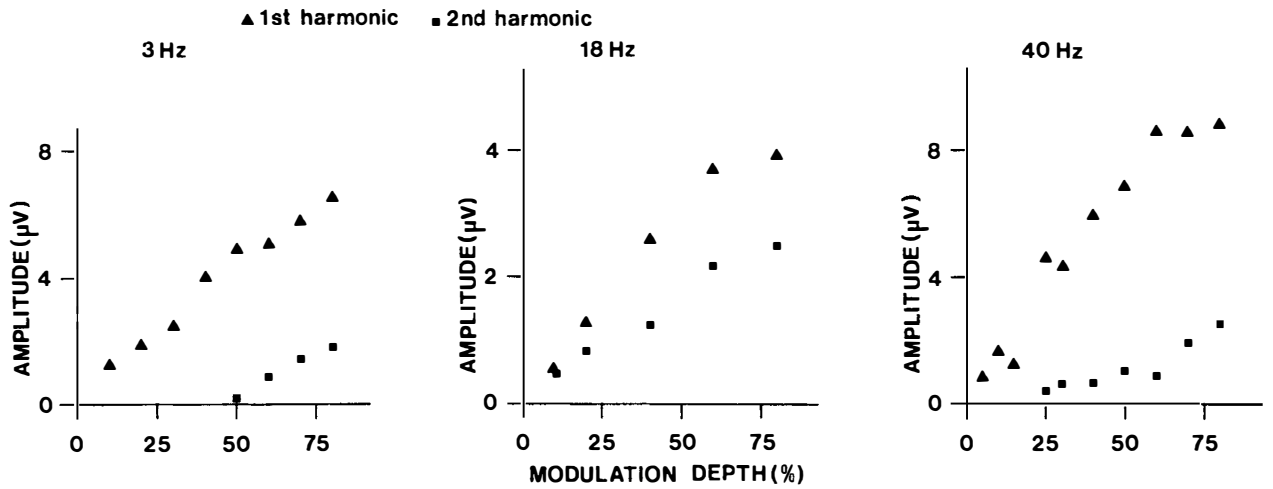
▲ 1st harmonic   ■ 2nd harmonic

3 Hz   18 Hz   40 Hz

Fig. 7. *Amplitude of fundamental and second harmonic of ERG as a function of modulation depth for the three subsystems.*

could be defined, one acting at frequencies lower than approximately 15 Hz and another beyond c. 25 Hz (Fig. 9).

The first one, with a phase delay* of c. 150–200 ms, exhibits in many individuals resonance properties around 10 Hz, sometimes with an unexpectedly high selectivity (Fig. 10), that has a direct correspondence with the alpha-rhythm. This indicated that the resonance is a cortical phenomenon. The other region above c. 25 Hz

*With sine wave studies for the VEP we prefer the term phase delay (apparent latency) because minimum phase correction for amplitude characteristics is often difficult.
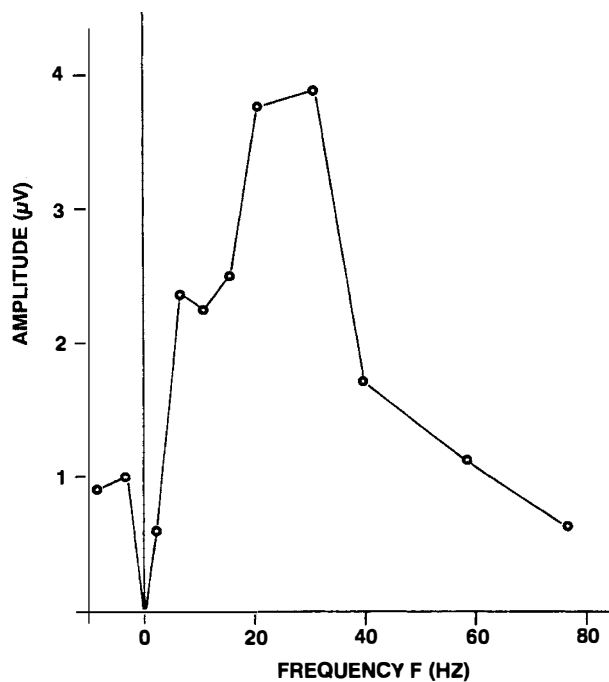
showed a phase-delay of 60–100 ms (Fig. 9). The delays proved to be dependent on luminance; a higher luminance produces shorter latencies.

Regan[22] soon added a medium-frequency system (c. 18 Hz and 100 ms phase delay) to the already discovered low- and high-frequency systems or pathways (Fig. 11).

Confirmation that the pathways of the three frequency bands are indeed separate, follows also from the cortical topology of the responses, which is different for the three frequency subsystems.

The beta-frequencies in the EEG and the newly coined gamma-frequencies are attracting much attention at present with regard to the so-called binding problem, i.e.

Fig. 8. *The two-frequency technique applied to the human VEP. Stimulation with the frequencies F and F + 18 Hz. Amplitude plot of the 18 Hz EP component, i.e. the difference frequency. The result is independent of cortical frequency characteristics.*
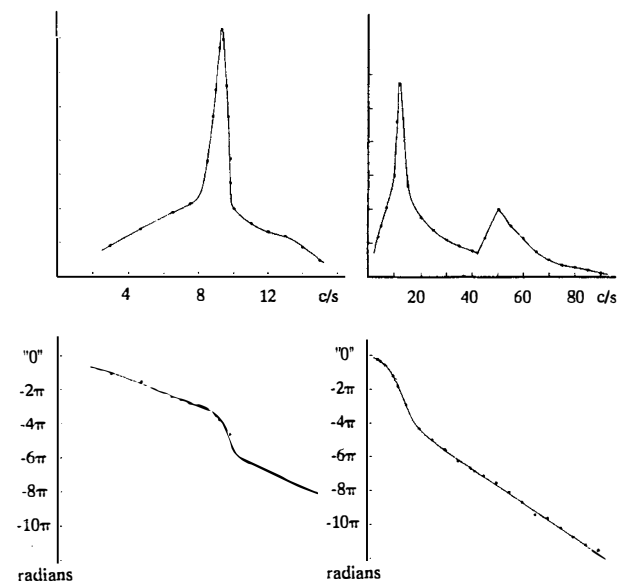

Fig. 9. *EP amplitude and phase characteristics of two subjects with sinusoidal stimulation at different luminances. The frequency scale is linear, amplitudes in relative units. In the subject on the left there is resonance in the amplitude as well as in the phase plot. In the subject on the right there are two preference regions, but less sharp (note difference in frequency scales). No clear signs of resonance are found in amplitude and phase plots. Phase delays at low frequencies are much larger than at high frequencies. Reproduced from Spekreijse.[21]*
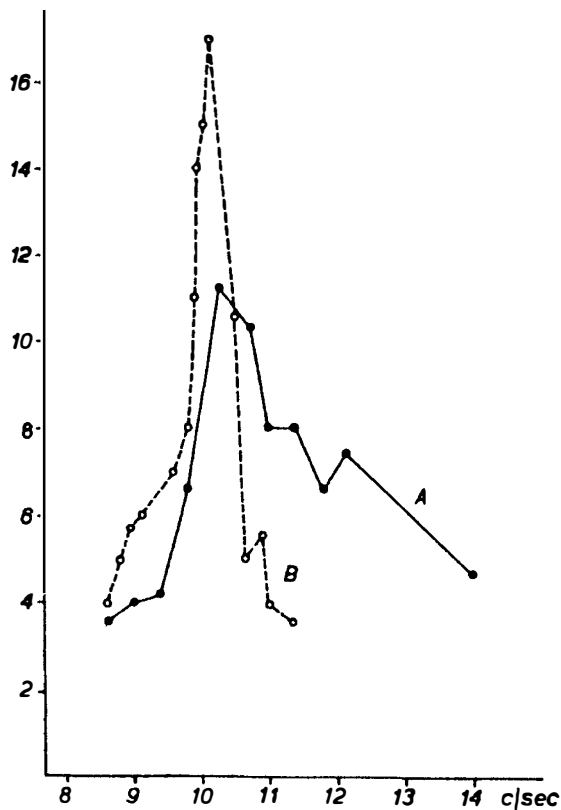
Fig. 10. *EP amplitude and phase plots of two subjects (A, B) who show large differences in frequency characteristics. The high selectivity of B is also expressed in an extra phase shift of c. 180° at the resonance frequency. The linear phase shift with frequency is equivalent to a delay of c. 250 ms. Reproduced from van der Tweel and Verduyn Lunel.[20]*

how the visual system integrates the visual scene. The old gestalt theory plays a dominant role in this. We do not know whether our sinusoidal responses have anything to do with this, just as we are ignorant of the psycho-physiological meaning of the alpha-resonance.

