studies in perception

DEDICATED TO M. A. BOUMAN

STUDIES IN PERCEPTION

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M. A. BOUMAN

INSTITUTE FOR PERCEPTION RVO-TNO

NATIONAL DEFENCE RESEARCH ORGANIZATION TNO

SOESTERBERG - THE NETHERLANDS

Instituut voor Zintuigfysiologie RVO-TNO
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PREFACE

In 1949 the Netherlands military authorities approached the National Defence Research Organization TNO for advice on personnel selection as regards capacity for 'night vision', i.e. visual perception at very low luminances.

The Board of the said organization took the ground that sensory perception, not only in this case, is an important facet of a military task. As a matter of fact it plays an essential and often critical part under many conditions of military practice and in a variety of ways. Following this line of thought the Board decided to establish a Working-Party for Perception. It was assigned to render advice and scientific assistance to the military authorities on the basis of available expert knowledge, and to perform applied and basic research with regard to problems of perception, arising from military practice. Initially this assignment emphasized work in respect of the execution of tasks and duties involving visual perception.

Looking around for a scientist, who would be capable and ready to conduct such a Working-Party, the attention was drawn to Dr. M. A. Bouman, because of his important investigations on the quantum explanation of vision, performed in the Physics Laboratory of the State University of Utrecht. To the Board's satisfaction Dr. Bouman consented to being leader of the envisaged Working-Party. The expectation that this new researchgroup would meet the needs of the military authorities, even though initially these needs had perhaps not yet been fully recognized, was found to be realistic.

Actually, the Working-Party was soon confronted with problems of auditive, as well as with those of visual perception. Moreover, along with matters pertaining to sensory physiology, the psychological aspects of observation and perception had to be tackled as well. Whereas complex technical equipment has to be handled in modern military practice, the Working-Party quite naturally came to devote attention to problems of human engineering and human factors research. In fact, Dr. Bouman was the first to coin a Dutch name for the branch of science which covers these fields of investigation: 'Technische Menskunde'.

After a few years the Working-Party had its special niche in the National Defence Research Organization TNO, and had gradually obtained an established position in the relations of this organization with the military authorities. Therefore, the Board decided, in 1956, to grant it the status of a research institute under the name 'Instituut voor Zintuigfysiologie RVO-TNO'. This institute, under Dr. Bouman's excellent direction, has meanwhile developed to one that is nationally and internationally well-known for its work in fields of sensory physiology, experimental psychology and human factors research.

To the Netherlands military forces, besides, this centre of scientific competence has proved to be an indispensable tool for solving their problems in these fields. The civil section of society can, through placing orders for sponsored research, likewise call on the facilities, experience and expert knowledge that are available in this institute for applied scientific research.

The scientific value of Dr. Bouman's work was acknowledged by his nomination, in 1962, as extraordinary professor at the State University of Utrecht. In 1964 he was appointed as ordinary professor in medical and physiological physics at the same University. In consequence thereof Professor Bouman will resign his office of Director of the Institute for Perception on December 31st, 1965. To the Board's great satisfaction two of his collaborators, Dr. P. L. Walraven and Mr. R. Plomp were ready to take over his task at the Institute for Perception as its Director and Deputy-Director respectively.

In view of the resignment of Professor Bouman, as director of the institute, his co-workers have conspired to write the present *Festschrift*. Through a number of studies, which are all related to studies carried out, or being in progress at the institute, they like to give an idea of the institute's scope. At the same time the compilers of this collection intend these studies to be a token of gratitude towards their director and of esteem for the institute's founder.

The Board of the National Defence Research Organization TNO welcomes this initiative and is pleased to enable the publication of this volume. In doing so, the Board avails itself of the opportunity to emphasize its respect for and appreciation of the important work which Prof. Dr. M. A. Bouman has performed, in the interest of our country and to the benefit of defence research as well as to that of science and society. The Board feels confident that the institute will continue its work in the same spirit under the guidance of the new direction.

G. J. SIZOO
Chairman of the National
Defence Research Organization TNO

CONTENTS

DEDICATION

When, in 1949, Maarten A. Bouman started what is now known as the Institute for Perception RVO-TNO, it was a one-man-one-room business, housed in the Physics Laboratory of the State University in Utrecht. Now, seventeen years later, he quits as director a fifty men institute – though he will stay on as advisor fortunately – and returns to his old University as professor in Medical and Physiological Physics. Thus can be described, in a nutshell, the history of the Institute. Inadequately, however, as it does not reveal how its growth was both in width and in depth. Because it does not make clear that it was Bouman's continuous drive for quality which gave the Institute credit in its most general sense.

Understandably we, whom he has made his collaborators in the Institute, wanted to prepare him a fitting farewell. And how could we better show our gratitude for what he induced in us, than by preparing a collection of studies in his field, the field of perception?

From the titles it will be clear that in our concept, perception is not restricted to sensory activity. One cannot study perceptual problems without looking at the response on stimuli, either verbal, motoric, or whatever. It is the whole chain from sensory input to motoric output, and the feedback of motor control, which we consider our domain of interest. Hence one will, for instance, find here studies on electroretinography and on perceptual motorload next to more typical sensory studies on tonal consonance and on colour discrimination.

At first sight this book may look quite a hotchpotch of papers, but it is fascinating then to discover how much they have in common, notwithstanding differences in subject and in approach. Apparently the close neighbourship of mainly physicists and psychologists in one institute has not missed its effect; it resulted in profitable interaction.

Fourteen men have co-authored in these studies. But, of course, many more members of the Institute have contributed directly or indirectly. To build equipment, perform experiments, and get a manuscript ready for printing calls for dedicated assistance by technical and administrative staff. We shall not mention here their names: they were too many. However, this farewell present to Bouman is a much theirs as that of the authors.

These studies on fundamental aspects of perception might look an unusual presentation for an Institute of Applied Scientific Research – as our institute is as part of the National Defence Research Organization. But 'pure' and 'applied' are not contradictory, but complementary in nature.

If Bouman has made anything clear in these seventeen years, it is the truth of this adage. The practical record of the Institute shows one side of the medal. These studies may show the other side.

I

THE FLUCTUATION THEORY OF COLOUR DISCRIMINATION

P. L. Walraven

The fluctuation concept of threshold vision has from the very beginning run as a red thread through the Institute's research programme. It is very appropriate, therefore, to open this collection with a reflective study of its most striking offshoot: the fluctuation theory of colour discrimination. An application of this theory is found, for instance, in the description of colour tolerances.
Details about the investigations incorporated in this study can be found in publications 111, 114, and 145 of the cumulative bibliography.

THE FLUCTUATION THEORY OF COLOUR DISCRIMINATION

P. L. Walraven

Theoretical work on luminance discrimination got a firm foundation from the contribution of De Vries (1943) and Rose (1948), who considered that a luminance difference ΔB might be at the threshold if ΔB was just in excess of the statistical quantum fluctuations in the background B. They explained the fact that $\Delta B/B$ is proportional to $1/\sqrt{B}$ over a large range of luminances. On those grounds this theory was developed to describe threshold behaviour only under quite simple experimental conditions, such as with small, short flashes (Van den Brink, 1957), and with only one receptor system participating. In more complex situations, complicating results from adaptation have to be taken into account. Bouman (1961) has given an extensive review of these matters.

Things get even more complicated, of course, when colour discrimination is considered since more than one receptor system is involved. Might it nonetheless be possible to apply the same basic idea here? In order to do so, one has to start with some well defined concepts of the mechanism of colour vision. Recent microspectrophotometric experiments on single cones (Marks et al., 1964; Brown and Wald, 1964) indicate that there really are three types of cones, with different visual pigments, just as had long been assumed, by proponents of the three-receptor model, from psychophysical evidence. On the other hand, electrophysiological evidence (Svaetichin and MacNichol, 1958; De-Valois, et al., 1962) has indicated that in the nervous transmission a brightness and two antagonistic chromaticness channels can be discerned. Thus, the old and competing model of opponent colour mediating systems (Hurvich and Jameson, 1955) was confirmed as well. A theory which takes both aspects into account was put forward by us a few years ago (Walraven, 1961). Before we can discuss the consequences of the fluctuation theory for colour discrimination, we will have to deal in more detail with this zone model of colour vision.

Zone model of colour vision

The essential features of our model of colour vision are represented in Fig. 1. The photopic retina is built up of 'red' (R), 'green' (G), and 'blue' (B) cones, in a ratio of roughly 10 : 10 : 1. The absorption curves assumed for these receptors are essentially those of Pitt (1944), cor-

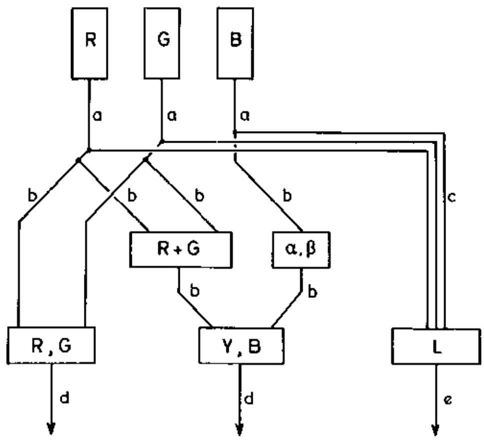

Fig. 1. Scheme of a zone model of colour vision.

rected for absorption by the eye media. The necessity for applying small corrections to these which take into account the new data on the luminosity curve, is discussed elsewhere (Walraven and Bouman, 1965). The ratios of the numbers of different types of cones are derived from the heights of the absorption curves under the assumption that the density per cone at maximum absorption is the same for all receptors. The differences in sensitivity of the three systems are thus attributed to different population densities. These different population densities are consistent with experiments by Brindley (1953) and by Blackwell and Blackwell (1960) which show low visual acuity if only the blue system is involved.

The brightness signal is taken as the sum of the brightness contributions of each of the cone systems. The brightness signal L is transmitted through channel e; the signals from the separate cone systems are transmitted separately to the point of summation through channels a and c. The chromaticness information on the other hand is transmitted through channels b, separate from the brightness channel. The information from the red and green cones goes to a red-green centre, from which the (R,G)-signal is transmitted to higher centres. We think of the yellow signal as the sum of the red and green signals: $R + G$. The blue signal is thought of as the signal from the blue cones multiplied by a chromaticness valence factor α. The value of α turns out to be approximately 10, as indicated by the properties of the Bezold-Brücke phenomenon (Walraven, 1961) and by colour naming experiments (Walraven, 1962). The yellow and blue signals are led to the yellow-blue centre, from which the (Y,B)-signal is transmitted to the higher centres.

The assumption that there are three different types of cones is based upon the long-known arguments of the Young-Helmholtz theory. We became more convinced about this theory by an analysis of the shape of the luminosity curve at the threshold (Bouman, 1950), by an analysis of the chromatic Stiles-Crawford effect (Walraven and Bouman 1960), and by an analysis of the change in shape of the luminosity curve after strong chromatic adaptation (Walraven, 1964).

Fluctuation theory for dichromats

Essential feature of the zone model diagramed in Fig. 1 is the existence of separate (R,G) and (Y,B) channels. This reminds one of the existence of two types of colour blindness: tritanopia and deuteranopia, which are just characterized by only one chromaticness channel. Tritanopes seem to be lacking the (Y,B) channel, deuteranopes the (R,G) channel. It is possible, therefore, to assume – and we will do so – that the normal observer is a kind of 'double dichromat', rather than a trichromat. For this reason we will first treat separately the more simple colour vision of tritanopes and deuteranopes. Using this treatment as an introduction to normal trichromatism, we will leave out of discussion protanopia. Suffice to mention that also here the (R,G) channel is lacking due to lack of the 'red' system.

Normally, in colour spaces, stimulus strength is plotted linearly along the axes. This provides an easy way to describe colour mixture laws.

However, to describe colour discrimination from a fluctuation concept, a square root plotting is definitely more appropriate. As

$$\Delta\,(\sqrt{n}) = \frac{d(\sqrt{n})}{dn}\;\Delta\,(n) = \tfrac{1}{2}\,\frac{1}{\sqrt{n}}\;\sqrt{n} = \text{constant},$$

fluctuation regions are represented by line elements of constant length, regardless of the stimulus strength. This is illustrated in Fig. 2.

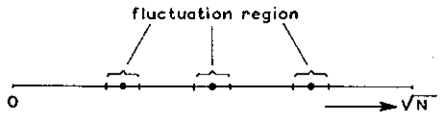

Fig. 2. The fluctuations cover a line element of constant length, if the square root of the stimulus strength is plotted rather than the strength itself.

In a two dimensional orthogonal plot, the elementary area of statistical stimulus incertainty becomes a circle of constant size. For tritanopia, we plot $\sqrt{\bar{n}_r}$ against $\sqrt{\bar{n}_g}$, $\bar{n}_r$ and $\bar{n}_g$ being the average number of quanta effectively absorbed by the 'red' and 'green' systems. In this plot, lines of constant luminance are represented by concentric circles around the origin ($\bar{n}_r + \bar{n}_g = \text{constant}$), whereas the radius vectors ($\bar{n}_r \,/\, \bar{n}_g = \text{constant}$) represent lines of constant wavelength. Now the fluctuation theory of colour discrimination says that only those wavelengths – read radius vectors – which are separated by elementary fluctuation circles can be discriminated from each other. Thus, just noticeable wavelengths differences can be found by a series of geometrical constructions. This is illustrated in the tritanopic square root plot of Fig. 3.

In this figure, the wavelength scale has been derived from the relative sensitivities of the 'red' and 'green' systems, according to the revised Pitt data. The resulting theoretical curve has been compared with experimental data in Fig. 4. The theoretical curve has been adjusted in height to obtain a best fit. Although Friele (1965) starts from nearly the same physiological concept, his basic assumption about discrimination is quite different, and leads to other results.

Wavelength discrimination in deuteranopia is a more complicated problem than was the case in tritanopia, because there is a change in wavelength discrimination with increasing luminance. This is illustrated in Fig. 5. The minimum in the wavelength discrimination curve gradually shifts from 460 to 490 nm with increasing light levels. A

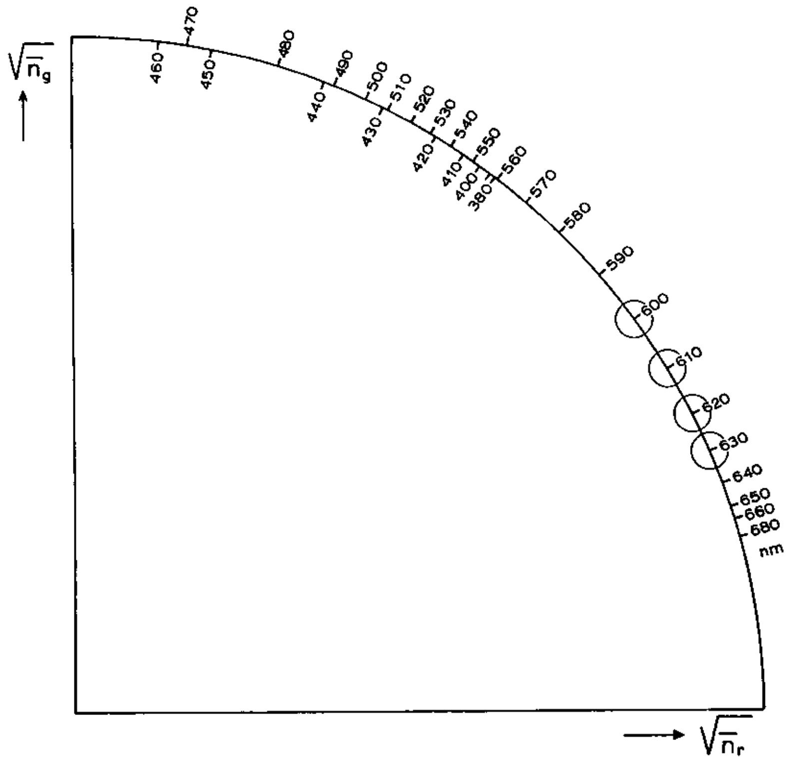

Fig. 3. Square root diagram for tritanopia.

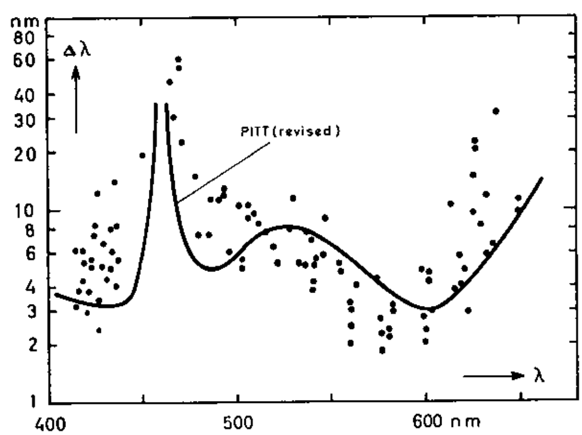

Fig. 4. Wavelength discrimination in tritanopia. Measuring points according to Wright (1952) and Fischer et al (1951).

similar shift was noticed earlier by Thomson and Trezona (1951) in protanopes, and by McCree (1960) and Weale (1952) in normal trichromats. Apparently such a hue shift occurs whenever the blue system is involved.