Whereas, within limits, linear techniques proved to be applicable to the ERG even for high modulation depths as described, this became much more complicated for the VEP, although it was surprising that for high-selective subjects build-up and decay at c. 10 Hz with sine wave trains corresponded so well with the selectivity
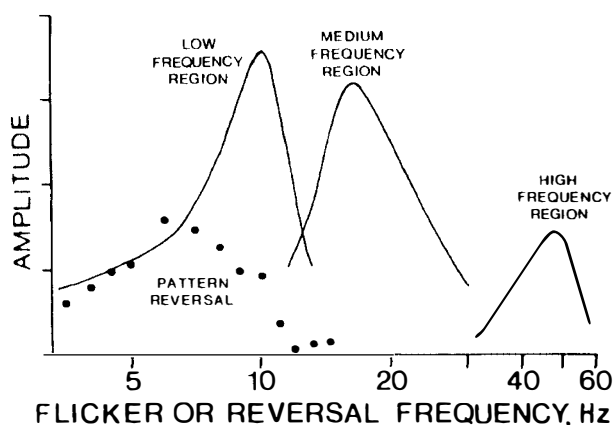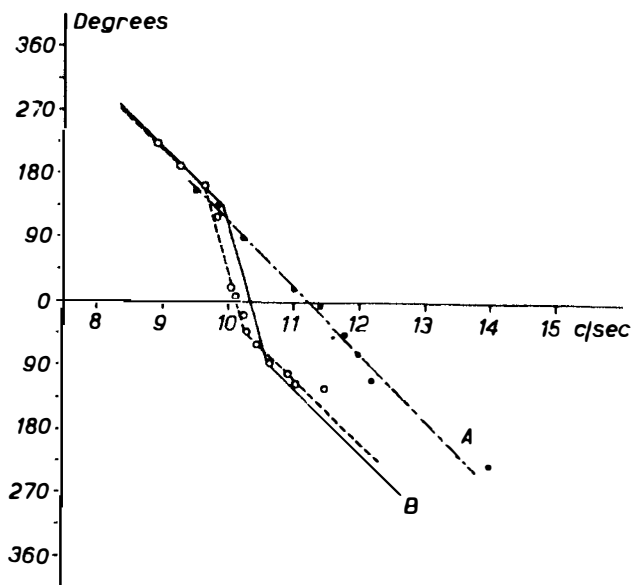
measured in the amplitude characteristics (Fig. 12). Moreover in our experiments the response is mainly an addition to the spontaneous activities, although Vijn[23] has shown that under special conditions strong visual stimulation may decrease spontaneous activity. Evidently this is a different phenomenon from alpha-blocking.

Already in our first experiments it was found that under photopic conditions, even far below subjective threshold, ERG and VEP responses could be obtained, in a way depending on the endurance of the subject. A
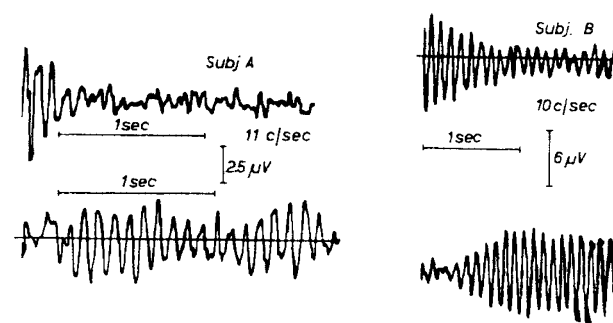

Fig. 11. *Frequency response according to Regan[22] (with permission) of the three parallel flicker VEP subsystems and of pattern reversal for checks less than 15'–20'. Particularly the medium-frequency, but also the high-frequency responses are emphasised by using large stimulus fields.*

Fig. 12. *VEPs to sine wave trains. Decay (upper) and build-up (lower) curves of the two subjects of Fig. 10 to sine wave trains of 11 and 10 Hz respectively. Subject A does not show a gradual decay and build-up. The responses show a latency of c. 250 ms. The responses of subject B resemble those of a resonant circuit with Q = c. 12 (compatible with Fig. 10). Subject A has a poor alpha-rhythm, whereas subject B has a large very persistent alpha-rhythm. Psychophysically no differences are found between the two subjects. Reproduced from van der Tweel and Verduyn Lunel.[20]*
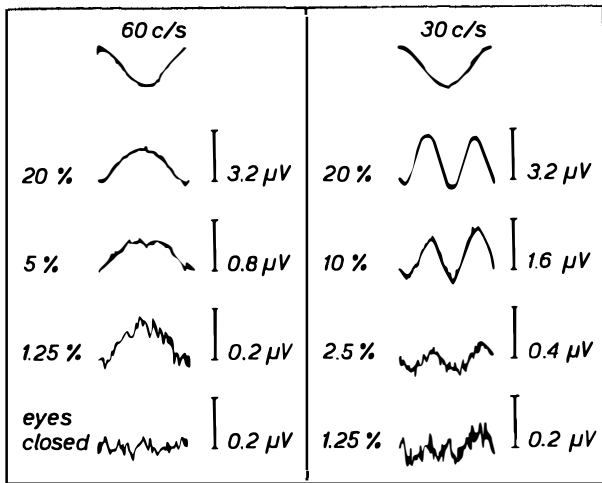
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	60 c/s			30 c/s	
20 %		3.2 µV	20 %		3.2 µV
5 %		0.8 µV	10 %		1.6 µV
1.25 %		0.2 µV	2.5 %		0.4 µV
eyes closed		0.2 µV	1.25 %		0.2 µV

Fig. 13. *Occipital responses to 30 and 60 Hz (c/s) sine wave stimulation. Mid-line electrodes; Maxwellian view; stimulus field 20°; 3000 cd/m². The number of runs is inversely proportional to MD; for linearity all responses per column should be identical. It is clear that this does not apply to the second harmonics of 30 Hz, indicating a transition zone. Even for 1.25% MD the response to 60 Hz meets the criterion of linearity. Moreover the subjective threshold was about 60%. Reproduced from Spekreijse.[21]*

striking example is shown in Fig. 13.[21,24] Such a result can be made plausible by assuming that whereas psychophysical thresholds are based – as every threshold – on non-linear processes, this does not imply that all electrical responses to the stimulation have disappeared. Our technique in principle allows infinitely long

integration; the visual threshold process, however, does not integrate more than a few seconds. The same applies to the relation with spatial integration, which psychophysically does not extend much beyond c. 5–10°, contrary to evoked potentials which may represent large cortical areas. So altogether perhaps two orders of magnitude can be bridged. This is quite different for contrast evoked potentials (EPs) where definite electrophysiological thresholds are found that approach the psychophysical ones.[25]

In themselves sub-threshold EPs may seem intriguing, but especially the results of Fig. 14 pose a problem that in our view has not yet been solved. This figure shows that the high-frequency electrophysiological slope under the experimental conditions was considerably lower than the corresponding psychophysical one. In the part devoted to the ERG it was also shown that the high-frequency slope accounted only for maximally 24 db/oct. This is all difficult to reconcile with results reported in the literature. Fuortes and Hodgkin,[26] for example, report dramatic low-pass filtering in *Limulus* ommatidia, as does Leutscher[27] in the retinula cells of the blowfly. Campbell and Robson[28] find the same in an artful experiment with human pupil constriction as a criterion. Spekreijse et al.,[29] however, confirm our earlier results of much less attentuation by reporting only 12 db/oct in monkey geniculate. Brindley[30] points out on the basis of beats between electric phosphenes and flicker above CFF, that not all attenuation can result from the receptors. See also the results in the sequel with respect to objective
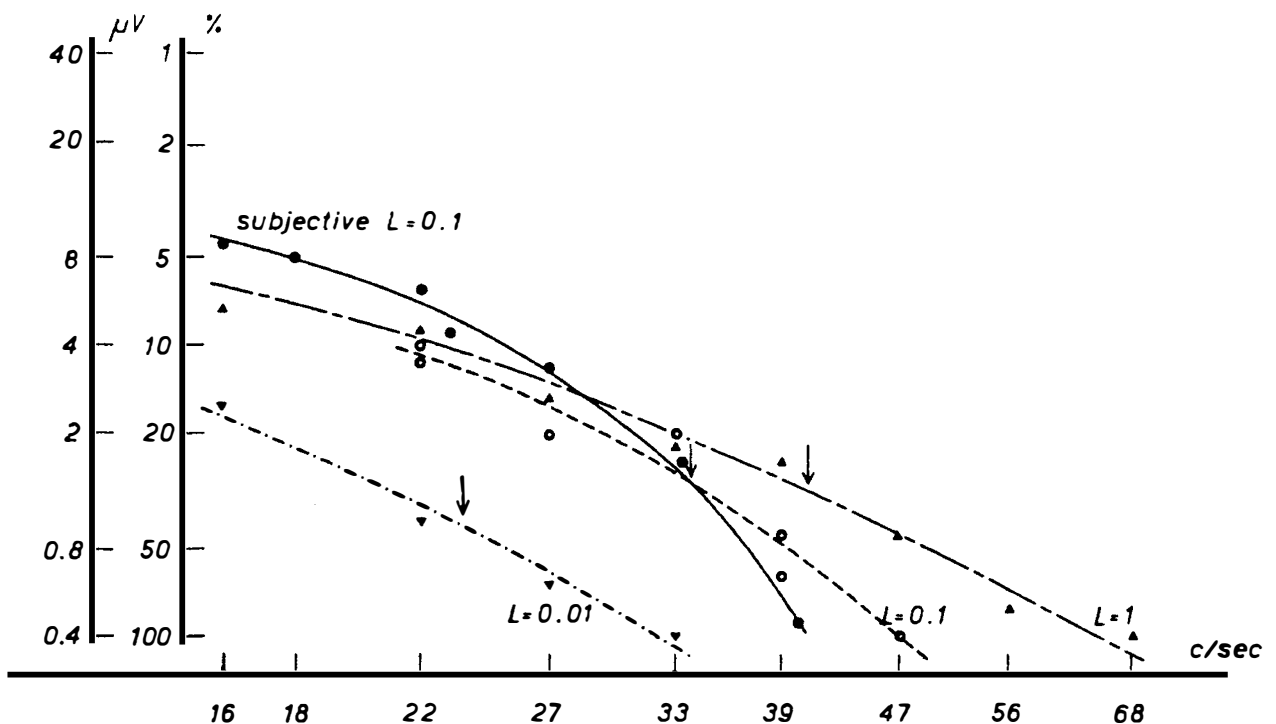

Fig. 14. *VEPs to constant 25% modulation for L = c. 6000, 600 and 60 td. Field size 15°. The continuous line represents the subjective results at 600 td. CFF for the other luminances is indicated by vertical arrows. The arrow for L = 0.1 is at the intersection between the curves for fusion and VEP; therefore direct comparison of the slopes is allowed. The VEP curve is less steep than the subjective one. Note also that all curves are continuously bending. The responses do not decrease proportionally with the retinal illumination, presumably because of light adaptation. Reproduced from van der Tweel and Verduyn Lunel.[20]*

measuring of retinal filtering, where only three or four stages of high-frequency cut-off are reported, combined with a low-frequency cut-off as required to enable rectification.

The problems involved seem a legitimate but difficult subject for further study!

Non-linear analysis

Contrary to the interchangeability in the sequence of various processes in a linear system with regard to its transfer function, non-linearities give opportunities for sequence analysis, although as already mentioned there is no general theory about non-linear systems.

In our research it proved useful to distinguish 'essential' and gradual non-linearities. It should be noted that in so far as this concerns our research of non-linearities in the evoked response systems, in this review we restrict ourselves mainly to static non-linearities, i.e. they are frequency-independent within the frequency range studied, as actually proves to be a good approximation.

Gradual non-linearities: saturation

Although Weber's law describes a basic function in vision, in electrophysiology often a larger range exists where responses grow linearly with stimulus strength to reach a maximum more or less abruptly, in quite a few cases to (substantially) diminish again. This phenomenon was termed by Storm van Leeuwen 'paradoxical diminution'. Saturation is a phenomenon in principle to be found in every (bio)physical system; in vision it also causes distortions (adding second harmonics with sinusoidal stimulation) that grow approximately with the square of the amplitude of the input, as for instance will be the case for a logarithmic response function.

Whereas saturation in the ERG occurs at relatively high modulation depths, saturation is prominent when recording VEPs. This also enables localisation within the visual pathways, especially for separating retinal and cortical processes. The strongest saturation with luminance stimulation was found for the low-frequency system (Fig. 15).

Also here an unsolved problem was met: saturation proved to be governed by the total cortical amplitude, such that, for example, at 10 Hz the amplitude/ modulation depth slopes for one and two eyes at the start have a ratio of approximately 1:2, meaning independence of the two eyes. However, the saturation occurs at an equal total EP-voltage in both situations. Smaller fields may also show this type of saturation, but only if the same ceiling is reached at increasing modulation depth. In Fig. 15 is also presented the result with a 2° field that, of course, shows a much smaller slope which diminishes at very high modulation depths; nevertheless the response continues to grow.

The results described here look mysterious; one is not quite ready to accept that the brain would have at its disposal a kind of supervisor that has access to the sum
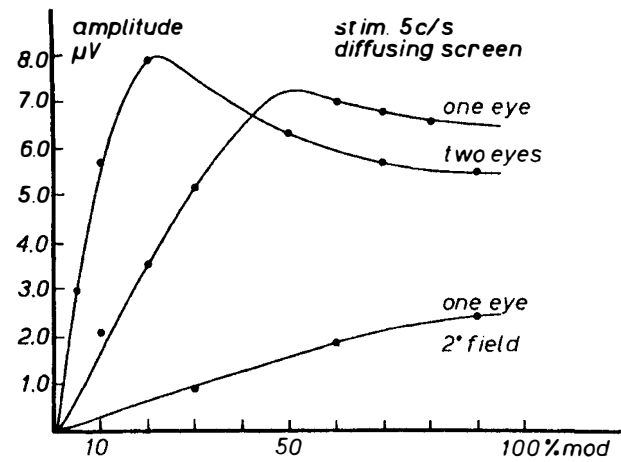

Fig. 15. *Amplitudes of second harmonic of 5 Hz stimulation; electrodes on mid-line; diffuse field, 60 cd/m^2. Long-latency/low-frequency system. Amplitudes of the second harmonic of 5 Hz stimulation. With monocular stimulation the fellow eye is illuminated with the same mean luminance. Final saturation level for large fields is equal for one and two eyes. For a 2° field some sign of saturation can be observed at high MDs. Reproduced from Spekreijse.[21]*

of all responses of the separate regions and prohibits further growth. But, alas, we lack an alternative explanation; moreover co-operative phenomena are by no means rare in vision.