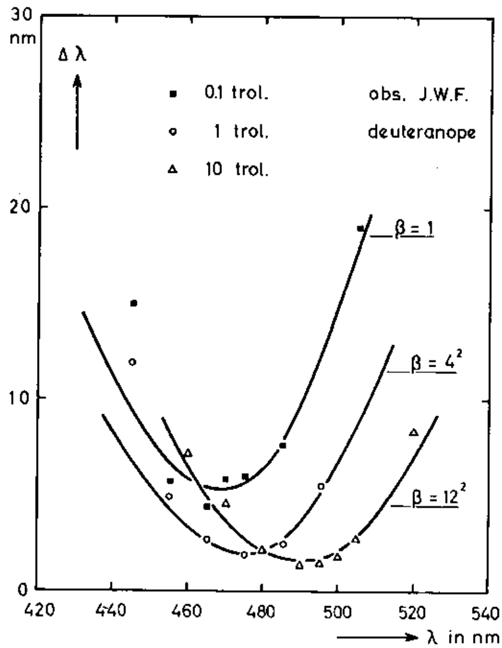

Fig. 5. Wavelength discrimination in deuteranopia at various luminances.

Fig. 6 shows the square root diagram for deuteranopia. According to a suggestion by Pitt (1944), the yellow signal has been taken as $1.3\ \bar{n}_r + 0.75\ \bar{n}_g$, to allow for the somewhat deviant luminosity of deuteranopes. The position of the minimum, and the shape of the wavelength discrimination curve correspond satisfactorily to the experimental data at the lowest luminances (Fig. 4, curve indicated by $\beta = 1$). To account for the shift in the wavelength discrimination function, however, we have to assume that the blue system gains more weight with increasing luminance. Rather than taking equal steps along a line of constant luminance $(1.3\ \bar{n}_r + 0.75\ \bar{n}_g) + \bar{n}_b =$ constant, we must take them along a line where $(1.3\ \bar{n}_r + 0.75\ \bar{n}_g) + \beta\bar{n}_b =$ constant, β being the weight factor for the blue system. This weight factor increases with increasing luminance. As is shown in Fig. 4, a satisfactory fit could be obtained by appropriate choice of β for each luminance.

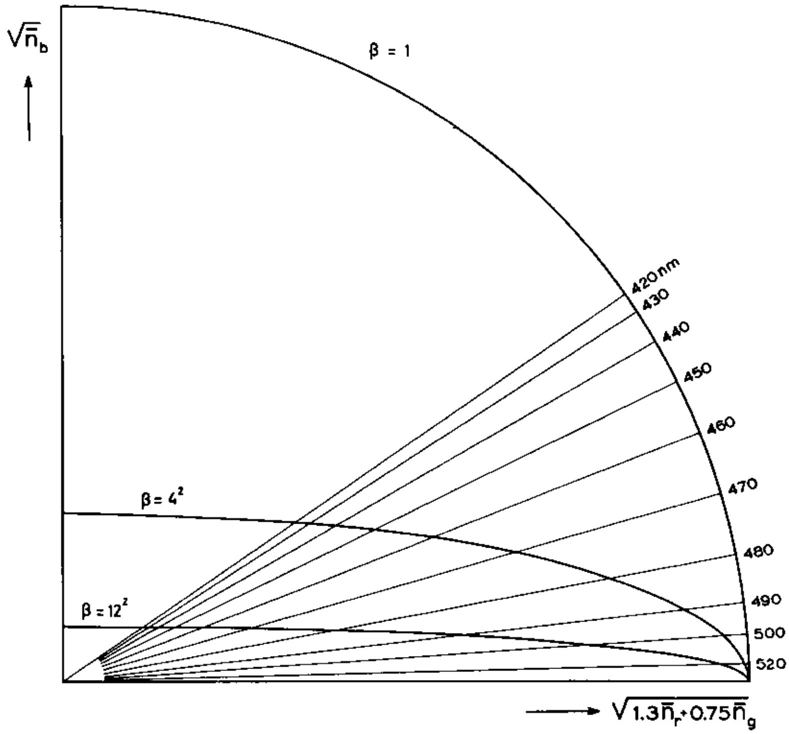

Fig. 6. Square root diagram for deuteranopia.

In introducing the weight factor β, we come to a point where we must recognize that we deal with physiological mechanisms as well as physics. The change in β, which is an adaptational phenomenon, tremendously complicates any theory of colour discrimination. β is expressed here as the square of another figure because we presume a relation to that other weight factor, α, mentioned in the foregoing section. By accident, or by system, β_{max} just about equals α^2. Since this relation is anything but clear at the moment, we will not enter into a comparison here.

Fluctuation theory applied to normal trichromatic vision

To describe the colour discrimination of normal trichromats, we must switch to a three dimensional square root plot in which the domains of statistical stimulus incertainty are represented by elementary spheres of constant size. This is a purely physical description, however, and does not take into account the consideration that trichromasy is a state of double trichromasy, a mixture of deutera- and tritanopia. This means that we must consider the red-green and the yellow-blue directions as essentially independent; in other words, the sections of the fluctuation domains with the sphere of constant luminance do not need to be circles, but may be ellipses. As a matter of fact, the extent to which it must be an elipse in order to explain the experimental findings (k_2/k_1 be the ratio of the axes) depends on the size of the stimulus field upon the retina (Fig. 7).

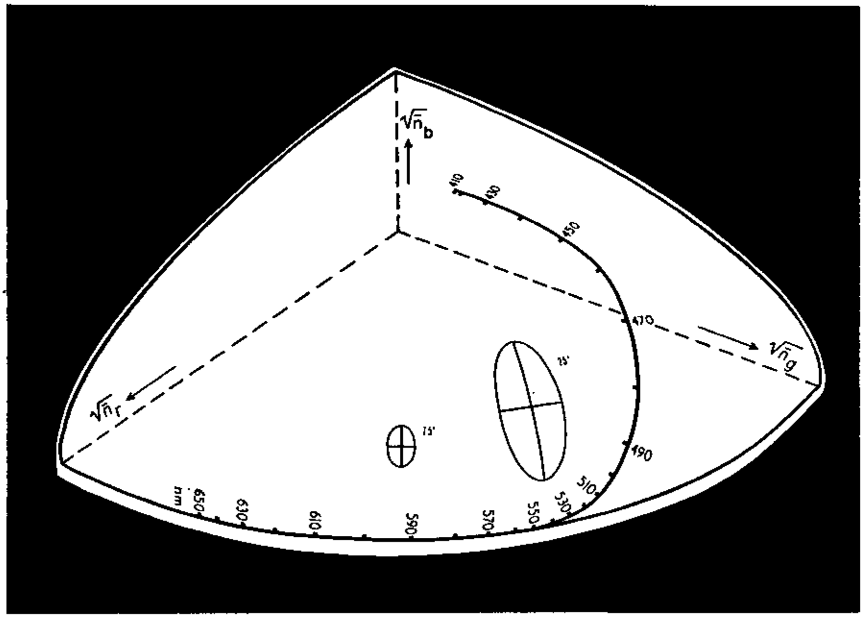

Fig. 7. Three dimensional square root diagram. It contains an ellipsoidal surface on which the fluctuation areas can be measured (compressed equi-luminance sphere over a factor β), and elliptical uncertainty areas because of the independence of the deuteranopic (Y,B) and tritanopic (R,G) systems. The extent to which the uncertainty areas are eliptical depends on the size of the stimulus field.

Furthermore, we have to assume that the sphere of constant luminance collapses with increasing luminance by a factor β in the vertical direction as far as colour discrimination is concerned, just as was postulated for deuteranopia. The fluctuation areas therefore have to be measured upon a strongly flattened ellipsoid at higher luminances.

As long as the discussion of colour discrimination is restricted to wavelength discrimination we do not even need a three dimensional plot. It suffices to superimpose the curves of Figs 4 and 5, with appropriate heights and an appropriate choice of k_2/k_1. The results of such a procedure, together with experimental data to be explained later, are shown in Fig. 8. The uncertainty domains have been assumed to become increasingly elliptical with decreasing stimulus size, as indicated in the inset of Fig. 8. This produces foveal tritanomaly.

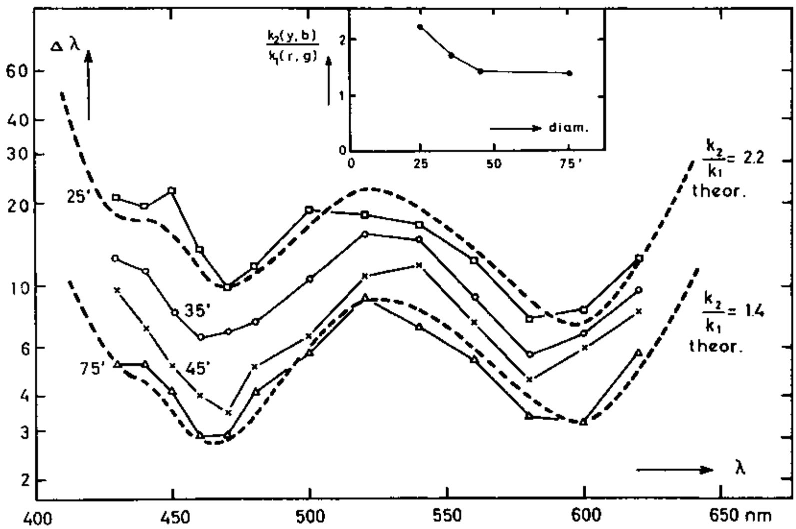

Fig. 8. Wavelength discrimination at a low retinal illumination level (0.85 trol), with stimulus size as parameter. $\beta = 3^2$.

When we consider colour discrimination inside the spectral locus, we have to use the three dimensional square root plot again. The best, and best known, experimental data upon hue and saturation discrimination inside the colour triangle are those of MacAdam (1942) (Fig. 9).

The theory gives a satisfactory description of the experimental ellipses given an appropriate choice of β and k_2/k_1, as indicated in the graph. Since MacAdam obtained the discrimination ellipses at a high luminance, a high value of β is necessitated.

The good agreement between theory and experiment is surprising, because the theory is restricted, by its nature, to those luminances where the de Vries-Rose law is valid. At the luminances MacAdam used Weber's law, not the de Vries-Rose law applies. Nevertheless

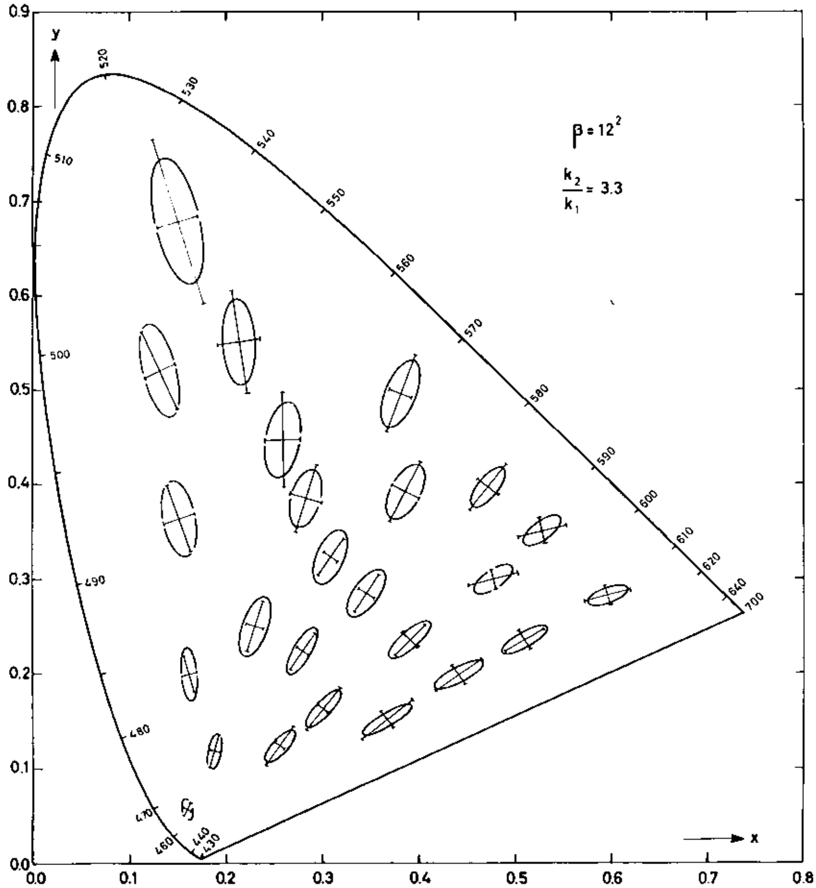

Fig. 9. The CIE colour mixture diagram with the experimental McAdam ellipses (indicated by the axes), and the theoretical ellipses (drawn) according the fluctuation theory.

application of the fluctuation theory reveals a good fit to the experiments. Bouman et al. (1963) tried to set Weber's law in the fluctuation theory framework by postulating the saturation of the nerve channels. Many questions are still unanswered, and much more work must be done to understand colour discrimination as a function of relevant parameters. It is clear, however, that it is impossible to give a good description of colour discrimination without taking into account the physiological mechanisms of colour vision.

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II

THE EAR AS A FREQUENCY ANALYZER

R. Plomp

In vision the resolving power of the eye plays an important role. In analogy to it the ear can be characterized by the degree to which it discriminates between tones sounding simultaneously. It is obvious that the ability to recognize so many different sounds in speech and music we owe for a large part to this frequency-analyzing power. About the limits of this power, however, the experimental data are scarce. In the following study the results of an investigation are communicated indicating that tones can be heard separately only when their frequency distance exceeds the so-called critical bandwidth.
Detailed experimental data about this investigation can be found in publication 138 of the cumulative bibliography. A monograph covering the present subject in context of other, related, subjects, is in preparation.

THE EAR AS A FREQUENCY ANALYZER

R. Plomp

In 1843, Ohm formulated his definition of tone, stating that a tone with frequency m is heard only when the sound contains $\sin 2\pi\,(mt + p)$ as a component (Ohm, 1843). This definition, known as Ohm's acoustical law, implies that periodic sound waves are analyzed by the hearing organ in a similar way as periodic functions can be analyzed mathematically in a series of sinusoids by applying Fourier's famous theorem. In fact the law says that the ear has to be considered as an ideal frequency analyzer, in other words, as a very large set of very small bandfilters.

Helmholtz adopted this definition and used it as a basis of his theory on the perception of tones (Helmholtz, 1863). Because of the fact that, for small frequency distances, two simple tones (sinusoids) give rise to beats by interference, he assumed that the analyzing power of the hearing organ is limited. In view of the ear's high sensitivity to frequency differences, however, Helmholtz considered the filterbands as rather narrow. This opinion was accepted by many investigators after him.

Apart from a few incidental statements about the number of harmonics that some investigators could distinguish in complex tones as produced by musical instruments, all dating from the 19th century and before, there are no experimental data available concerning the frequency-analyzing power of the ear. Since this capacity may be considered as one of the basic properties of the hearing organ, some experiments, determining to what extent complex sounds can be discriminated, were carried out in order to obtain more insight in this question.

In the first experiment subjects were presented with multitone stimuli consisting of 12 simple tones at equal loudness level of about 60 phon (normal listening-level of speech and music). In one condition the frequency ratios between the partials were 1 : 2 : 3 : 4 : 5 : 6 : 7 : 8 : 9 : 10 : 11 : 12 and in another condition 1.00 : 1.95 : 2.85 : 3.70 : 4.50 : 5.25 : 5.95 : 6.60 : 7.20 : 7.75 : 8.25 : 8.70, so that the tones were ordered harmonically and inharmonically, respectively.
As the discrimination of tones is a difficult task, it was necessary to facilitate it as much as possible by calling attention to the pitch of any tone that could be audible individually. Moreover, a reliable criterion of judgement was wanted. After some trials, a method was chosen satisfying both requirements. This method is illustrated in Fig. 1. The subject had at his disposal a switch with three positions,

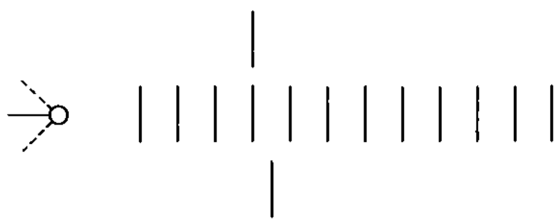

Fig. 1. Illustration of the method used to determine the audibility of partials of a multitone stimulus.

indicated schematically at the left. In the middle position the multitone stimulus (vertical lines) was heard. In the other two positions of the switch, simple tones were audible, one of them with the same frequency as a tone of the complex and the other one with a frequency just between this partial and the next higher or lower one. The subject was allowed to switch over freely from one position to another, so that he could listen to the three stimuli in any order. In a forced-choice procedure, he had to decide which of the two simple tones did coincide in pitch with one of the partials of the complex of tones. The *a priori* chance to give a correct response was always 0.5, so the *a posteriori* chance varied between 1 and 0.5, corresponding to 100% audibility of the partial and 0% (response completely guessed), respectively. By shifting the frequencies of the comparison tones over the relevant frequency range the audibility of each of the 12 partials could be tested at random order.

In a typical test session the experiments were carried out, also in a random order, for 11 different frequencies of the lowest partial of the multitone stimulus between 64 and 2000 cps. The stimuli were presented monaurally by headphone. The tests were repeated five times and the responses averaged. Two subjects were involved in the measurements, both trained in advance to exclude learning effects. Figure 2 shows how for the harmonic complexes the percentage of correct responses, averaged over the 11 different frequencies of the lowest tone (fundamental), varied as a function of partial number. As it appeared that in most cases the responses for the 9th and higher partials were completely guessed, generally no more than the first 8 harmonics were examined. The graph demonstrates that the percentage of correct responses gradually decreased as a function of partial number. Accepting 75% correct responses as a criterion of the audibility of a partial, we may conclude that, on the average, the first 5 to 6 harmonics were distinguished individually.

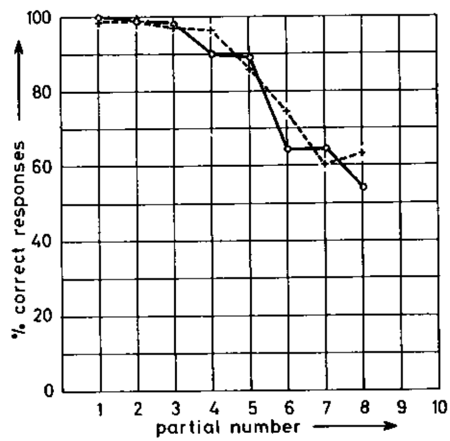

Fig. 2. Percentage of correct responses as a function of partial number for complex tones, averaged over 11 different frequencies of the lowest partial. The symbols correspond with two subjects.

In Fig. 3, the number of distinguishable partials is plotted for each frequency of the fundamental separately, averaged over both observers. The lower and upper ends of the vertical dashes correspond with 92% and 58% correct responses, respectively. If the transition from 100% to 50% correct responses may be considered as an integrated Gaussian distribution, the dashes represent its standard deviation.

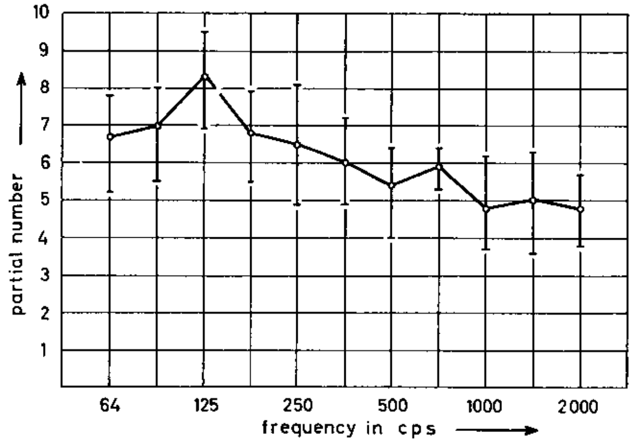

Fig. 3. Number of distinguishable partials of a complex tone as a function of the frequency of the lowest partial, averaged over two subjects. The points correspond with 75%, the vertical dashes with 58% and 92% correct responses.

The experimental data can also be interpreted in another way, more directly related to the ear's analyzing power. This can be illustrated by the following example. Figure 3 indicates that for a fundamental of 250 cps 75% correct responses corresponds with partial number 6.5. This means that at $6.5 \times 250 = 1625$ cps the frequency distance between partials must be more than 250 cps for hearing the partials individually. This critical frequency difference may be considered as a measure of the ear's analyzing power at 1625 cps. On basis of the data points of Fig. 3 this critical value was also calculated for other frequencies. The results are reproduced in Fig. 4 (open points). The most left-hand point corresponds with an additional measurement with 44 cps as the lowest partial in which case only the fundamental could be distinguished. Because it is not improbable that the audibility of this tone was due to the fact that its pitch coincides with the pitch of the complex tone as a whole, the minimum frequency difference required to distinguish partials may be larger than indicated by the data point; this is symbolized by the arrow.

In the same way as for the harmonic tone complexes, the critical frequency difference required to 'hear out' the partials of the complexes of inharmonically related tones was determined. The results are reproduced by the solid points of Fig. 4. The fact that both the solid and open points can be fitted very well by the same curve (dashed line) demonstrates that the audibility of partials out of a complex of

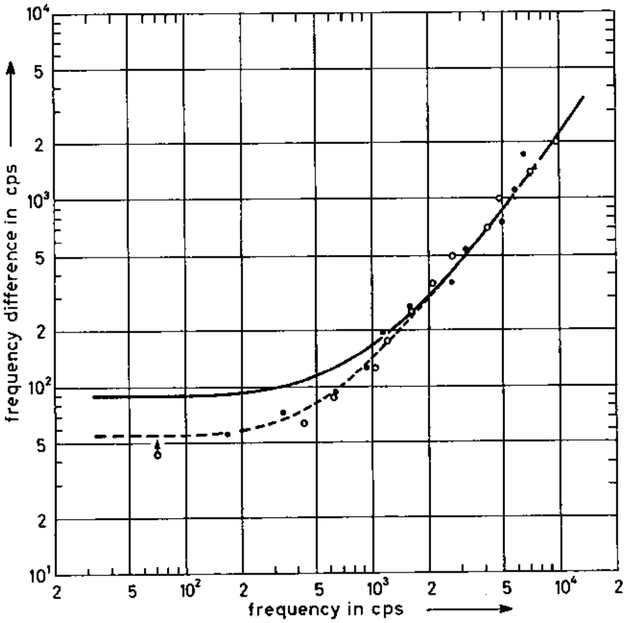

Fig. 4. Frequency difference between the partials of multitone stimuli required to hear them separately. The open points represent the values for complex tones, the solid points for inharmonic complexes of tones. The solid curve represent the critical bandwidth as a function of frequency, after Zwicker, Flottorp and Stevens.

tones does not depend on the question whether or not the partials are related harmonically.

During recent years, the concept of critical band has proved to be of basic significance in hearing. Many investigators have shown that the ear's behavior in response to acoustic stimuli with a frequency spectrum exceeding the critical band is different from its behavior to stimuli not exceeding this band (Scharf, 1961). This applies to the absolute and masked threshold, the ear's sensitivity to phase and to loudness summation. The width of the critical band as a function of frequency, as proposed by Zwicker, Flottorp and Stevens (1957), is given by the solid curve of Fig. 4. Above 1000 cps this curve is in excellent agreement with the data points; below that value the points would predict a somewhat smaller bandwidth. It is an open question, however, whether we have to attach any value to this discrepancy. Below 500 cps there are not much data available, both in the experiments on which the critical-bandwidth curve is based and in our experiments. For that reason it seems to be justified to conclude that the partials of a complex of tones can be distinguished only if their frequency separation exceeds the critical bandwidth. This supports the view that critical bandwidth has to be considered as one of the most fundamental properties of the hearing process.

Masking pattern of a complex tone

Another approach for investigating the ear's analyzing power is to carry out masking experiments. During the last decades the degree to which a simple tone is masked by another tone or a band of noise has been studied extensively and the resulting masking pattern, defined as the threshold shift as a function of frequency, is usually considered as a measure of the extent of the excitation pattern on the basilar membrane. Therefore it appeared to be of interest to investigate the masking pattern of a multitone stimulus.

The masking pattern of a complex tone of 500 cps was determined by measuring, as a function of frequency, the threshold shift of a short tone pulse presented immediately after the stimulating pulse. This method was chosen in order to avoid the interference of the two signals (beats) when presented simultaneously. The threshold-shift values were

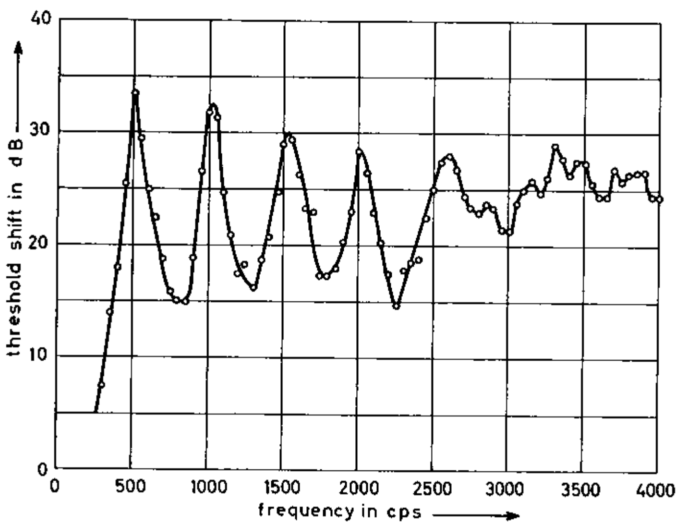

Fig. 5. Masking of a tone pulse of 20 msec presented immediately after a 200-msec pulse of a complex tone consisting of the first 12 harmonics of 500 cps. The points indicate the average values of four subjects.

measured by following a two-alternative forced-choice procedure. The complex tone consisted of the first 12 harmonics of 500 cps at equal-loudness level (loudness level of the complex tone about 60 phon). The duration of the complex-tone pulses was 200 milliseconds (msec) and of the simple-tone pulses 20 msec. The threshold shift of the latter pulse due to the presence of the complex-tone pulse was determined for all multiples of 50 cps between 300 and 4000 cps. The measurements were made monaurally by means of a headphone. To minimize the effects of individual irregularities in the hearing threshold, the experiment was carried out by 4 subjects, the subjects used in the preceding experiments included.

Figure 5 represents the results averaged over the subjects. The graph shows that peaks in the masking pattern do only correspond with the first 5 harmonics. This limit is equal to the number of distinguishable harmonics of a 500-cps tone (Fig. 3) and confirms the hypothesis that the limit of the ear's analyzing power is given by the critical bandwidth.

Discussion

The finding that the ear is able to discriminate partials of a complex of tones only when their frequency distance exceeds the critical bandwidth supports the hypothesis that these bands correspond with the width of the peaks of the excitation pattern of simple tones on the basilar membrane. Although there is ample evidence nowadays that Helmholtz's view of the cochlea as a frequency analyzer was correct, his opinion that the basilar membrane has to be considered as a large set of sharply tuned resonators has been rejected, both on anatomical and physiological grounds. Experiments of von Békésy have shown that simple tones, in particular at low frequencies, stimulate a large part of the basilar membrane with a rather wide maximum (von Békésy, 1943). As it is very difficult to imagine in which way the nervous system would be able to discriminate the partials of a complex of tones, especially when they are related inharmonically in which case there are neither integer frequency ratios nor fixed phase relations between the partials, it is much more likely that this discrimination must be identified with the spatial spread of the maxima on the basilar membrane.

On the basis of the experimental results for multitone stimuli we may expect the significance of critical bandwidth as an underlying mechanism of other discrimination tasks of the hearing organ. For example, it is not improbable that speech sounds, too, are discriminated on the basis of the relative loudness of the frequency components in different critical bands. In this respect it is of interest that the frequency range important for speech recognition corresponds with about 14 critical bands in total, whereas it is found empirically that a comparable number of band filters is sufficient to extract the information-bearing elements of speech sounds (in channel vocoder systems; cf. Flanagan, 1965). Experiments to investigate more extensively the relevance of critical bandwidth in speech perception are required before a definite answer can be given.

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III

PERIPHERAL VIEWING AND COGNITIVE ORGANIZATION

A. F. Sanders

The peripheral visual system may seem little endowed in comparison with the foveal region, its function as to reconnaissance and detection can hardly be overrated. In complex man-machine systems – a cockpit for instance – adequate digestion of the continuous stream of incoming information is possible only thanks to the acquisitive function of the periphery. It is obvious that, with increasing automation and thus with increasing perceptual load upon man in the man-machine systems, a better understanding is urgent of the role of peripheral viewing and visual strategy.
The present study is largely based on investigations about which is communicated in more detail in publications listed under no. 135 and 154 in the cumulative bibliography.

PERIPHERAL VIEWING AND COGNITIVE ORGANIZATION

A. F. Sanders

Most research on display design has been carried out under conditions of central viewing. Usually the object under investigation – a pointer, for instance – is presented tachistoscopically at a known position. The best pointer is the one that can be seen optimally, and discriminated at a very short presentation. This situation is, of course, quite different from the actual practice in more complex man-machine systems – a cockpit for instance. Here, the bigger part of a continuous stream of information reaches the periphery rather than the fovea. Only by successive fixations of the eye is there a possibility of foveal processing – if the information is that long available. This would mean that peripheral detection of relevant signals – eventually followed by an eye fixation for more detailed analysis – is important to ascertain optimum performance. Consequently, an analysis of the conditions under which peripheral detection may occur, is indicated.

The argument may seem straight and logical and the problem is generally recognized. Mostly there has been a tacit assumption, however, that peripheral viewing will add little, if any, to the operator's performance. This conviction was primarily based on two categories of data: the rapid drop of visual acuity outside the fovea – e.g. Chapanis (1949) – and, secondly, the failure to identify individual elements in a group, when the whole is peripherally presented – summarized by Woodworth and Schlosberg (1954). It has been known for long, of course, that the peripheral system is sensitive enough to detect movement and also objects in the dark, but these principles are scarcely applied in display design. But even if it is restricted to static signals under normal illumination, peripheral viewing may show less deficient than expected. This is emphasized by a number of recent studies. Senders, Webb and Baker (1955), for example, studied peripheral reading of dials and found an almost perfect discrimination between pointer positions, when the instrument was displayed at 40° from the line of sight. Even at 80°, performance was better than would have been predicted on a chance basis. The experiment was conducted in view of the observation that pilots spend less time to read a particular dial than do subjects in a laboratory study. The important hypothesis was developed that the peripheral image of a dial on the retina would still convey some information, so that at least an expectancy could arise about the position of the pointer before actual fixation. If this were true – and the results supported the validity of the hypothesis – fixation of a target would have the meaning of a verification of an existing hypothesis, rather than of a new percept. A similar idea is found in recent work by Poulton (1963). In an experiment on reading, subjects read typescript that was presented through a window. Size of the window and speed of presentation were varied. Errors increased significantly, when the size of the window was reduced from a full line to five words. Apparently, some information about new words can be obtained while processing earlier ones – and this on the basis of peripheral vision[1].

The present author (Sanders, 1964) has found expectancies on the same basis in a reaction time setting. When two signals are presented simultaneously, the reaction time to the first signal, Rt_1, is considerably longer than that to the second signal, Rt_2. Rt_1 is only slightly longer than Rt, while Rt_2 is considerably shorter than Rt – i.e. the reaction time when only one signal is given. The two signals both consisted of a column of dots (dot diameter 1 cm; distance between dots 1 cm; distance of observation 70 cm), which contained either four or five dots with equal chance of occurrence. So Rt_1 and Rt_2 were both 1-bit choice reaction times. The signals were given at eye level, and under a systematically varied visual angle. Subjects were instructed

[1] The peripheral nature of the expectancy has to be stressed, since other expectancies are possible on the basis of sequential redundancy of the reading material. Also in the dial experiment, pilots may spend less time because they have a prefixed expectancy on the basis of prior experience, (e.g. Senders, 1954). Poulton made the useful distinction between 'receptor anticipation' and 'perceptual anticipation', when dealing with expectancy in a tracking situation.

to respond to the left signal, S_l, before shifting the eye to the right one, S_r, which instruction was controlled by measurement of eye movements. Thus the reduction of Rt_2 must be due to at least a partial processing of S_r before actual fixation. This can occur together with processing S_l or possibly during the eye shift. The latter hypothesis seemed to be less attractive however because perception is known to be strongly suppressed during eye movements (Latour, 1962) and it could, more directly be rejected in a later experiment (Sanders op. cit. pp. 90-92).

The results of the reaction time experiment – means for six subjects – are shown in Table 1.

TABLE I. Rt, Rt_1, and Rt_2 – averaged over six subjects – as a function of visual angle. M indicates the time to move the eye from the left to the right signal.

Display angle	Rt_1	M	Rt_2
12°	.63	0.04	.37
24°	.61	0.06	.34
47°	.56	0.11	.36
77°	.56	0.16	.40
99°	.54	0.22	.50
Rt	.53		

The data show that the reduction of Rt_2 has almost disappeared at the largest visual angle (99°). In that case $Rt = Rt_1 = Rt_2$ (approximately) as should be expected, when the subject carries out two independent reactions. Apparently, no expectation about S_2 could be obtained at angular distances of that size. This deduction was tested as follows: Again, two signals (S_l,S_r) were presented simultaneously. After responding to S_l, an eye shift to S_r was made in the usual way. However, at a certain moment during these activities S_r was taken away, so that no actual fixation of S_r could take place. The task was to judge S_r – i.e. whether this signal had either four or five dots. The results of this study are summarized in Table II.

The pertinency of the interpretation of the previous experiment is confirmed clearly by the data of Table 2. A significant number of correct judgments is made when the visual angle is less than about 85°. Every judgment was accompanied by a confidence rating on a five points scale. It appeared that most ratings were quite low – i.e. they

TABLE II. Summary of the statistical significances (χ^2) of the correct judgment of the right signal (S_r) as a function of visual angle and eye position. Eye position denotes the position of the eye at the moment that S_r disappeared. Four categories were discerned. I: S_r disappeared at least 0.08 sec before the eyeshift started. II: Ditto, but between 0.00 and 0.08 sec. III : S_r disappeared during the eye movement. IV : S_r disappeared after the eye had reached S_r.
— = not significant ($p > 0.05$); + = $p < 0.05$; ++ = $p < 0.02$;
+++ = $p < 0.01$; . = too few measurements to decide.