In the luminance-short-latency system (Fig. 16) the fundamental saturates (intensity-dependent) per small retinal field and *not* cortically (smaller fields than 2° could not be used due to too long a duration of sessions). The VEP amplitude is then the sum over the total stimulated area. Moreover one finds approximate summation of the two eyes with saturation starting at the same modulation depth (Fig. 17).

In general there is not so much correspondence between the results of electrophysiological and psychophysical aspects of flicker; in the present case, for instance, flicker sensation is still increasing in strength above saturation modulation depth.
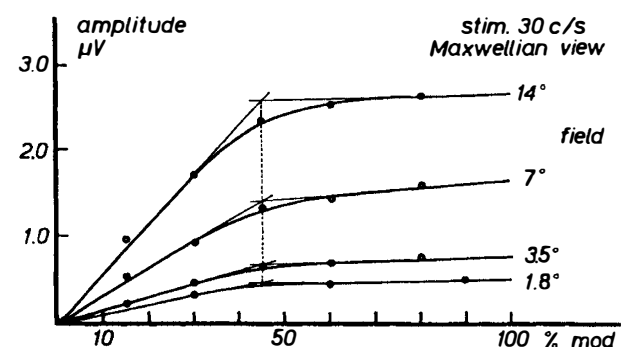

Fig. 16. *Saturation of the second harmonic to 30 Hz stimulation as a function of field size. Maxwellian view; 3000 cd/m^2, dilated pupil. A surrounding field of equal luminance was employed. Reproduced from Spekreijse.[21]*
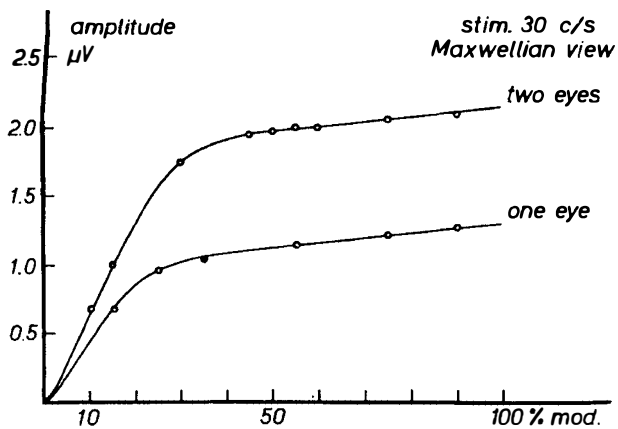
Fig. 17. *Monocular and binocular saturation of second harmonic component. Stimulus field 20°; dilated pupil; 3000 cd/m² unstimulated eye covered; main saturation has an ocular origin. Reproduced from Spekreijse.²¹*

Essential non-linearities: rectification

Whereas the former examples dealt mainly with saturation, and indeed information could be obtained about the various stages in the process, the most important results were obtained with essential non-linearities, i.e. with rectification. This could be studied in great detail because of the invention of the linearising technique — about which more later.

Already in the Oslo experiments[13,14] we noted the existence of strong second harmonics, also at lower modulation depths. In consecutive experiments[20] with an averager, at c. 5 Hz and c. 27 Hz very strong second harmonics emerged. Spekreijse[21] confirmed this and found striking second harmonics around 30 Hz stimulation even at low modulation depths (see Fig. 13). The purity of the second harmonics depends on cortical characteristics. For example, the second harmonic responses (10 Hz) to 5 Hz stimulation were the most prominent for high monorhythmic alpha-subjects etc. because of the high selectivity at 10 Hz.

An interesting experiment, in this respect, was to use counterphase modulation on the two eyes. At all frequencies the fundamental was cancelled and mainly a second harmonic resulted. This physiological creation of second harmonics proved to be a simple method for their isolation as used in Fig. 16. Since this counterphase technique proved feasible in many subjects, it suggests that for this kind of counterphase stimulation conceivable eye dominance is not reflected in the electrical responses! Recent research of Cavonius[31] and Cavonius, Estévez and van der Tweel[32] has shown that binocular counterphase modulation can be a fruitful technique, in psychophysics also. At low frequencies the fundamental disappears and a second harmonic is observed that can be measured by comparison with a true second harmonic presented at an adjoining site in the stimulus field.

Returning to rectification, we were struck by the sharpness of the 'rectifiers'. In every discontinuity, certainly at the temperatures we are dealing with, there is a transitional area which must be very small in our
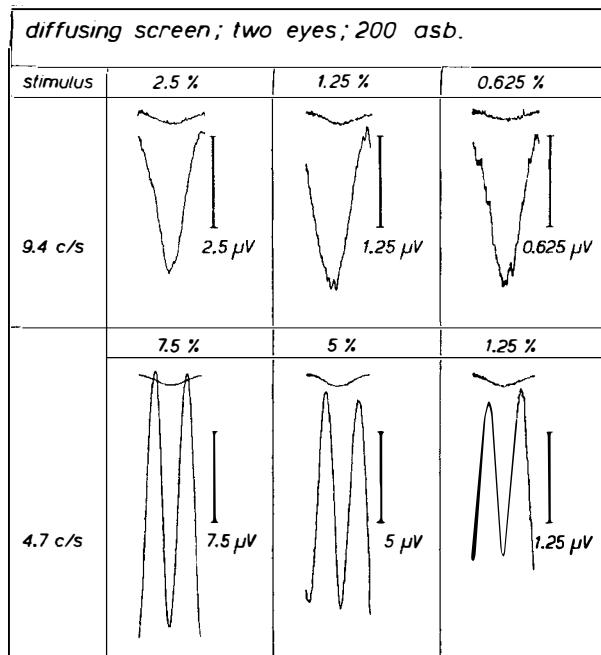

Fig. 18. *Illustrative sample of occipital responses (fundamental and second harmonic at 9.4 Hz and 4.7 Hz respectively) for a high resonant subject. Number of integrations is inversely proportional to modulation depth. In the linear case all recordings should be equal in size. Second harmonics decrease disproportionally to MD, but are still substantial. Reproduced from Spekreijse and van der Tweel.²⁴*

material, considering the appearance of substantial second harmonics at modulation depths of no more than 1–2%. This means that they are found near and probably below subjective threshold (Fig. 18; see also Fig. 13).