	Visual angle							
	66°				81°			
Subjects	JM	ThE	AS	BS	JM	ThE	AS	BS
Eye-position:								
I	.	+++	+++	.	.	.	+	—
II	+	+++	++	+++	—	+++	+++	—
III	+++	+++	+++	+++	+++	+++	+++	+
IV	+++	+++	+++	+++	+++	+++	+++	+++

	88°			94°		99°
Subjects	JM	ThE	BS	JM	AS	AS
Eye-position: I	—	—	—	—	—	—
II	—	—	—	—	—	—
III	+++	—	—	—	++	—
IV	+++	+++	+++	+++	+++	+++

expressed a large subjective uncertainty in spite of the high percentage of correct judgments (see Sanders op. cit. p. 90). Accordingly, the data show that the judgments have the character of an expectation, and sometimes a very vague one, that has to be checked by a fixation before the subject will respond. These results were checked and found useful, in a large number of other studies, in which also quite different stimulus contexts were used. All these experiments demonstrated the expectancy phenomenon within certain definite limits of visual angle. The value of this perceptual limit proved to be dependent on the complexity of the task. Therefore, the present value of about 85° is strictly bound to the stimulus context that was used. In more difficult tasks, this area was considerably reduced, while it was extended in still easier situations. The important feature of this perceptual limit is that it coincides with the visual angle at which head movements start

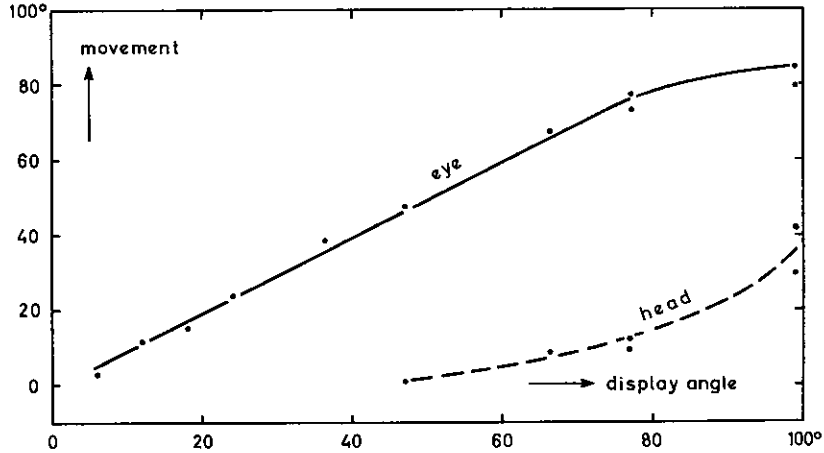

Fig. 1. Eye and head movements as a function of the visual angle between the left and right stimulus.

to play a substantial role in the shift from S_l to S_r. This is demonstrated in Fig. 1, which gives the results of simultaneous measurements of eye and head movements.

The increase of the saccadic eye shift as a function of visual angle suggests a complete coverage of the path between S_l and S_r until 80°. The small head movements between 40° and 80° are counteracted by a compensatory eye movement, as illustrated in Fig. 2. Beyond 80° they play a supplementary role, however, and 80° is very near the 'expectation limit'. Therefore, in this case at least, expectations can be only obtained in the angular area that is covered by the mobile eye (eye field). The same was found in other experiments, where head

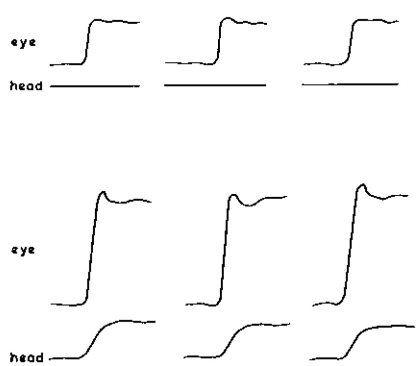

Fig. 2. Samples of recordings of eye and head movements from S_l to S_r.

movements occurred only beyond the critical expectation limit. 'Eye field' can be distinguished from 'head field', which will indicate the area where head movements are a necessary supplement and where no expectancies arise.
There are indications that the same principles will hold, when more than two signals are presented simultaneously. It is postulated that an expectation will be obtained about all signals, if the total display is within the limits of the eye field. In one experiment six dot columns were presented: five contained four dots and one had five dots; the task was to find the location of the latter (see Fig. 3). The subject had to press the corresponding response key, which was immediately followed by a new presentation. This task was carried out for eight minutes without interruption, and performed under various display angles (68°, 81°, 94°).

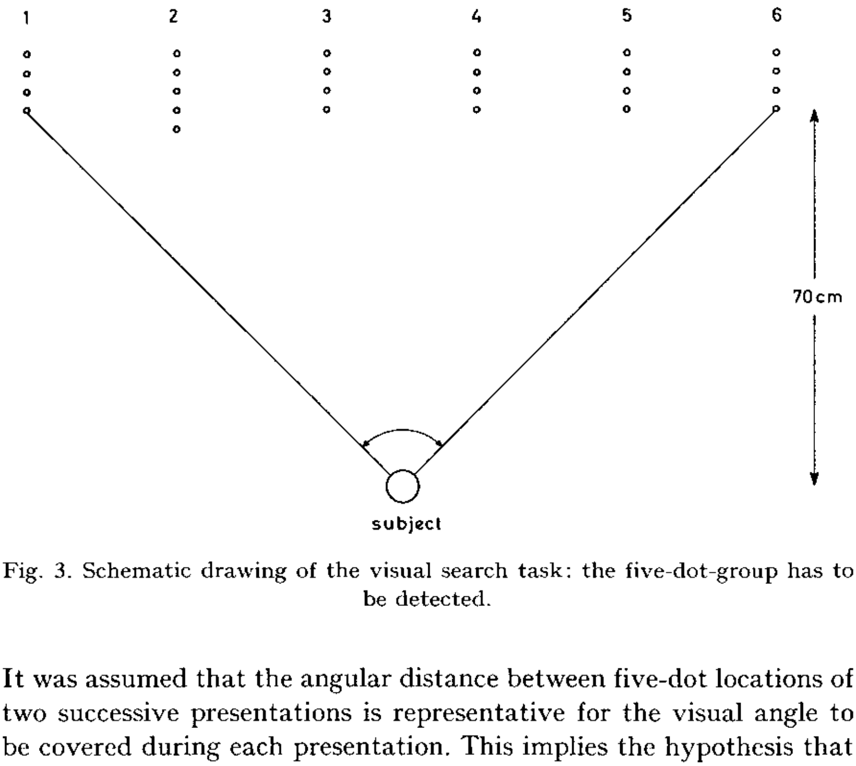

Fig. 3. Schematic drawing of the visual search task: the five-dot-group has to be detected.

It was assumed that the angular distance between five-dot locations of two successive presentations is representative for the visual angle to be covered during each presentation. This implies the hypothesis that subjects will start search at the location where the five dots were most recently present.
The visual angle was thus determined for every pair of successive

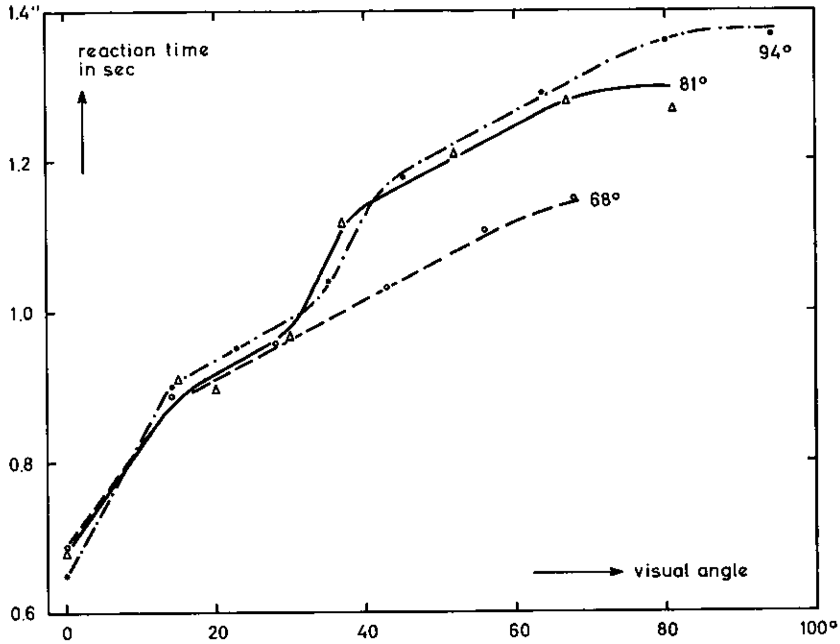

Fig. 4. Reaction time as a function of visual angle-to-be-covered in two successive presentations.

signals, and reaction times at equal or nearly equal visual angles were averaged. The results of this analysis are given in Fig. 4.
The reaction time is relatively short at a visual angle of 0° – indicating the same location at two successive presentations – and this result supports the assumption that subjects start inspection at the previous five-dot location. The speed of the reaction suggests that no search has been involved. With a total display angle of 68° there is a linear relation between reaction time and visual angle, disregarding the zero angle value, of course. When the time to move the eye directly from one to another location is subtracted from the reaction time – by taking the values of Fig. 1 – only a small increase as a function of visual angle is left. This suggests that subjects have not much more difficulty to detect the signal when it is at the same angular distance than when it is fairly near.
The theory of the functional visual field assumes that, after presentation, the subject acquires hypotheses for all locations. The location with the highest expectation is checked first, so that no dramatic time differences between the visual angles are to be expected. The hypothe-

sis for the locations at small visual angles may be more outspoken, thus leading to a more rapid decision to check that location. Any model that does not incorporate peripheral information would predict a much steeper increase of reaction time, since it must assume a number of new percepts, each providing only information about one specific location. Direct measurements of eye movements were not feasible in this study. Head movements were measured, however, and showed that the head field is entered between 68° and 81°. According to the theory, it will be impossible to obtain a complete expectancy pattern under these conditions. Thus the area is split up in two parts. About one area – covering 40° approximately – hypotheses are obtained and checked so that, when the five dots are within this area, the reaction times are no longer than when the total display is within the eye field (see Fig. 4). If the critical signal is not in this area, the remainder of the field is inspected. This implies a new process of hypothesis formation and checking, and, therefore, it is time consuming. The increase of reaction time around 40° at 81° and 94° display angle, is explained in this way.

The theory, following these studies, states that after arrival of new information, a certain period of time is devoted to 'expectancy formulation'. This period will be dependent on the number of signal sources and probably, on the amount of information that is provided by each of them. In the present study, it could be estimated to take some 200-300 msec – being the difference in *Rt* between the 0° and 14° presentations. It is supposed that the eye will only start moving after this initial period, and will carry out a number of rapid checks. Head movements, if any, will appear still later in the process. In one experiment, eight items were presented simultaneously in order to be memorized. Eye and head movements were both recorded. Evidence was found indeed for an initial 'viewing' period. This period was considerably longer than a primary reaction period (Sanders op cit. p. 145). The period proved to be independent of the presentation time, and this should be the case if it were to be considered as a sort of basic time, laying the foundation for the search process to follow. It is supposed that during the viewing period, a sort of unified perceptual sampling process is going on. The quantity that is sampled will have some maximum, depending on the information-per-signal source and the number of signal sources. Although no research on these points can be reported, the following may be essential.

1 With more information per signal source, the expectancies may become less pronounced and will become useless to prepare a response before precise fixation;
2 With much information in the signal source, which happens to be centrally inspected, the sampling capacity may be completely filled, so that no other expectations can be transmitted at the same time;
3 With too many signal sources a memory problem may arise. Following Mackworth (1965) it might be assumed that the material, sampled over signal sources, is stored in a short term memory. This memory might be identical to Sperlings 'visual image' (Sperling, 1960), which is characterized by a large capacity and a very rapid decay of the material. There are indications that the data are successively processed from the visual image (e.g. Mackworth, 1963). When too much information is present, decay may prevent the use of the last part of the material.

These remarks emphasize three important factors in the processing of, peripherally presented material which probably constitute as many limitations. They are reduced discriminability, limited channel capacity for transmitting information and, finally, memory restrictions. In some way, these three factors, and perhaps more, cooperate to produce the present picture about handling peripheral information: A considerable funnelling to the central area when 'too much' is present, and on the other hand, a reasonable peripheral handling when 'not too much' is given.
It will be clear after this discussion that, under a number of circumstances, peripheral information can be very important for the human operator who is inspecting a multi-source display. The expectancy principle guarantees continuity of successive perceptual samples, and provides order and plan in the visual scanning process.

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IV

A MODEL FOR THE SCOTOPIC ELECTRORETINOGRAPHIC SYSTEM

A. Troelstra* and N. M. J. Schweitzer

The perceptual system has many times been compared with a 'black box'. We put the subject questions, we get to know the answer. And from this experimental play of question and answer we have to guess what is inside the box. The black box of the visual system yields some of its secrets in the electric potential which can be derived from the intact eye. This 'electroretinogram' tells only a small part of the story, but any information about what happens between receptor and cortex may increase our knowledge about the intricate mechanisms which convert light to sensation.
The experimental material is more extensively reported in the publications 125, 129, 137, and 144 of the cumulative bibliography.

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A MODEL FOR THE SCOTOPIC ELECTRORETINOGRAPHIC SYSTEM

A. Troelstra and N. M. J. Schweitzer

Among the several objective methods available to probe the visual system, electroretinography has its special merits: recordings can be obtained from the unopened eye, and the respons bears a direct, though highly complicated relationship to the stimulus. Since several characteristics of the electroretinogram (ERG) resemble phenomena encountered in visual perception, the study of the easily accessible electrical response has an heuristic value in the interpretation of psychophysical data.

The intricate relationship between the ERG and the parameters of the stimulus requires a basic understanding of the way these variables interact and finally determine both shape and amplitude of the response. Faced by such problems the investigator often turns to the construction of a model in the hope of obtaining an insight into the experimentally found input-output relationships. In the next sections we will describe certain basic aspects of one such model, and show how its several parameters can be determined in a particular situation. At the end we will give some examples to show how it can be applied to predict certain interesting ERG responses of the scotopic system.

Choice of a model

It can be shown that any model must contain at least two elements, a linear low-pass filter, L, and a non-linear element, N, which is only amplitude dependent. The linear filter is required in order that the system complies with Talbot-Plateau's law for electroretinography.

This law, formulated already in 1834 for the perceptive system, states that a light, flickering at higher than the flicker fusion frequency, has a brightness, equal to that of a constant light stimulus of equal time-averaged intensity. In a more general way, Talbot's law can be stated

$$\overline{F\,[i(t)]} \equiv \mathrm{F}\,[\overline{i(t)}]$$

where $i(t)$ represents a periodic stimulus, and $F[i(t)]$ the response. The bar over the time function means that an average has been taken with respect to time. Although Talbot formulated this law with regard to visual perception, we can demonstrate that it also holds for the electro-retinographic response if frequencies higher than about 30 cps are considered, which are still below the visual flicker fusion frequency.
In the case of a non-linear system, by definition

$$\overline{N\,[i(t)]} \neq N\,[\overline{i(t)}].$$

Therefore, a linear system is a prerequisite in any model of the electro-retinographic system. Now, although a linear element may be required in order to comply with Talbot's law, a non-linear one, acting with respect to amplitude, is equally essential, in order to handle such notably non-linear features as the intensity-amplitude characteristics, the intensity-differential threshold function, and the deviation from Talbot's law at low frequencies. Therefore, the model must at least contain a linear low pass filter followed by a amplitude dependent non-linear element (Fig. 1).

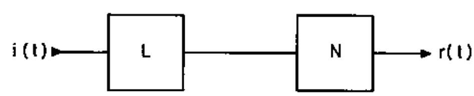

Fig. 1. A linear element, L, and a non-linear element, N, in that order, are basic parts of any model for an electroretinographic system.

The sequence of these operators produces non-linear behaviour for low frequencies, whereas, at high frequencies, the low-pass filter prevents any action from N upon the time-varying part of the input. It is to be noted that De Lange, on analogous grounds, proposed a similar model for the perceptive system (De Lange, 1954). This model appears to be too simple, however, to explain either the perceptual or the electroretinographic data. De Lange, for instance, was compelled to assume that the filter L changed its characteristics with the state of adaptation. In electroretinography we are in the favourable situation

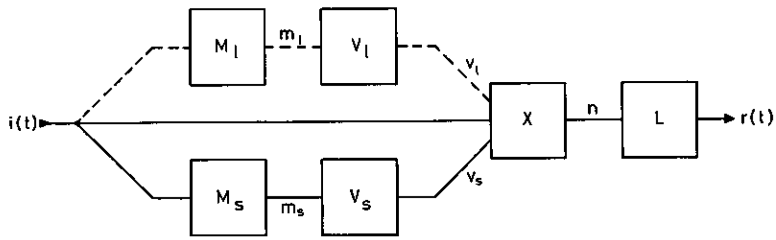

Fig. 2. A more elaborate model for the electroretinographic system. For explanation, see text.

of being able to measure both the exact amplitude of the response and the phase-relationship between in- and output. The additional information thus obtained leads to a modification of the simple scheme described above into the more elaborate model shown in Fig. 2.

The incoming signal is connected by three parallel channels to the element X, which is a multiplier. One channel is a straight through connection, without any filter, delay, or deformation. It is proposed to be the signal transmitting channel proper. The other two channels both contain L-N networks as described above. The linear elements, indicated now by M, act as leaking integrators:

$$m(\tau) = \int_{t=-\infty}^{\tau} i(t)\, e^{-\frac{\tau-t}{\vartheta}}\, dt \qquad (1)$$

and thus provide a memory with memory-time. There is evidence (Schweitzer and Troelstra, 1964) that the electroretinographic system contains two memory elements, a short term memory (demonstrable for example in double-flash experiments) and a long term memory (apparent in experiments on true dark-adaptation). We therefore need two memory elements $M_{s(hort)}$ and $M_{l(ong)}$ with appropriate memory times ϑ_s and ϑ_l. Fig. 3 shows the biphasic recovery of the b-wave during dark-adaptation following adaptation to a moderate light intensity for some minutes. This figure shows also the order of magnitude of the two memory times involved.

The output $m(t)$ of each memory element subsequently reaches the non-linear element V, which acts as a volume control and converts $m(t)$ into $v(t)$. In the situation of absolute dark adaptation v has to be 1, in order that the incoming signal $i(t)$ may pass the multiplier X unchanged. With increasing level of illumination v gradually reduces to zero, thus inhibiting the direct signal i. Finally the multiplied signal:

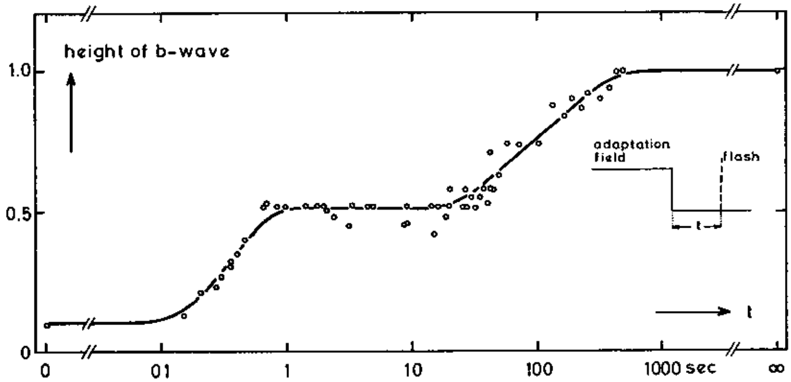

Fig. 3. Recovery of the scotopic b-wave during dark adaptation. Time and intensity of preadaptation were chosen to best show the biphasic recovery

$n(t) = i(t) \times v_s(t) \times v_l(t)$ passes the low-pass filter L, which governs the flicker fusion frequency and the shape of the ultimate electroretinographic response.

It should be noted that our model holds only for that range of scotopic stimulus intensities which, in the dark adapted eye, results in a *b*-wave. It needs a modification for strong stimuli which give rise to the *a*-wave in the *ERG*; and for large stimulus fields of very low intensity, where a further elaboration will be required as a consequence of the microstructure of the response.

Parameters of the model

Once the type of the model has been decided upon, the next step is to establish the parameters of its several elements M, V and L.

The impulse response of L has the same shape as the impulse response of the model as a whole, because its input is an equally short impulse (though with an amplitude which may have been reduced by one of the volume control elements V, acting through the multiplier M). Therefore the impulse response of L will be represented by the well-known electroretinographic *b*-wave, as generated by a flash.

The non-linear volume control element V_s can be interpreted as representing the sensitivity of the system. The signal v is determined by the shape of the h *vs.* E curve, where h is the height of the *b*-wave evoked by a flash of energy E:

$$v(E) = \frac{d\,h}{d\,E} \tag{2}$$

Our experimental determination of the amplitude characteristic $h(E)$ showed that $v(E)$ can be expressed in an analytical way by

$$v(E) = \frac{1}{(1 + aE)\ (1 + bE)} \tag{3}$$

The constants a and b depend on the units in which E and h have been measured.
The most convenient way to find the characteristics of M_s is to measure the amplitudes (h_1 and h_2) of the two responses evoked by a double-flash. If the two flashes are of equal energy, E, and if they are separated by an interval τ, the amplitude ratio of the second to the first b-wave (h_2/h_1) conforms to

$$\frac{h_2}{h_1} = \frac{h\,[E + g_s(\tau)\,E] - h\,[g_s(\tau)\,E]}{h\,(E)} \tag{4}$$

in which $g_s(\tau)$ represents the leak function of the memory system. The function $h(E)$ has been defined already in connection with Eq. (2). Experimentally it is found that the impulse response $g_s(t)$, of M_s, can be fairly approximated by

$$g_s\,(t) = e^{-t/\vartheta_s} \tag{5}$$

where ϑ_s has a value between 0.10 and 0.15 sec.
The parameters of the M_l-V_l chain, reflecting long-term adaptational effects, will not be discussed here; they can hardly affect the responses on ordinary stimuli. It can be seen in Fig. 3 that the long term adaptation has so large a time constant that the state of adaptation can be considered constant during any experiment lasting less than seconds.

Aplications and predictions

We will give two examples of important stimulus patterns and their responses to help clarify the action of the model. The agreement in these instances between the responses predicted by the model and the experimental findings lends support to this model.
First, let $i(t)$ be a step-function stimulus of variable intensity I_0. We will calculate the final value of the response to this stimulus, that is the DC-level after sufficient time for all transients to have damped out. The input to M_s is I_0. Because m_s is a linear low-pass filter, the final value of the output of M_s will be $m_s = I_0\,\vartheta_s$ according to Eq. 1. Because V is an amplitude dependent non-linearity only, the final

output of V will be $v(I_o\, \vartheta_s)$. The output of the multiplier is $I_o .\, v(I_o\, \vartheta_s)$, and again, because L has a linear low-pass characteristic, the final output of the system is

$$DC\text{-potential} = \gamma .\, I_o \,.\, v(I_o\ {}_s) \tag{6}$$

where γ is a proportionality constant.
Using for v the formula of Eq. 3, we find

$$DC\text{-potential} = \frac{I_o}{(1 + a\, I_o\, \vartheta_s)\ (1 + b\, I_o\, \vartheta_s)} \tag{7}$$

Eq. (7) gives the DC-potential in the electroretinographic response as a function of the intensity I_o of the step-function stimulus. For both low and high intensities this DC-potential approaches zero ($\sim I_o$ and $\sim 1/I_o$, respectively). It will have a maximum value at some medium intensity. The electroretinographic DC-potential was determined experimentally at various intensities, using an average response computer to increase the accuracy. The results are shown in Fig. 4, together with the calculated values according to Eq. 7.
In a second test of the model we will examine the phase relations which the model predicts for sinusoidal light stimulation. If the input is a sinusoidally modulated light signal $i(t) = I_o\ (1 + \sin \omega t)$, the output will be a sine-wave of the same frequency if a sufficiently small ϱ is chosen for all second or higher powers of ϱ to be negligible. This is usually called small-signal linearization.

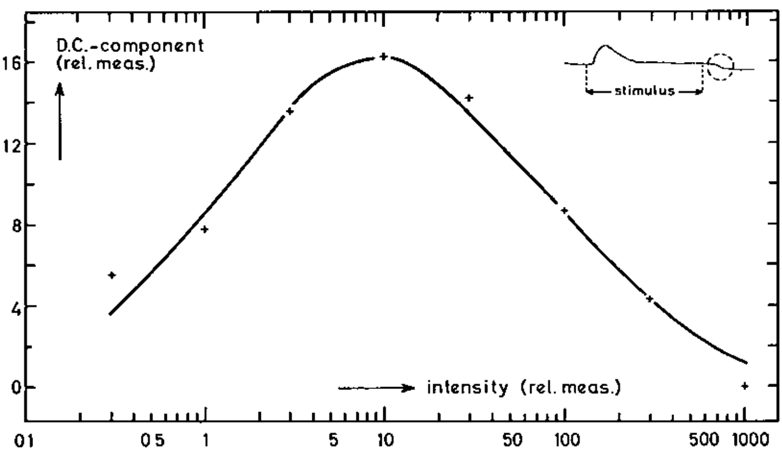

Fig. 4. The amplitude of the DC-components of the response, given by the end-effect to a long lasting stimulus, as a function of the stimulus intensity.

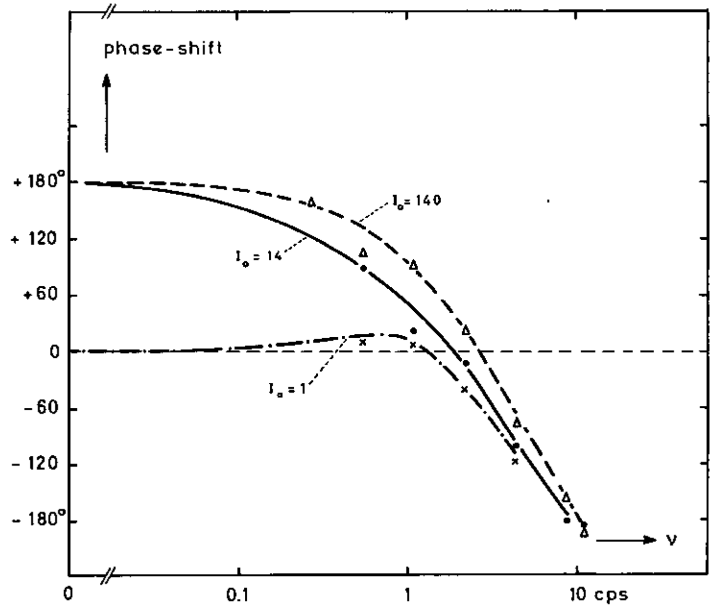

Fig. 5. Phase shift between stimulus and response for a sinusoidally modulated light stimulus.

In Fig. 5 the experimental measurements of the phase difference between light input and electroretinographic output are plotted against the frequency of the sinusoidal light stimulation. This has been done for various average intensities I_o.

It is seen that with decreasing frequency the phase shift approaches zero for the lower intensities and 180° for the higher ones. This behaviour can be explained with the aid of our model. The output of the model can be calculated under these conditions because the operators M, L, and V are known. The theoretically computed curves are indicated as drawn lines in Fig. 5 and satisfactorily fit the experimental data.

We will not follow here the laborious calculations required to compute the output, but only show why the curves exhibit peculiar low frequency divergence. Because of the low-pass filter action of the linear elements M_s and L these filters may be replaced by straight through connections, apart from the constant DC-gain factors ϑ_s and γ.

Eq. (8) gives the output of the model under these conditions.

$$\text{output} = \frac{(I_o + \varrho\, I_o \sin \omega\, t)}{[1 + a\,(I_o + \varrho\, I_o \sin \omega\, t)]\,[1 + b\,(I_o + \varrho\, I_o \sin \omega\, t)]} \tag{8}$$

Neglecting second and higher powers of ϱ and the DC-component in the output, one gets the

$$AC \text{ output} = \frac{\varrho\, I_o}{(1 + aI_o)^2\, (1 + bI_o)^2}\ (1 - abI_0^2) \sin \omega\, t \qquad (9)$$

We must remember that Eq. (10) is valid only at the low-frequency limit, as $\omega \to o$.

Eq. (9) shows that the phase difference between input and output approaches zero if $1 - abI_0^2 > o$; if $1 - abI_0^2 < o$ we have a phase advance of output with respect to the input of 180°. The value of I_o, that is the average intensity of the sine-wave stimulation, determines whether the quantity $1 - ab\ I_0^2$ is positive or negative. The phase reversal takes place at the intensity $I_o = 1/\sqrt{ab}$ where – in agreement with the experimental findings again – the AC output vanishes completely.

Concluding remarks

In principle it is possible to calculate the electroretinographic response to any scotopic light stimulus using the model diagramed in Fig. 2, which is based on three independently operating elements M, V and L. We have discussed only two examples here, but we have tested the model under many other stimulus conditions, both in the light and dark adapted eye. Under all circumstances the actual responses agreed well with those predicted by the model.

The model discussed above may prove to be applicable on other comparible situations, such as the photopic *ERG* and visual perception itself. The promising results of preliminary studies of visual flicker may prove the truth of our suggestion that studies of the *ERG* may be of great value in the interpretation of psychophysical data.

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V

THE PERCEPTUAL CONFLICT IN BINOCULAR RIVALRY

W. J. M. Levelt*

Normally, the human mind makes a portrait of the visual world with the aid of both eyes. The small differences between the retinal images, due to their differences in point of view, yield the well known binocular impression of depth. With the use of instruments, the natural correspondence may easily be disturbed. In microscopy, for instance, fusion problems may arise and, if not successfully met, they can lead to the occurrence of binocular rivalry. The present study throws a light on the origin of this binocular rivalry. More detailed communication can be found in the publications 157 *and* 164 *of the cumulative bibliography.*

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THE PERCEPTUAL CONFLICT IN BINOCULAR RIVALRY

W. J. M. Levelt

More than two centuries ago, Du Tour (1760) concluded from the existence of binocular rivalry that in normal binocular vision, every point of the visual field is only perceived with one eye. He understood that by stimulating the two eyes with incongruent patterns, more knowledge in the structure of normal binocular vision could be obtained. This structural question has occupied a number of distinguished scientists ever since. Among them, Helmholtz may be mentioned. He gave a 'mental' interpretation of fusion and rivalry (Helmholtz, 1866). From each of the eyes an independent percept is produced. Therefore, there is double perception in the rivalry situation. But we are aware of only one of them, which is selected by processes of attention. There is no physiological interaction between the two sensorial processes. In fact, this view has been developed in opposition to Hering's theory (1866). Hering assumed sensorial mixture of the two excitations. The shares of the two eyes may be different in this mixture, but absolute dominance of one of the eyes is only the limiting state of mixture. Normally the excitations compete in the binocular field. The result of the competition is, among other things, determined by the presence of contours, which are always dominant. We mention these theories in order to suggest the occurrence of very divergent possibilities for a structural theory of rivalry and fusion. Arguments pro and con are given elsewhere (Levelt, 1965). Suffice it to say that the present author is much inclined towards the views of Hering.
In this century, much of the work on binocular rivalry has been done without reference to the structural problem. Starting with Breese

(1899, 1909), most authors have studied the effect of all kinds of stimulus variables on the binocular alternation process in rivalry. Actually, they have mainly been interested in dominance times and alternation frequencies, generally without questioning why such a perceptual conflict should arise. However, any fertile treatment of the alternation problem is only feasible on the basis of proper evaluation of the visual conflict which is apparent in the rivalry situation. In this paper some of the experiments are described which have enabled the conclusion that a perceptual conflict should arise in the complex binocular situation, when binocular proximity of non-corresponding contours occurs. This conflict is traced down to the incompatibility of two simple mechanisms of binocular interaction. One is called 'binocular brightness averaging' according to the law of complementary shares, and the other is the 'contour mechanism'.

Binocular brightness averaging

If the eyes are presented with identical fields of equal luminance (E_b), and the luminance of the left field is increased (up to E_l), one may keep the apparent binocular brightness constant by simultaneously decreasing the luminance of the right field (to, say E_r). In this way one can measure an equibrightness curve, i.e. the locus of luminance pairs, producing the same binocular brightness.

a. Equibrightness curves

Procedure. Equibrightness curves were measured by alternatingly presenting an observer with a binocular comparison field and a binocular test field. The comparison field provided the observer with a brightness standard. It is shown in Fig. 1. For the comparison field

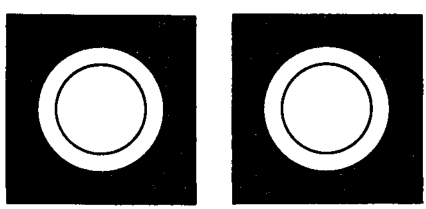

Fig. 1. Stimuli used to determine equibrightness curves. The discs subtend 3° of visual angle. The left and the right test and comparison fields contained a concentric circle, 2° in diameter, with outline diameter ot 3', in this first experiment.

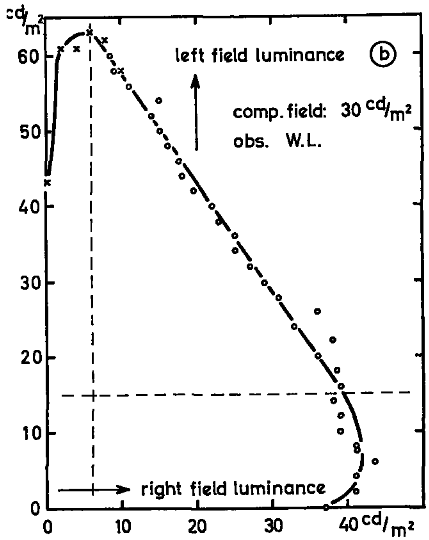

Fig. 2. Equibrightness curve (observer W.L.)
Comparison field luminance: 30 cd/m².
o Observer adjusts the luminance of the right test field
x Observer adjusts the luminance of the left test field.

the luminances of the monocular fields are equal and constant. They are foveally presented in an experimental stereoscope. The observer looks through artificial 1 mm pupils. By pushing a button the observer replaces the pair of comparison fields by a pair of test fields. They are presented to the same parts of the retinas and are geometrically equal to the comparison fields. However, the luminance of one of the test fields is set by the experimenter, whereas the luminance of the other test field has to be adjusted by the observer by changing the lamp current, so that the binocular brightness – produced by the pair of test fields – is equal to the brightness of the pair of comparison fields. The observer can alternate test and comparison fields at will, until he is satisfied with his adjustment.