Linearising technique

A powerful tool was devised on basis of the above-mentioned linearising phenomenon. On theoretical grounds it was expected that any non-correlated signal suppresses rectification effects, restoring the original shape at increasing strength (Fig. 19).³³ Fig. 20 demonstrates that the very first experiment performed
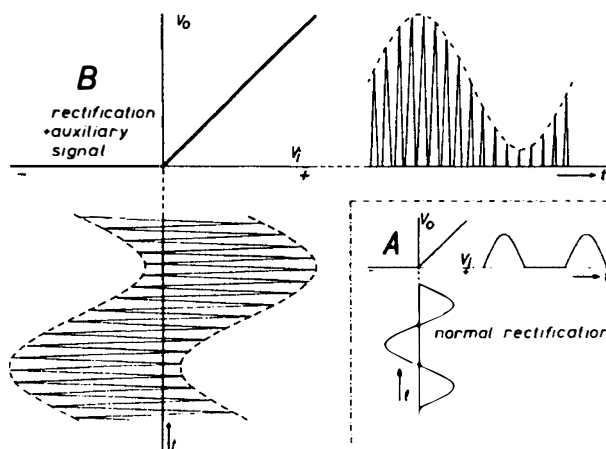

Fig. 19. *Schematic representation of linearising by an auxiliary signal. The inset (A) shows rectification of a sine wave. Adding a triangular wave to the sine wave restores the sinusoidal shape when averaging is applied. Reproduced from van der Tweel and Spekreijse.³³*
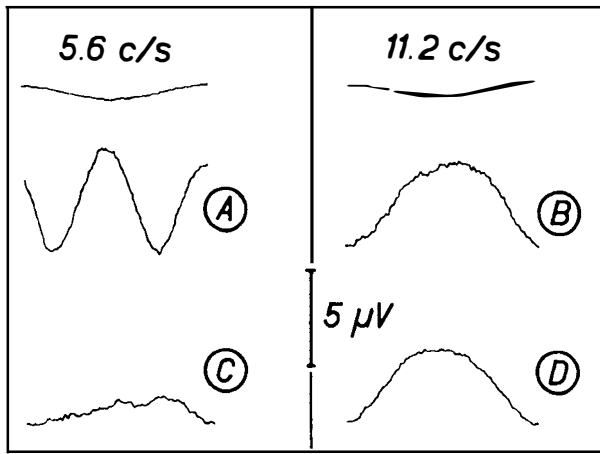
5.6 c/s	11.2 c/s
(A)	(B)
5 μV	
(C)	(D)

Fig. 20. *Occiptal responses to 5.6 and 11.2 Hz. Diffuse illumination; 10% modulation; natural pupil; 200 cd/m² Upper traces: modulated light. (A) and (B) Responses to sinusoidal modulation, i.e. second harmonic response and fundamental. (C) and (D) As for (A) and (B) but with additional Gaussian noise A²/2s ² = 0.04. The second harmonic is suppressed. Reproduced from Spekreijse and van der Tweel.*[34]

by Spekreijse and van der Tweel[34] confirmed the theoretical concept. This indicated at the same time that the physiological respectively quantal noise at the site of the rectifier, must be small, because at modulation depths as low as 1% second harmonics are still found. Therefore it is concluded that spatial integration has to take place distal to the rectifier. We shall come back to this later on.

It was soon realised that a sinusoidal auxiliary signal would not only be a more effective lineariser than Gaussian noise because of its more effective amplitude distribution, but would also offer an easy and objective way to determine the transfer function of linear operators
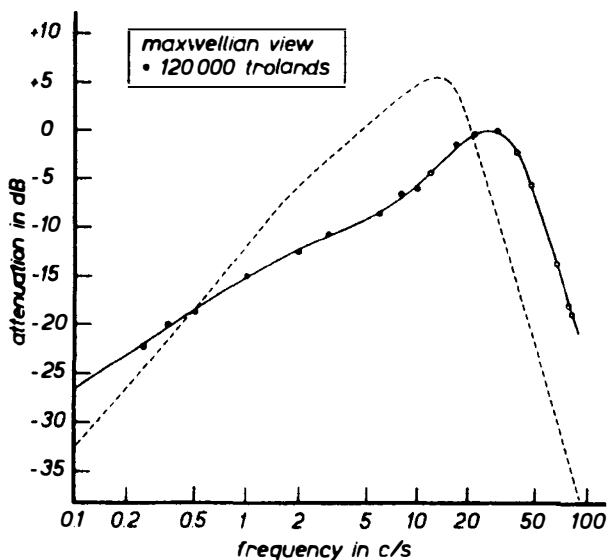
preceding the rectifier. As explained above, the sinusoidal shape of this auxiliary signal will not be affected by linear filtering. The linearising effect therefore depends only on the relative amplitudes of additional and test signals at the rectifying site. The technique was to use a constant sinusoidal test signal and to vary the amplitude and frequency of auxiliary sinusoidal signals in such a way that each time a constant (averaged) criterion response is obtained. In this way it proved possible to determine filter characteristics distal to the rectifying processes, i.e. early in the retina. There proved to be high-pass filtering with some 6 db/oct with a time constant on the order of 50 ms for the low- and high-frequency systems, and subsequently 12 and 18 db low-pass filtering respectively with c. 5–10 ms time constants for the two systems (Fig. 21). The exact data are quite complicated and differ for the two systems, which indicates that they are already separated before rectification. In contrast the medium-frequency system has a more linear character that makes it difficult to perform a sequence analysis.

A strong physiological basis for our method was laid by Spekreijse[35] with his recordings using the same technique in the ganglion cells of the goldfish (Fig. 22), making the localisation in the ganglion cells, in man also, practically certain. In this way, therefore, definite proof was obtained for early (linear) processes apparently followed, after (asymmetric) rectification, by separate more central ones.

This strengthens at the same time our former conclusion that, because the selectivity to sinusoidal homogeneous field stimulation fits so well the characteristics of the alpha-rhythm, this selectivity will be a cortical phenomenon. (There is due indication that the geniculate does not show a comparable selectivity.)
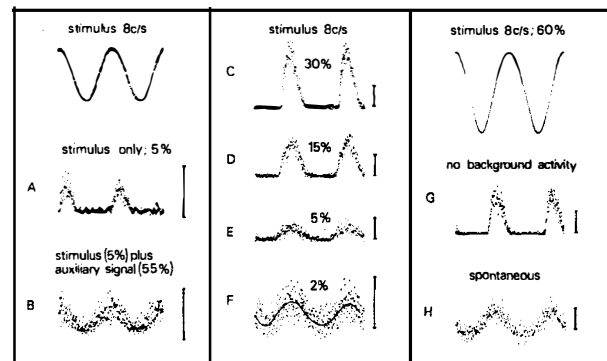

Fig. 21. *Distal filtering of the low- and high-frequency subsystems, as measured with the linearising technique. Dashed curve: 1500 td; diffusing screen. Although there are differences between the two curves, the general trend is the same: 12–18 db/oct high-frequency cut-off and low-frequency cut-off c. 6 db/oct below 7–10 Hz, as required for rectification. Reproduced from Spekreijse.*[21]

Fig. 22. *Linearising red 'off' units of a ganglion cell in an isolated goldfish retina. Diameter of light spot focused on the retina 1.2 mm (first column), 6 mm (second column), and 2.5 mm (third column); 300 summations for A, C, D and E; 400 for B, G and H; 600 for F. Calibration 20 spikes/bin. Bin duration 625 μs. The period-averaged responses C, D, E and F show approximate proportionality with MD. At the lowest MD a linear response (F) is obtained due to the linearising effect of internal noise. In A, C, D, E and G, lowest points represent zero count level. This holds approximately for B and F, whereas for H lowest points represent a spontaneous firing rate on the order of 4 spikes/s, causing internal linearising. The average intensity of the stimulus, passed through a Wratten 29 filter, is c. 1 μW/cm². Reproduced from Spekreijse.*[35]

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In his recent, elaborate book about electrical brain activity Barlow[36] criticises the filtered noise model for the alpha-rhythm and points to the phenomenon that also in monorhythmic subjects an abrupt ending of the activity can occur, which should not agree with the decay times of sharp filters. We wish to refer to Fig. 12, however, in which the build-up and decay of the response to sine wave trains are in accordance with the physical characteristics of a filter compatible with Fig. 10. Moreover, in a number of cases we studied, a quality factor attributed to the alpha-activity and one deduced from the EP characteristics are compatible within experimental error.