Results. One of the equibrightness curves thus measured is presented in Fig. 2. The comparison fields had been fixed at a luminance of 30 cd/m² for this series of measurements. The general trend of this curve (and of the others) appears to be as follows: For test field luminances higher than a particular value – indicated by dotted lines in the figure – the function is linear. It can be expressed as $w_l E_l + w_r E_r = C$. The slope of this curve is different for different subjects; w_l and w_r can be interpreted as weighting coefficients, which reflect eye dominance. The observer in this experiment was strongly right-dominant apparently. The fact that the curves are linear (if we disregard their tails for the moment) implies that binocular brightness can simply be described in terms of averaged monocular luminances, and that thus far there is no reason to claim that it is a matter of averaging of 'sensations'. The latter claim was made by Sherrington (1908). He went so far as to speculate that the sensorium of the right eye is completely separated from that of the left eye. Whatever may be the truth in this Helmholtzian view, our curves suggest that the binocular brightness impression does not result from simple averaging of monocular sensations. For it is known from psychophysical studies that monocular, as well as normal binocular, subjective brightness is a non-linear function of stimulus intensity. Irrespective of whether this is a logarithmic function (Fechner) or a power function (Stevens), or any other non-linear function, if sensations were merely averaged, an equibrightness curve could not show a linear relation between monocular luminances, as it does in our result. Therefore, if binocular brightness is a matter of combining sensations, the results suggest that they would have to be combined in a more complicated manner, in such a way, in fact, that the resulting binocular brightness is the same as if luminances were averaged.

b. The law of complementary shares

The putative mechanisms in binocular rivalry can now be specified by assessing the effect of a monocular contour on the binocular brightness impression. For this, an experiment was performed which is a natural extension of the one described above.

Procedure. The experiment is the same in all respects except one. Whereas in the former experiment a circle was present in both test fields, in the present experiment a circle is introduced in only one of them, i.e. it is a monocular contour now. This was also the case for the comparison fields, but we could show that elimination of a contour from one of the comparison fields did not affect their apparent binocular brightness, i.e. the experimental standard.

Results. Fig. 3 shows a pair of curves thus obtained. Fig. 3a is the equibrightness curve for the monocular circle in the left field, Fig. 3b the one for a circle in the right field only. The curves are linear again, except for the tails. The linear part of each of these curves may again be described by $w_l E_l + w_r E_r = C$. The apparent brightness is per

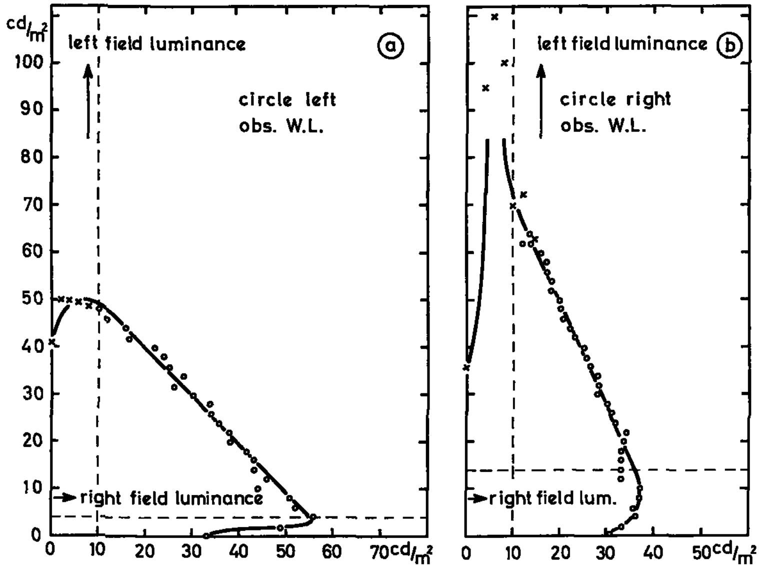

Fig. 3a, b. Equibrightness curves with monocular contour information (observer W.L.). Circles in left and right field, respectively. Comparison field luminance 30 cd/m².

definition the same for the curves of Figs. 2 and 3 (the same standard was used). For this observer, but also for all others, we find that the three curves coincide in the point $E_l = E_r = E$. As the brightness impression is equal for these three situations we have $(w_{l,1} + w_{r,1})\ E = (w_{l,2} + w_{r,2})\ E = (w_{l,3} + w_{r,3})\ E$. Stated otherwise: the sum of the weighting coefficients is the same for these points, and hence is a constant for the three curves. But the ratio of the weighting coefficients is different in the three situations. This may be called *the law of complementary shares*. It simply states that, if the weighting coefficient for the field in one eye is increased, the weighting coefficient for the corresponding field in the other eye is decreased in the same measure. It is convenient to define a share as a proportional contribution, i.e. with values between 0 and 1. We know that the sum of w_l and w_r is constant. This constant is indefinite, therefore we may put $w_l + w_r = 1$, without loss of generality; w_l and w_r are proportional shares, then. Thus, under this particular definition of 'share', the law of complementary shares is expressed by $w_l + w_r = 1$.

The shift in weighting coefficients in the just described experiment is induced by the mere presence of a contour. If a circle is presented in the left field only, w_l is increased at the expense of w_r, and *vice versa* for the situation in which a circle is given in the right field only. The weighting coefficients are constant, however, if the contour information does not change. This may be called *the rule of constancy*. But w is not an all-or-none function of the presence of a contour. For the fixation point, w appears to increase when the angular distance between the fixation point and the monocular contour is made smaller and smaller for the eye concerned. To get an impression of the maximum w-value for an eye, and thus for the minimum w for the contralateral eye, the following experiment was performed.

a. *Amplitude of the variation in weighting coefficient*

Procedure. The stimulus conditions for this experiment are shown in Fig. 4. The right test field is a square of 14° × 14°. Its luminance is fixed at 100 cd/m². The right comparison field is identical, but its luminance is adjustable by the observer. The left test field consists of two parts: a central disc of variable size, with luminance fixed at 12 cd/m², and a surrounding field (14° × 14°) at luminance 3.6 cd/m². The left comparison field has the same pattern; the luminance of the central disc is always the same as that adjusted by the observer for

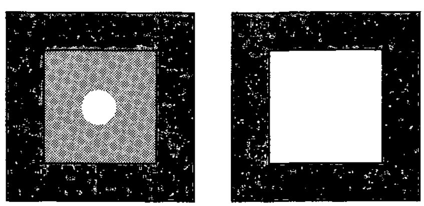

Fig. 4. Stimuli used to determine w_l as a function of field size.

the right field, the luminance of the surrounding area is always 30% of that of the central disc. The observer had to adjust the pair of comparison fields, until the brightness of the central disc appeared equal for both test field and comparison field. The observer was requested to fixate the centre of the disc. Experimental variable was the size of the disc; the four values are 7°, 5°, 3°, and 1° of visual angle. The conditions were presented in an order according to a latin square design. Two groups of four observers took part in the experiment.

TABLE I. w_l-values of eight observers at different disc sizes.

Size	1°	3°	5°	7°
Observer				
1	.84	.79	.74	.80
2	.96	.87	.95	.88
3	1.00	.98	.97	.97
4	.91	.83	.77	.79
5	.94	.91	.82	.80
6	.99	.90	.88	.86
7	.82	.81	.79	.77
8	1.00	1.00	.94	.94
Mean	.93	.89	.86	.85

Results. Individual values of w_l have been calculated for the four disc sizes. The results are given in Table I. An analysis of variance shows that w_l increases with decreasing diameter of the discs (the regression is significant at the 0.001-level). In Table I it is seen that at 1° for observers 3, 6, and 8, w_l approaches the unit value as closely as adjustment errors permit. In view, moreover, of the increasing trend in the mean w-values with decreasing size of the disc, the data strongly suggest that in the immediate neighbourhood of a monocularly presented contour, binocular brightness impression is exclusively determined by the luminance of this monocular field. This may be called the *contour mechanism*. Where the distance d between fixation point and contour is decreased, the w for this monocular area is increased to a maximum of unity: $w \to 1$, if $d \to 0$.

The law of complementary shares, the rule of constancy and the definition of shares as proportional contributions provide us with an easy means to determine what an observer sees, if we know that his shares are w_l and w_r and that the respective luminances of the two fields are E_r and E_l, because his brightness impression is the same as that when he looks with both eyes at a field with luminance $E_b = w_lE_l + w_rE_r$. For, the so defined pair of monocular fields (E_b,E_b) is on the same equibrightness curve as pair (E_l,E_r), because $w_lE_b + w_rE_b = (w_l + w_r)E_b = (w_l + w_r).\ (w_lE_l + w_rE_r) = w_lE_l + w_rE_r$. In the following we shall speak of the apparent brightness produced by some stimulus pair (E_l,E_r) in terms of E_b. E_b is not the psychological quantity of apparent brightness, then, but it is the luminance of a field observed with both eyes, which produces the same apparent brightness as (E_l,E_r). We know that the apparent brightness is a monotonically increasing function of E_b, but the nature of this function is irrelevant to our further discussion.

b. *'Tails' of the equibrightness curves*

So far we have not considered the non-linear 'tails' of the equibrightness curves. In terms of the constancy rule for weighting coefficients, we should say that this rule is not valid for the extreme parts of the curve, i.e. if one of the test field luminances is low. But in fact, this behaviour can also be attributed to the contour mechanism. For it is clear that if the luminance of one test field, say the left one, is below threshold, contour information is present in the right field only. Therefore, for these low values of E_l, w_r will increase at the expense of w_l. In order to match with (E_b,E_b), it should be true that $w_rE_r + w_lE_l = E_b = 30\ cd/m^2$. If $E_l = 0$ and $w_r = 1$, this means that $E_r = E_b = 30\ cd/m^2$, and so the curve has to turn back to $E_r = 30\ cd/m^2$, for $E_l = 0$. But for fields of the size used in these experiments (3°), we may expect that $w_r < 1$, and therefore that $E_r > 30\ cd/m^2$ in these situations. This is clearly the case. It should be remarked that Fechner's paradox – the increase in brightness impression when the weakest stimulated eye is closed – can be explained in the same way.

c. *A brightness paradox*

Rather paradoxical stimulus situations can be constructed on the basis of knowledge of the law of complementary shares and the contour mechanism. An example is given in Fig. 5.

Consider Fig. 5 and compare discs *A* and *C*. For the centre of these discs the stimulations of the eyes are identical, black for the left eye, white for the right eye. Will therefore the apparent brightness of *A* be equal to the stereoscopic brightness of *C*? And compare discs *B* and *C*. The stimulation is quite different for these discs, both are black in the left field, but *C* is white in the right eye, whereas *B* is black again. Does *C* in fact look substantially brighter than *B* does? These questions may be answered by applying the said rules. For the sake of simplicity, the luminance of the black discs is supposed to be zero, whereas the bright field has luminance 1.

Disc *A*: a contour is present in both eyes, therefore – disregarding eye dominance – we have $E_b = \frac{1}{2}.0 + \frac{1}{2}.1 = \frac{1}{2}$.

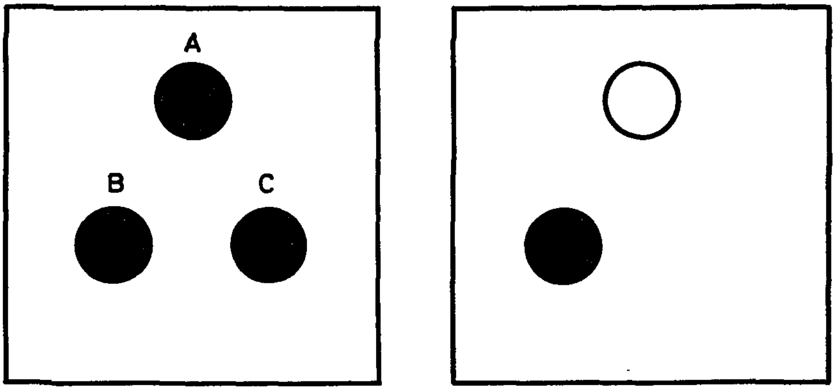

Fig. 5. Stereoscopically the disc A is considerably brighter than C, while B and C are not very different in brightness.

Disc B: corresponding contours in both eyes: $E_b = \frac{1}{2}.0 + \frac{1}{2}.0 = 0$.
Disc C: a contour is only present in the left field, hence $w_l \to 1$. For $w_l = 1$ we get $E_b = 1.0 + 0.1 = 0$, so $E_b \to 0$ in this situation, dependent on the size of the disc.
Hence both questions should be answered negatively. Disc A will look brighter than C, whereas B and C will not differ very much. The reader may verify these predictions himself by using a stereoscope to examine Fig. 5.
This type of effects can be produced at will now. Another example is shown in Fig. 6. It has been designed as an argument against the

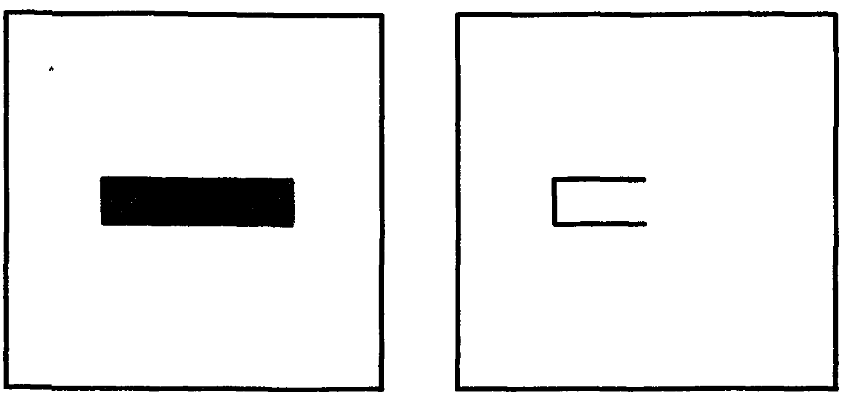

Fig. 6. An argument against the Gestalt explanation of rivalry. The Gestalt of the bar is disturbed stereoscopically. The left half appears grey, shading into black in the right half.

Gestalt-theory of binocular rivalry (Gellhorn, 1924). This theory says that a Gestalt is present or absent *in toto* in binocular rivalry, but is never disturbed.

Our theory, however, predicts distortion of the black bar in the binocular perception of Fig. 6. The left part of the figure should be similar to A in Fig. 5, whereas the right part of the bar is in the situation of C in Fig. 5. So, it is predicted that the bar looks grey in the left half, shading into black in the right half. This is also easily verified by means of a stereoscope. The bar is clearly disturbed. Binocular interaction functionally precedes Gestalt-formation.

Conflict of averaging and contour mechanism

a. Rivalry

Having established, firstly the mechanism of binocular brightness averaging according to the law of complementary shares ($w_l + w_r = 1$), and secondly the contour mechanism ($w \to 1$, if $d \to 0$), it is not difficult to show that these two mechanisms necessarily come into conflict if two non-corresponding but adjacent contours are presented to the eyes. Within a binocular area T, these contours give rise to a conflict in the partition of the weights. The contour in the left field produces a tendency for w_l to increase in area T, and the non-corresponding contour in the right eye, in its turn, will produce a tendency for an increase of w_r; in both cases on the basis of the contour mechanism. But an increase of both w_l and w_r would obviously violate the law of complementary shares: w_l and w_r would no longer add up to unity. This is the situation of binocular contour rivalry. From the interaction of two rather simple mechanisms it can thus be concluded that a perceptual conflict should arise in the complex binocular situation where there is proximity of non-corresponding contours. Apparently the conflict is resolved by the abrogation of the rule of constancy, in such a way that the first tendency – increase of w_l – triumphs over the other – increase of w_r – for some time, after which the position is reversed. The law of complementary shares is thus saved by an alternating process. The aim of this paper is only to show the source of conflict; characteristics of this alternation process are described elsewhere (Levelt, 1965).

There is no reason to expect the case of corresponding contours to be different from that of non-corresponding contours. There is no strict reason to believe in a special 'fused situation', in which the weighting coefficients are suddenly $\frac{1}{2}$ for both eyes, homogeneously over the whole visual field. On the contrary, it is quite likely that in this case, too, parts of the fields will enter into rivalry. However, one will not be aware of this, as long as the stimuli are the same for the two eyes. For, if $E_l = E_r = E$, then $E_b = (w_l + w_r)\ E$ which is a constant by the law of complementary shares, even if w_l and w_r fluctuate. And for equally patterned but unequally illuminated fields rivalry will not be perceived either if sufficiently small parts of the binocular field are subject to rivalry more or less independently. This possibility is compatible with Hubel and Wiesel's findings on eye-dominance in the receptive field of the cat (Hubel and Wiesel, 1962): two cells with largely overlapping receptive fields could be of different eye dominance. This would mean that the rule of constancy is invalid for sufficiently small areas.