Oscillations and oscillators

In relation to the above we wish to make some further comments on models for rhythmic activity in the cortex, especially the alpha-rhythm.

We start with the filtered noise model. This is based on positive feedback, but not causing sustained oscillation. In such a model parallel input of cortical (white) noise and periodic stimulation can produce alpha-rhythm together with EPs at the stimulation frequency, peaking at the basic frequency of the feedback loop, as indeed found in our research. In the literature the expression 'linear oscillator' is sometimes used; it shquld be understood that there are no linear (feedback) oscillators in the true sense. There has always to be a limiting of amplitude which at the same time means the introduction of harmonics. It is interesting to note that such a distorted oscillator can be synchronised by the harmonic frequencies present in the distortion. The basic oscillator frequency then becomes a subharmonic of the synchronising one. Synchronising an active oscillator at or near its proper frequency is tricky and does not result

in a considerable increase in amplitude, contrary to what happens with passive selective circuits. In that case the amplitude will be greatest when stimulus and centre frequency are (nearly) equal and it will – in our case below a certain modulation depth – be proportional to the input. In such a model there is indeed a possibility for a fast ending of oscillations, i.e. if the feedback loop is interrupted.

In technical systems the feedback of selective amplifiers is mostly of a linear character, but one can not expect such a thing in complicated physiological processes. On the one hand it may be considered exceptional that linear physical laws apply so well; on the other hand non-linear feedback can be the cause of generation of subharmonics. With subtle experimenting small subharmonics can indeed sometimes be found. In the case of averaging, blinking should be avoided, e.g. by experimenting with closed eyes, because phase jumps may lead to cancellation.

That it proves so difficult to obtain substantial subharmonics is a strong argument against a relaxation oscillator (the extreme of distortion in an oscillator) as a model for the alpha-rhythm as has been proposed, because one of the striking properties of this type of oscillator is its easy synchronisation by its harmonics. In another biological example, i.e. the heart, where the sine node is a typical relaxation oscillator, we can easily synchronise this pacemaker by small sinusoidal currents, with a frequency even up to 6 times the spontaneous rate.[37] We should like to present as one of the conclusions of this paper that spontaneous rhythms including their proposed models should also be tested with small (sinusoidal) signals.
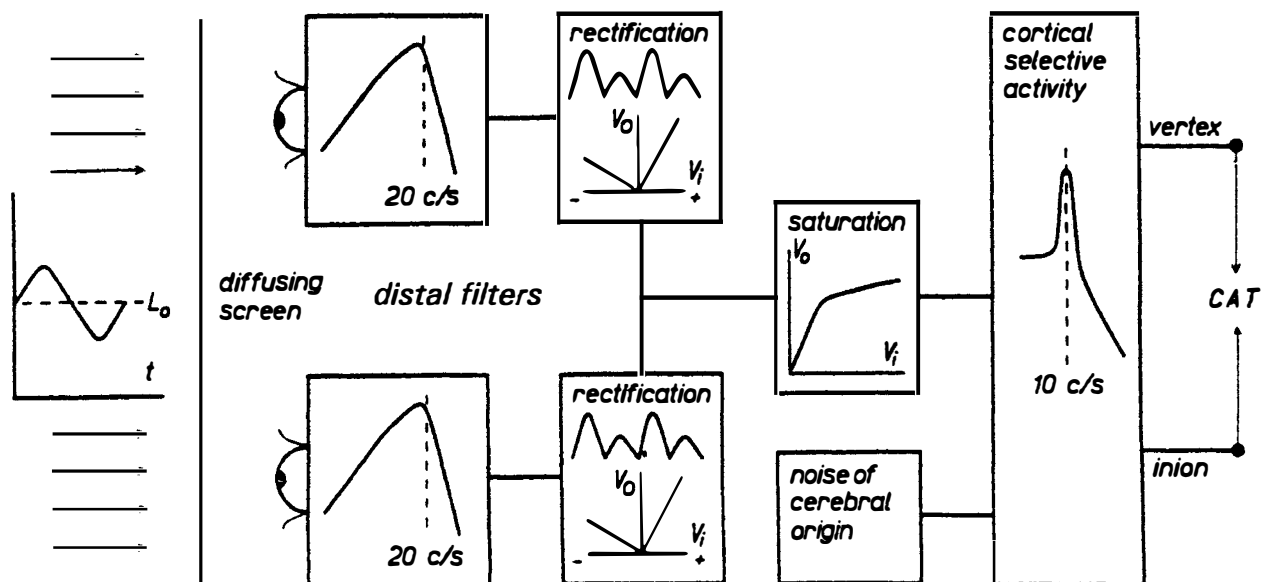
Fig. 23. *Simplified model of the retina-cortex subsystem with long latency. Its magnitude (175–250 ms) depends on various parameters including the illumination level. It was mentioned before that distal to the rectifier there is a delay of c. 20 ms; most of the rest of the delay is thought to be of cortical origin. In reality there are probably two saturating elements. The sites of the latencies are not indicated. Reproduced from Spekreijse.[21]*
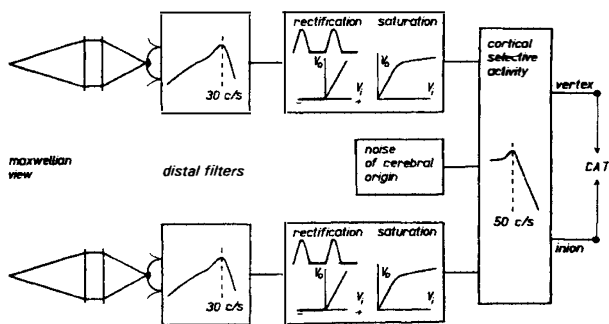
Fig. 24. *Simplified model of the subsystem with short latency (60–100 ms). Rectification is half-wave. Saturation is near or on the rectifier. There is a delay of c. 20 ms distal to the rectifier. The sites of the latencies are not indicated. Reproduced from Spekreijse.[21]*

DC-restoration of rectifiers

There is also an other intriguing problem with rectification: in the experiments with modulated light, the main technique applied by us, the light stimulus moves at the most between darkness and twice the average. In the receptor the illumination causes hyperpolarisation. Without input signal there should be no potential difference between the two 'sides' of a rectifier; however, and indeed as is shown in Fig. 21, there is early high-pass filtering involved (d.c. blocking). A complicating factor is that, whether or not it belongs to the low-frequency system, there should also still be a d.c. transport; even with stabilised image techniques – how much a homogeneous field may be suppressed in experienced intensity – this is never total. Moreover it may take several seconds before the stabilising effects appear.

One experimental drawback, however, is that in EP work, contrary to single-cell studies where sustained activity can easily be recorded, d.c. recording (or
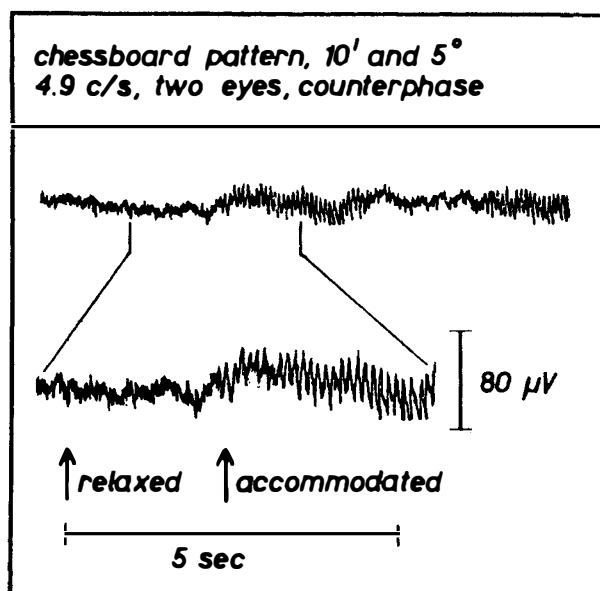
experimenting at very low frequencies) is practically impossible. One can hope that neuro-magnetic recording will overcome this obstacle.

We have described that already in the retina different frequency systems can be discerned, but the selectivity at c. 10 Hz and (less sharply) at c. 50 Hz encountered in the luminance EPs does not appear in the ERG; these have a cortical origin.

It was mentioned above that (idealised) Gaussian noise remains Gaussian under linear filtering. There is an important theorem by Bussgang[38] which teaches that with static non-linearities the cross-correlation function of Gaussian noise input and output with only linear filters in the input and output, produces the overall transfer function. The cross-correlation function will be scaled according to the shape of the non-linearity. This can be generalised to input signals with elliptically symmetric amplitude distributions.[39] From these results, combined with bispectra, further separation in pre- and post-rectifier filtering can be obtained. They corroborate the results obtained with sinusoidal modulation.

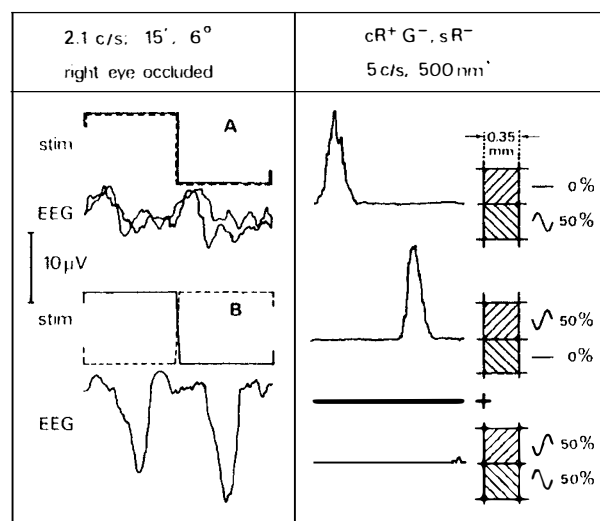It falls outside the scope of this review to go into detail about this.

Fig. 25. *Very first recording of a pure contrast EP; no averaging was needed. Bipolar leads on the mid-line; 3000 cd/m². Reproduced from Spekreijse.[21]*

Fig. 26. *Comparison of EPs in man with ganglion cell responses in isolated goldfish retina. Left-hand column: (A) EPs to homogeneous field (in-phase) modulation; (B) as for (A) but with counterphase modulation (reversal) of the two sets of squares. If the two responses have the same origin, (B) should be equal to or smaller than (A). The reverse is unmistakably the case, proving a different origin of (A) and (B). Right-hand column: period averaged spike data for a green off-centre process in the goldfish retina. The top figure gives the average spike response to modulation (50%) of one set of squares (0.35 mm sides). The other set of squares is steadily illuminated at the mean intensity. Reversing the situation changes the phase of the response, as expected. Simultaneous counterphase modulation of both sets of squares eliminates the responses, which suggests location of the summation preceding rectification. Mean intensity of the stimulus light through an Ealing FTP interference filter is c. 4 μW/cm². Number of summations, 100; modulation frequency, 5 Hz; patterned retinal spot has a diameter of 2 mm. Reproduced from Spekreijse and van der Tweel.[24]*
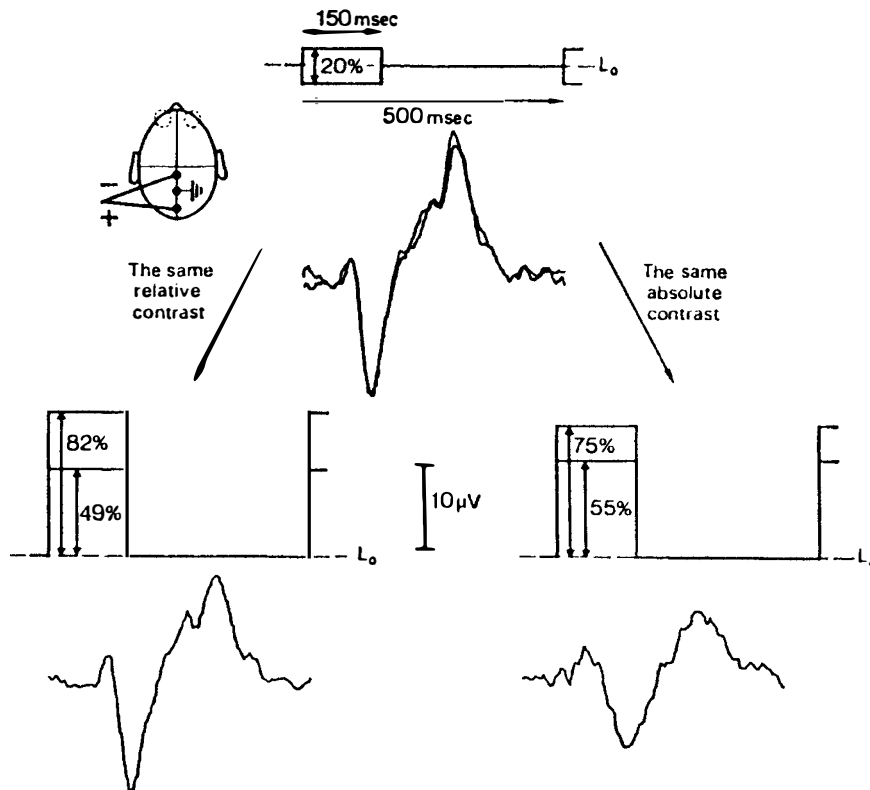
Fig. 27. *Cortical responses to an appearing-disappearing checkerboard (top). A simultaneous jump in luminance does not affect the response materially if the relative difference is made constant (bottom left). If the absolute difference is kept constant the response changes considerably (bottom right). Reproduced from Spekreijse et al.[40]*

Models

The analysis results as described were brought together in two models:[21] one for the low-frequency system (Fig. 23) and one for high frequencies (Fig. 24). We are aware that we still lack a definite link between the frequency characteristics as expressed in the ERG and those in the VEP model.

Temporal and spatial analysis

Contrary to what is the case in hearing, the visual system has no special behaviour with regard to periodic functions, i.e. neither for sinusoidal grids nor for periodicity of flicker; this applies to temporal and spatial psychophysics as well as to electrophysiology.

The cortical resonances that were described, for instance, have nothing to do with perception, as was once suggested by van der Tweel[5] and some others. In colour processing the basic criterion is of course frequency (or wavelength), but this concerns another frequency domain: so-called harmony in colour representations such as in paintings, has nothing to do with 'harmonic' wavelengths.