This 'rivalry explanation' of fusion is attractive for several reasons. One of them may be mentioned: it is possible to give such a rivalry-explanation of Panum's fusional areas. Two lines, not falling exactly on corresponding regions of the retinas, but shifted apart by some minutes of arc are nevertheless seen as one. The extent to which this is possible determines Panum's area. But under the present assumption there is no reason any more to distinguish the case of parallel non-corresponding lines from the case of e.g. crossing lines. The 'fusion' of the lines within Panum's area may be understood as the inhibition of the line presented to one eye by the line presented to the other eye. If these two cases are to be ascribed to the same mechanism, the Panum area should have the same extent as the inhibitive contralateral action of one contour with respect to another. This may be checked. Ogle's measurements on the horizontal extent of Panum's area (Ogle, 1950) give values of 6-8′ in the foveal field. This is the region within which always only one line is seen, when a binocularly disparate pair is presented. We can compare this with Kaufman's data on the extent of contralateral suppression of binocularly crossing lines. It appeared that two vertical lines in one eye, separated by an angle ϑ, produced a contralateral suppression of a horizontal line segment between them (presented to the other eye) during about 50% of the time for all angles within $\vartheta = 14'$. Half of this value is the suppressive extension in one direction. This value of 7′ accords with Ogle's data on Panum's area.

This study may be concluded by one other remark on the rivalry-explanation of fusion. Verhoeff (1935), Asher (1953), and Hochberg (1965) likewise extrapolate the rivalry situation to the state of binocular fusion. All of them more or less explicitly use all-or-none terms to describe their assumptions: some point in the binocular field is perceived with either one or the other eye, nothing in between; in our terms: $w_l = 1$ or $w_r = 1$. However we found that intermediate situations ($1 > w > 0$) are quite normal, being dependent upon distance to contours. Moreover, Hubel and Wiesel's experiments also showed that absolute eye-dominance was exceptional in receptive fields of single cortical cells. The all-or-none thesis seems to be too simple. It is, moreover, an unnecessary assumption, if one wants to explain fusion and rivalry by the same mechanism.

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IV

ADDITION PHENOMENA IN VISION AND HEARING

G. van den Brink*

Studies on the threshold perception – first in the field of vision, later also in the field of hearing – have been a substantial part of the Institute's research programme from the beginning. Since only a few investigators had experience in both fields, an attempt to compare methods and results has never been made. The present author, one of these happy few 'amphibions', has tried here to synthesize his studies on addition in both fields and to relate Ricco's critical area in vision to the critical bandwidth in hearing in particular.
For more detailed information on both experimental procedures and results the reader is referred to the publications 13, 21, 53, 133, and 134 of the cumulative bibliography.

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ADDITION PHENOMENA IN VISION AND HEARING

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Roughly we can distinguish two types of physicists working in psychophysics. Those who lack interest and knowledge in electronics will seldom feel at home in hearing research. Hence, there is at least a statistical difference in nature and attitude between investigators in hearing and in vision research. Consequently, studies on vision and hearing are mostly made by different groups of workers who not seldom lack sufficiently close and frequent contacts. As a result, there is too little comparison of results and experimental procedures. If there were such a contact, it would be possible to exchange ideas and methods, and this might lead to new and fruitful developments in either of the fields.

In this paper we will try to compare procedures, which are applied or might be applied both in vision and hearing experiments on addition. We will indicate both parallels and differences between visual and auditive addition mechanisms. We will mention also procedures, applied in one field, which might be suitable for application in the other field. First the similarity between the determination of Ricco's area and one method to measure the width of the critical band will be discussed. It will be shown that threshold measurement as a function of the stimulus duration has aspects in hearing which are different from those in vision. A survey is given of experiments undertaken to obtain direct information about the operation characteristics of the addition mechanisms in vision and in hearing. In the last paragraph a description is given of a study on the detection of tone pulses of various duration in noise of various bandwidth. The procedure of the last experiment has also been applied in vision experiments.

In the present paper the word *addition* is used for a type of interaction that was indicated by *summation* in earlier publications. For definitions of these two types of interaction we refer to a recent publication on visual facilitation (Van den Brink, 1965).

Ricco's law and the critical band

The similarity of the experimental and functional aspects of Ricco's law in vision and the existence of a critical band in hearing is an example of parallelism in visual and auditory phenomena.

The threshold energy for a circular testflash appears to be independent of the diameter as long as the size of the flash does not exceed a critical, so called Ricco's area (Ricco, 1877). For diameters which are large compared with that of Ricco's area, the threshold energy increases proportionally with the diameter (Piper's law). These facts are confirmed under various conditions by many authors, among whom Piéron (1920), Graham and Margaria (1935), Van der Velden (1944, 1946), Bouman and Van der Velden (1947), and Baumgardt (1948). It appears irrelevant how the incident energy is distributed over the retinal image, whether it is presented for instance by one flash or by two or more smaller flashes, as long as all retinal images fall within Ricco's area.

Gässler (1954), on the other side, measured hearing thresholds of combinations of simultaneously presented pure tone pulses as a function of the number of such tones. The difference in frequency between adjacent tones was either 10 or 20 cps in this experiment. Below a certain critical number, the threshold intensity of either of the tones appeared to be inversely proportional to the number, for absolute as well as for masked thresholds. Actually this means that the total amount of energy for threshold hearing is constant, as long as the frequency range of stimulation does not exceed a certain value, which has been called 'Kopplungsbreite' by Gässler. Over a large range of frequencies this 'Kopplungsbreite' is about twice that of the critical band as it is measured by, for instance, Fletcher (1940) and Schäfer, Gales, Shewmaker, and Thompson (1950). They, however, followed different experimental procedures, to which we will come back later.

The parallelism between the two experiments described is evident. However, there is usually a difference in the way of presenting the results. Mostly the auditive threshold is presented in an intensity measure I per unit of frequency of the stimulus. Visual thresholds, on the contrary, are generally expressed in an energy measure IxtxA, t being the exposure time and A the area of the stimulus. These ways of presentation do not stress the similarity. When we plot the visual threshold energy as a function of the diameter of a testflash, this results in a horizontal line over a range of diameters up to a value that is equal to the diameter of Ricco's area. In auditory experiments the threshold intensity i.e. the energy per unit of frequency and per second, is plotted as a function of the bandwidth of the stimulus, which results in a curve with a negative slope of 3 db per factor 2 of the bandwidth for values up to the width of the critical band.

Ricco's area depends upon the place on the retina. The critical band depends upon the frequency, which actually means that it depends upon the place on the basilar membrane. Both, Ricco's law in vision and the existence of the critical band in hearing may turn out to be based upon comparable neural interaction mechanisms.

Threshold versus stimulus duration

In a similar way we can compare experiments where the threshold is measured as a function of the duration of a small-sized flash or of a tone or noise pulse. In the eye the threshold energy appears to be independent of the duration t, as long as t does not exceed Bloch's time (Bloch, 1885). When we measure the hearing threshold as a function of the duration, there is a complication: the spectral band of a tone pulse increases with decreasing duration. As soon as the duration of a tone pulse is so short that the spectral band exceeds the critical band, there is no longer a complete spatial addition of cochlear activity, elicited by the tone pulse.

The results of one group of experimentors show a 3 db decrease of the threshold level when the duration is doubled. According to their findings the threshold energy is constant for pulse durations up to about 200 msec (Scholl, 1962; Zwicker and Wright, 1963). Plomp and Bouman (1959), however, found that the slope of the curve giving the threshold level as a function of the pulse duration, depends upon the frequency of the tone pulse. They found that, the lower the frequency, the steeper the slope. For all frequencies the slope appeared to increase with decreasing pulse duration. They never found slopes below 3 db per factor 2. The results of Blodgedd, Jeffres and Taylor (1958) and those of Hamilton (1957) agree with those of Plomp and Bouman, so that, evidently, there is a discrepancy between the results of two groups of investigators. This discrepancy may be due to criterion differences either between experimental procedures or subjects (Van den Brink, 1964a).

Plomp and Bouman (1959) interpreted the deviations from the 3 db per factor 2 slope in terms of the above mentioned artefact, that as duration decreases, the spectral band increases. Below certain duration the critical band is exceeded and they calculated the width of the critical band as a function of the frequency. They even found satisfactory agreement with the results of authors who have applied other procedures to measure the critical band width (Fletcher, 1940; Schäfer, Gales, Shewmaker and Thompson, 1950; Gässler, 1954).

Van den Brink (1964a), however, studied the detectability of tone pulses of various duration in noise of various bandwidth. In these experiments, which were similar to Hamilton's experiments (1957), though over larger ranges of the parameters, no such a deviation was found (see Fig. 5b, upper curve). We will come back on this study in this paper.

All experiments mentioned in this and the preceding paragraph were undertaken to obtain information about the time and the distance within which addition of activity, elicited by the stimulus, occurs either in vision or in hearing. These data, however, are of insufficient help to obtain information about the operation characteristics of addition mechanisms, because they do not enable to determine the shape of the functions that give the chance of addition in dependence on time, and on distance or frequency difference between effects elicited either in the retina or in Corti's organ. For this reason we have made studies on vision (Bouman and Van den Brink, 1952; Van den Brink and Bouman, 1954; Van den Brink, 1957) as well as on audition (Van den Brink, 1964b), following a procedure which enabled us to obtain direct information about the operation characteristics of the addition mechanisms.

Experiments on visual and auditive addition

The experimental procedure followed in visual experiments to study spatial and temporal addition (Bouman and Van den Brink, 1952; Van den Brink and Bouman, 1954; Van den Brink, 1957) is based upon the presentation of two 'elementary' flashes. The size (1') and the duration (10 msec) of either of the flashes was sufficiently small with respect to the distance and time within which addition occurs. The distance δ and the interval τ between the flashes could be varied over a sufficiently large range. The luminances of the elementary flashes were adjusted to probabilities of seeing c_1 and c_2 respectively. When the two flashes are presented together and if there were no addition, which is the case for a sufficiently large distance or a sufficiently long interval between the flashes, the total probability of seeing is determined by the statistical sum of the separate probabilities. Then the total probability of seeing is $P(\infty) = 1 - (1\text{-}c_1)(1\text{-}c_2)$. For arbitrary values of τ and δ the probability of seeing be $P(\tau,\delta)$. If the values of τ and δ become sufficiently small, addition of subliminal effects elicited by the two flashes may occur: The probability of seeing increases when τ and δ decrease. The chance of addition of subliminal effects is maximum for $\tau = 0$ and $\delta = 0$, i.e. when the flashes coincide in time and place. Then the probability of seeing is $P(o)$. The chance of addition of subliminal effects as a function of τ and δ is given by the following formula:

$$f(\tau,\delta) = \frac{P(\tau,\delta) - P(\infty)}{P(o) - P(\infty)}$$

The probability of seeing either of the flashes was always adjusted at about 0.3. Most of the measurements are taken for $\tau = 0$ or for $\delta = 0$, so that we measured $f(\tau,o) \equiv p(\tau)$ and $f(o,\delta) \equiv q(\delta)$. Some measurements with varying τ and δ at the same time indicate that temporal and spatial addition are not mutually independent, so that $f(\tau,\delta) \neq p(\tau) . q(\delta)$. A study on this dependence is in preparation.

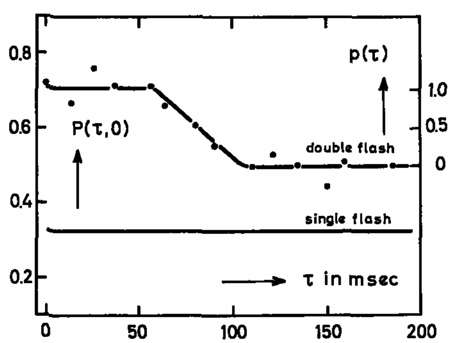


Fig. 1. An example of a measurement of the probability of seeing $P(\tau,o)$ as a function of the interval τ between two flashes. The right hand scale gives the chance of addition $p(\tau)$ according to the transformation formula (7° nasally, dark adapted eye, $\lambda = 510$ nm).

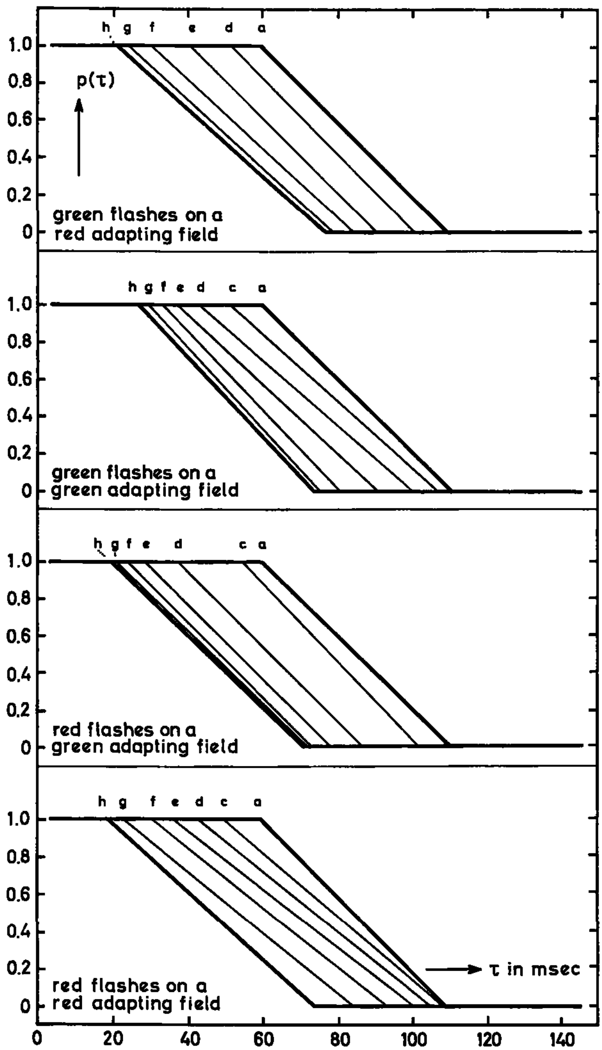


Fig. 2 left: The chance of visual temporal addition $p(\tau)$ for luminances ot the background and for various wavelength combinations of test flash and background at 7° nasally. Smoothed results from Van den Brink and Bouman (1954).

a: no background, b: $B = 5.10^{-7}$ $W/sr\ m^2$, c: $B = 5\ 10^{-6}$ $W/sr\ m^2$, ...
. . . . h: $B = 5.10^{-1}$ $W/sr\ m^2$

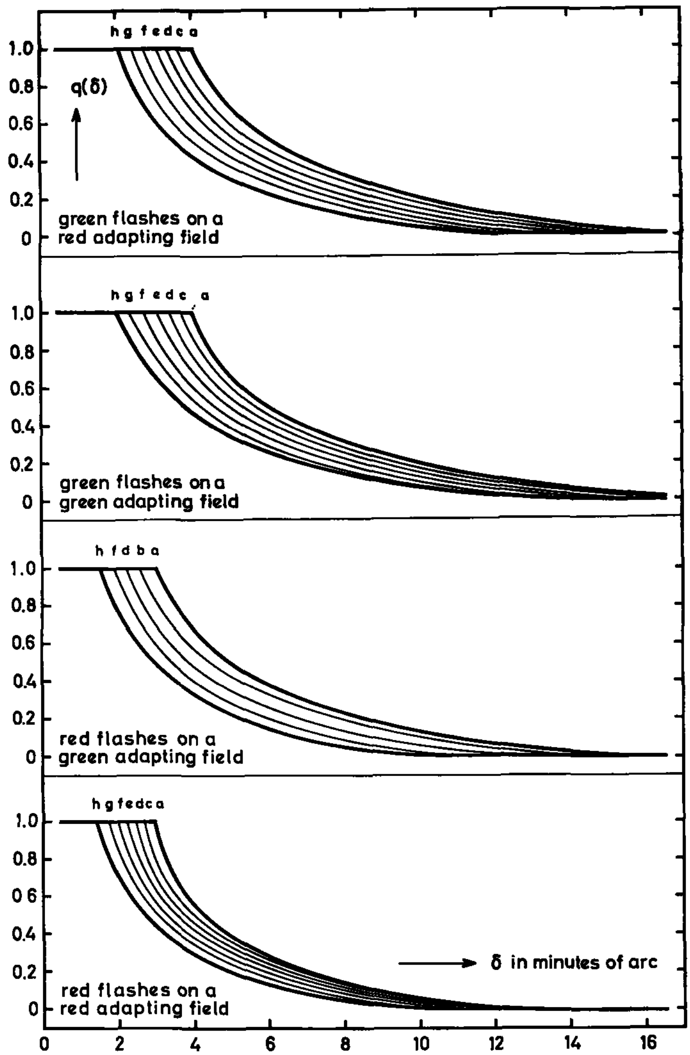


Fig. 2 right: Spatial addition under the same circumstances.

In Fig. 1 an example of a measurement of temporal addition is given. This experiment was done 7° nasally from the fovea centralis in the observer's dark adapted right eye. It gives the probability of seeing as a function of the interval between the flashes. The right hand scale gives the chance of addition, according to the transformation formula. The data represented in Fig. 2 give a survey of measurements with either red ($\lambda = 620$ nm) or green ($\lambda = 510$ nm) test flashes on either a red or a green background.