The above is not to say that sinusoidal grids can not provide a sensible tool for measuring the quality of vision, as, for example, with the Arden charts. One of the advantages is that, within limits, fixation will not be as important as, for example, with letter tests. Another advantage of harmonic grids is that they allow measurement of thresholds at low spatial frequencies;
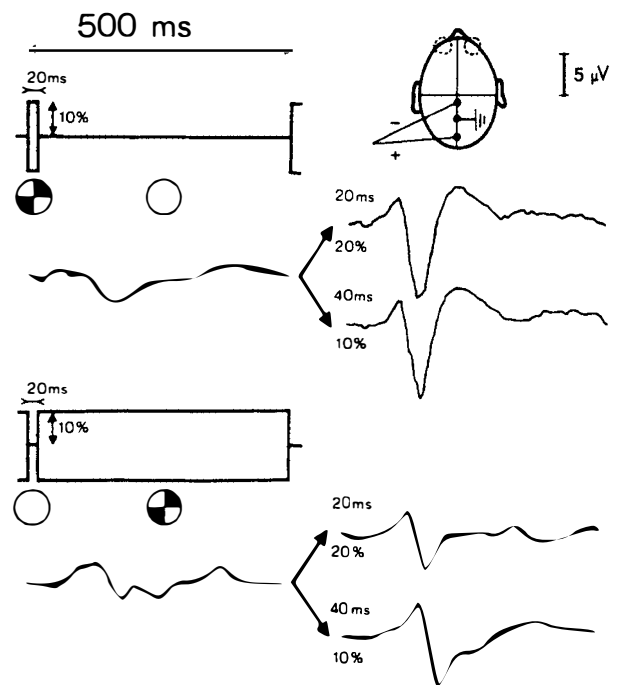
Fig. 28. *The top half of the figure gives the responses to short appearances of a checkerboard pattern with 10' checks. As long as the product of contrast and presentation time remains – within limits – constant, identical responses are obtained (Bloch's law for contrast EPs). The bottom half of the figure gives the response to short disappearances of the same checkerboard. In this condition presentation time and contrast are not interchangeable. Reproduced from Spekreijse et al.[40]*

with square grids at low spatial frequencies the threshold will be determined by the edges, just as in the time domain this applies, for example, to square waves.

Of course, Fourier techniques are fully applicable to spatial configurations, but this should not be generalised to be considered as the functional basis of vision; already the geometrical inhomogeneity of the retina would make such a thing very improbable.

This frame of reasoning will be illustrated at the end of the paper with, we hope, a stimulating and appropriate demonstration.

Integrative fields

When the prominence of second harmonics in homogeneous field stimulation was discovered, it was an intriguing question to try to find out the size of what we called 'integrative' fields lying at the basis of second harmonic formation. As discussed before, such fields had most probably to exist because, for example, for single cones the quantal noise would prohibit rectification owing to the described linearising effect of such. The estimation of the size of the integrative fields brought us naturally upon checkerboard reversal stimulation. The experiment was simple in the goldfish retina and at high frequencies in man: when decreasing the check size there

was a decently sharp transition from rectification per field to cancellation in counterphase stimulation of square fields (the highest-order polygons allowing counterphase stimulation!) When we, after many technical difficulties with obtaining reliable light sources, attempted this technique in man, with – in this case justified – sine wave reversal stimulation, we thought that there must have been made a mistake, because with the very first experiment we got the responses of Fig. 25,[23] actually thinking they were an artifact(!), and within the scope of our work contrast stimulation was born.

Fig. 26[24] shows a revealing comparison: the same technique applied at the goldfish retina where pure cancellation occurs. Actually luminance integrative fields could be determined also with the counterphase technique in man; and again there is separation of the two systems as described before, because the sizes of their integrative fields are clearly different!

The limits of 'classical' system analysis

System analysis is at its best with pure luminance stimulation, but at present contrast stimuli of many kinds are centre stage. Regrettably, but logically, contrast stimuli are not well accepted to regular system analysis,

Fig. 29. *Photographs of Arden and van der Tweel as an appropriate demonstration of the different impact of amplitude and phase in the two-dimensional Fourier transform, as explained in the text.*

as we discovered long ago. For instance, sine wave modulated contrast reversal stimuli are ambiguous because the cross-over speed changes with the changing amplitude (i.e. contrast), complicating the analysis. Fast transients, especially sudden appearance-disappearance of contrast, are much less ambiguous. It is therefore for contrast studies that traditional 'ad hoc' physiological techniques become relevant again. As an illustration of this we wish to present a few striking examples.

The first considers the so-called differential amplifier experiment[40] (Fig. 27). It is not only the case that in spatial vision perceived contrast is not much influenced by a simultaneous change in average illumination; this proved to be reflected well enough in the corresponding EPs, even with a considerable simultaneous general luminance jump. With smaller jumps of the overall luminance of, for example, c. 10–20%, the contrast responses do not differ much from that in the symmetrical case.

Also a kind of Bloch law for contrast (presentation time × contrast = constant gives a constant response) could be demonstrated (Fig. 28). It is evident from these few examples that the loss of techniques of system analysis in the case of contrast is compensated for by approaching nearer the essence of visual processing.

The discovery of the pure contrast response gave much inspiration to present-day research, considering the practically total dominance of contrast as a VEP stimulus; however, in our opinion classical system analysis applied to luminance experiments awaits a well-deserved revival.

A tribute to Geoffrey Arden

Contrary to Helmholtz's phase rule for hearing, expressing phase insensitivity of musical sounds, the phase spectrum of a visual scene is the main determining factor for recognition: the information comprised in the amplitudes is insignificant in comparison.

This can be demonstrated in the example of Fig. 29, chosen as a tribute to Geoffrey Arden. The technique is conventional: from two faces the two-dimensional amplitude and phase spectra were determined and separately processed. We find, at the top left, a (digitised) portrait of Geoffrey Arden, and at top right a similar portrait of the senior author. Bottom left shows the amplitude of Arden with the phase of van der Tweel, and bottom right the amplitude of van der Tweel with the phase of Arden.

A tribute to Henk van der Tweel
Henk Spekreijse

On 13 May 1997 Professor L.H. van der Tweel died at his canalside house in Amsterdam, his beloved city where he was born on 20 March 1915 and spent all his life. Henk van der Tweel was scientifically active until the end of his life and gave his last lecture two days before his death for a group of foreign students at the Technological University in Delft. The title of that talk was 'A personal view of technical aspects in medicine', and is illustrative of his warm and cordial relations as a laboratory man with clinicians.

Henk van der Tweel obtained his MS degree in experimental physics at the University of Amsterdam in 1941 and started after the war to build electro-encephalographs and electro-cardiographs, the beginning of his continuous collaboration with neurologists, cardiologists and ophthalmologists. In 1955 he founded the Laboratory of Medical Physics, which he directed from 1963 onwards as Professor in Medical Physics until his retirement in 1984. In 1971 the Queen of The Netherlands appointed him a Fellow of the Royal Netherlands Academy of Arts and Sciences.

The two main themes in his scientific life were electro-encephalography and electro-cardiography. His main accomplishment in the first field was the reconstruction, together with the cardiologist Professor Dirk Durrer, of the activation of the left ventricle of the revived human heart by direct recording with 72 intramural electrodes with 10 recording sites per electrode. The results of this study in 1970 still form the basis of propagation of wavefronts in the human heart and will never be repeated since human hearts are now urgently needed for transplantation. In the second field, Van der Tweel introduced the system analytical approach in the study of vision. On the basis of his evoked potential work with pattern and luminance stimulation, he was, as early as 1965, able to conclude parallel processing from the retina on along the visual pathway in man (now known as the parvo-magnocellular pathways). His contributions in this field were acknowledged with a Royal Academy workshop at the time of his retirement, the proceedings of which were published in 1986 as a special issue of *Vision Research* and dedicated to him.

Henk van der Tweel remained interested in vision and was in the laboratory almost daily until the end of his life. Yet he was not only a great physicist but also renowned for his knowledge of the graphic arts, of which he had a fine seventeenth-century collection. With his death we have lost a friend and colleague whose warm personality, generosity and hospitality have been experienced by many. Henk van der Tweel will be remembered as much for his knowledge of history and his love of art as for his scientific insight.

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