The most important results are:

1. For the dark-adapted eye, there is maximum addition of subliminal effects up to 60 msec, and no addition for intervals exceeding 110 msec. The addition functions are equal for rod and cone vision and are independent of the place on the retina, including the fovea.
2. Spatial addition appears to depend upon the place of the retina as well as upon the kind of receptors stimulated. For rod vision ($\lambda = 510$ nm) we found maximum addition up to about 4′ and no addition for distances exceeding about 20′ in the dark-adapted eye. For cones ($\lambda = 620$ nm) these angles are about 3′ and 15′, respectively, at 7° nasally. The values decrease with decreasing eccentricity.
3. Measurements with one red flash and one green flash result in similar functions, intermediate between those measured with either two green flashes or two red flashes. This demonstrates complete interaction between the rod and the cone systems as far as addition is concerned.
4. Measurements with a continuously present background, either red or green, show that p (τ) as well as q (δ) shift to lower values of τ and δ, respectively, with increasing luminance of the background. It might be interesting to repeat this experiment for different states of adaptation without simultaneous presentation of a background, in order to decide whether this effect is a contrast or an adaptation phenomenon.
5. In the fovea spatial addition occurs over a much smaller area than in the periphery. No significant differences are found either between the results with red and green flashes or between the results with or without a background. This may mean that the shape of this curve is rather due to diffraction, to aberrations in the optical system of the eye or to stray light, than to neural interaction (see also Ogle, 1962). In our opinion, this can not be the case with the results obtained in the periphery of the retina.

The analogous approach for the determination of spatial addition in hearing is the simultaneous presentation of pulses of two small noise bands as function of the frequency difference between these bands (Van den Brink, 1964b). The bandwidth of the pulses was 10 cps. The central frequency of one of the bands was 800 cps; the central frequency of the other band was continuously variable between 800 and 1000 cps. The noise signals of the two pulses came from separate noise generators in order to exclude correlation. This was important especially for small frequency differences. As the spectral band of a tone pulse increases with decreasing pulse duration we had to make its duration relatively long compared with that in the visual experiments. It was 200 msec in the present experiment. White background noise of 50 db *SPL* was presented continuously. The intensities of the noise pulses were adjusted so that the probabilities of hearing of either of the pulses c_1 and c_2 were again about 0.3, when presented separately. The probality of hearing $P\ (\Delta\nu)$ was then measured as a function of the frequency difference $\Delta\nu$ between the noise bands. It appeared that the total probability of hearing increased with decreasing $\Delta\nu$ and that for large $\Delta\nu$ values the probability of hearing was equal to the statistical sum of the separate probabilities of hearing: $P = 1 - (1 - c_1)\ (1 - c_2)$ as it was in the comparable visual experiment. Evidently, here, too, is a chance that a tone pulse elicits subliminal activity; when subliminal activity is elicited by both pulses, addition of these activities may occur if the frequency difference, i.e. the distance on the basilar membrane, is sufficiently small. By application of the transformation formula, mentioned in connection with the visual experiments, we calculated the chance of addition of subliminal activity $q\ (\Delta\nu)$ as a function of the frequency difference from the measured probabilities of hearing $P\ (\Delta\nu)$.

The results are shown in Fig. 3b, where the chance of auditive addition $q\ (\Delta\nu)$ is plotted as a function of the frequency difference. Fig. 3a is an example of visual addition (Van den Brink, 1957). The similarity between the curves of Fig. 3a and Fig. 3b is evident. In the range of frequency differences up to about 60 cps the chance of addition of subliminal activity is 1. In the range up to about 140 cps, addition decreases gradually to zero in about the same way as in vision.

Although we did this experiment only at 800 cps, it can be expected that this phenomenon depends upon the frequency i.e. upon the place on the basilar membrane, as does the width of the critical band. A complete study of auditive spatial addition over a large range of frequencies is planned for the near future.

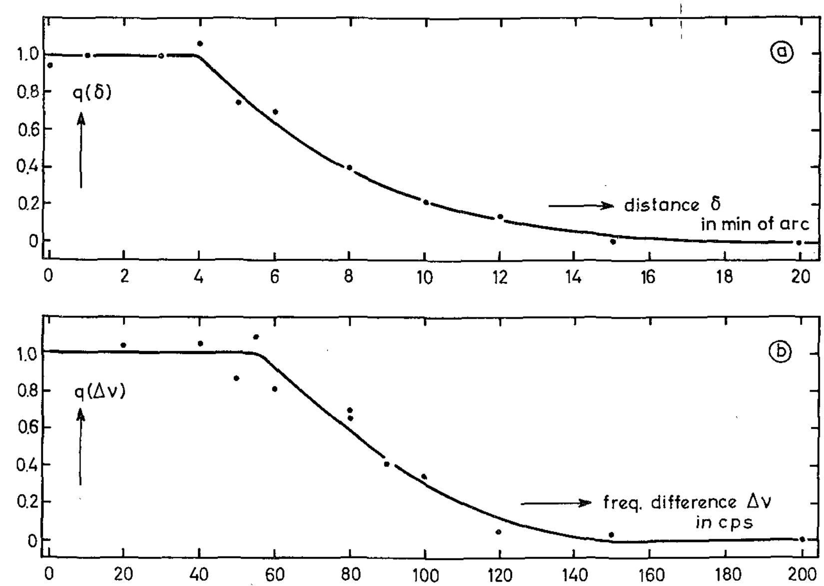


Fig. 3a. Visual spatial addition $q\ (\delta)$ as a function of the distance δ between two flashes (7° nasally, dark adapted eye, $\lambda = 510$ nm).
3b. Auditive addition $q\ (\Delta\nu)$ as a function of the frequency difference $\Delta\nu$ between two tone pulses ($\nu = 800$ cps).

Other procedures for critical band determination

Since Fletcher (1940) introduced his concept of the critical band, it has been frequently studied with various procedures. Fletcher himself measured the detectability of a tone pulse in filtered noise with variable bandwidth. Regardless of the indisputable merit of his work, Fletcher's conclusion seems to be partly based upon his expectation (which seems obvious), that, within a certain range of frequencies the masking influence of a noise band upon a test tone is proportional to the amount of energy within this band. The masked threshold of a tone pulse would then increase 3 db when the width of the band of the masking noise increases with a factor 2, if the intensity per unit of frequency of the noise band is kept constant. The masked threshold increases, when the bandwidth increases up to a critical value. For bandwidths exceeding this critical value the threshold is constant. This means that the energy outside this critical range has no masking effect upon the test-tone. The number of measuring points, however, used by Fletcher to confirm his expectation, is too small to draw definite conclusions. Schäfer, Gales, Shewmaker and Thompson (1950) did similar measurements with about equal results. They used, however, synthetic noise composed with a number of sine wave tones for some of their measuring points. Hamilton (1957) measured the threshold of tone pulses of 800 cps with various durations as a function of the bandwidth of the masking noise. He found that the slope of the curve giving the threshold as a function of the bandwidth is about half of the 3 db per factor 2 slope, found by Fletcher and by Schäfer et al. The results of Greenwood (1961), on the contrary, suggest that the slope, in at least some cases, is even more than 3 db per factor 2.

The disagreement between the results of the various authors with respect to the threshold as a function of the pulse duration and of the width of the masking noise band led us to an experiment that covered larger ranges of the parameters: pulse durations and bandwidth (Van

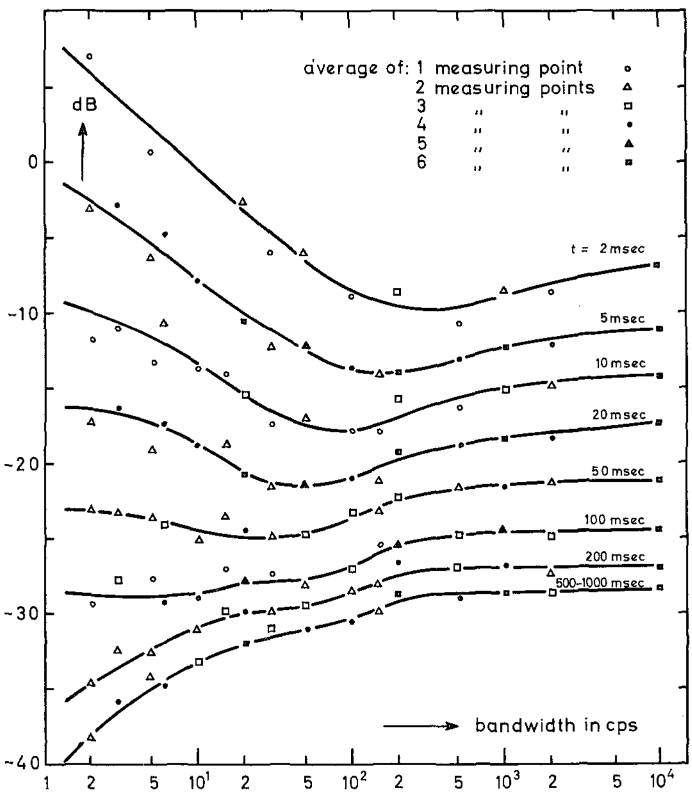


Fig. 4. Noise masked auditive threshold as a function of the bandwidth of the masking noise for various tone pulse durations (ν = 800 cps).

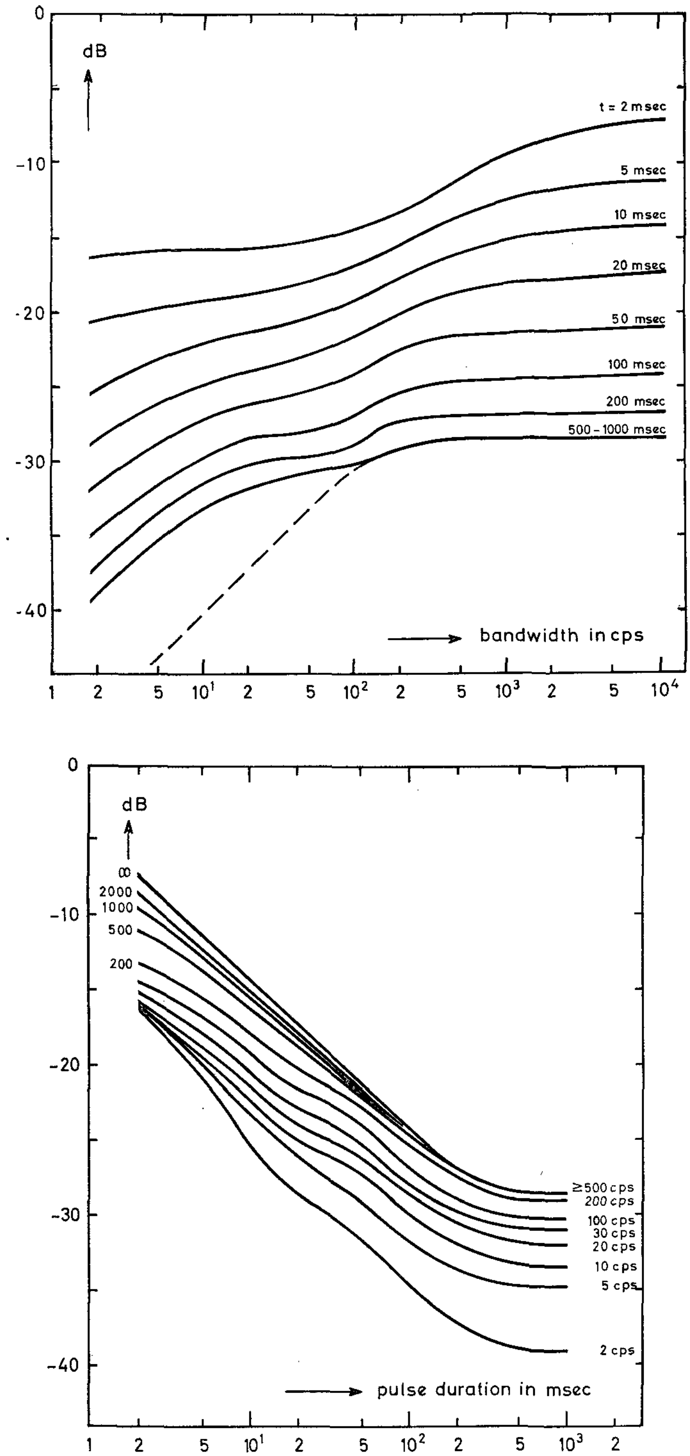
den Brink, 1964a). For details of the method used in this study we refer to this publication. It may be mentioned only, that filters were used in a bandwidth range between 2 and 2000 cps for the masking noise. The side slopes of the filters were more than 100 db per octave. Noise, filtered in this way, was presented continuously. The tone pulses passed the same filter as the noise. The duration of the tone pulses was varied between 2 msec and 1 sec. The results were corrected for false responses. Each threshold was determined with about 160 presentations. The level of the filtered noise was either 35, 50, or 65 db *SPL*. Thresholds were measured as a function of bandwidth and pulse duration.

The results are shown in Fig. 4. Here we presented the hearing threshold as a function of the bandwidth of the masking noise for different pulse durations. Because there were no significant differences between the signal-to-noise ratios for threshold hearing obtained with the three levels of the masking noise we averaged the results of these measurements. As far as Hamilton's parameters (Hamilton, 1957) covered the same ranges as ours, his data agree satisfactorily with our results.

The most striking feature in Fig. 4 is that for long durations, i.e. when the spectral spread of the tone pulses does not exceed even the smallest bandwidth used (lowest curves), the threshold decreases with the bandwidth, though not with a slope of 3 db but with an average slope of about 1.5 db per factor 2 of the bandwidth. For short pulse durations, however, the threshold begins to rise with decreasing bandwidth (upper curves). The smaller the duration, the larger the width of the noise band for which this threshold increase begins. This is of course due to the fact, that the spectral band of a tone pulse increases with decreasing duration. As soon as the width of this band exceeds the width of the pass band of the filter, part of the energy of the pulse is dissipated in the filter. The fraction of the energy dissipated, increases with increasing width of the energy band of the stimulus, i.e. with decreasing pulse duration.

We took this dissipation into account and we corrected the results (See Fig. 5a). Another way of plotting these data is presented in Fig. 5b, where we give the threshold as a function of the pulse duration with the bandwidth as a parameter. The curves for long durations in Fig. 5a are unchanged. The durves of Fig. 4 refer to threshold levels at the input of the filter, the curves of Fig. 5 refer to threshold levels at the output of the earphone.

The deviation of the 3 db per factor 2 slope (interrupted line) in the



Figs. 5a and 5b. The data of Fig. 4 after correction for the fact that the tone pulses were passing through the filter. The results are plotted in two ways.

range of small bandwidths for long durations (Fig. 5a) was ascribed to a change in the nature of the sound of the test tone (Van den Brink, 1964a). For bandwidths of the order of what is supposed to be the critical bandwidth, or larger, the masking signal has a real noise character and is perceived essentially different from the tone pulse, which sounds purely tonal. For decreasing bandwidths, below 10 cps, the noise becomes a pure tone with fluctuating loudness. The average fluctuation time is equal to the reciprocal of the bandwidth. A pulse that passes through the band filter has then a rise and decay time, of the order of the fluctuation time of the noise, so that the tone pulse and the noise have the same tonal character. Actually the measurement thus changes from a signal to noise into a difference limen determination with decreasing bandwidth. This may explain the bend of the curve between 20 and 100 cps, which is also evident in Hamilton's results. It may as well explain the fact that for bandwidths below 10 cps, finally, a slope is reached in agreement with the slope predicted by Fletcher (1940). This criterion shift concerns only the left hand part of Fig. 5a. The mutual positions of the curves in the right hand part of this figure give the relation between threshold and stimulus duration in white noise. This is more clearly shown by the upper curve in Fig. 5b. These data have been mentioned already in the discussion on the discrepancies between various authors about the relation between threshold and pulse duration. Unfortunately the present study does not clarify the mentioned discrepancies.

This experiment shows that the parallelism in hearing and vision is not complete. The problems in either of the fields may not be equally complex. A complication in this study on hearing is, that the plateaus for different pulse durations (Fig. 5a) are not reached at the same bandwidth. This led us to support the concept of a bandwidth-adjusting mechanism of Green, Birdsall and Tanner (1957). Nevertheless, we can apply the procedure in the latter study in experiments on vision. Although the data are not at our disposal, we want to refer to recent measurements of Westheimer (1965), who measured visual thresholds of a small flash as a function of the diameter of a background field. The data obtained in this experiment indicate, that inhibitory activity, caused by the background, plays a role here. It appears reasonable to suppose that the bandwidth-adjusting mechanism, mentioned before, is based on comparable inhibitory processes.

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VII

THE PROBLEM OF PERCEPTUAL MOTOR LOAD

J. A. Michon

The explosive development of automation has reduced the importance of manpower as an energetic resource. Work has become strenuous due to the perceptual load of accurately digesting information rather than the muscular activity involved. In modern traffic for instance accidents may result from perceptual, rather than from physical strains. Techniques to measure physical fatigue have long been known. It is urgent now to develop techniques which measure, in analogy, perceptual load. In the present study, a promising approach is discussed to the problem of measuring this perceptual load.
For details about experimental procedures and results we refer to the publications 147, and 156 of the cumulative bibliography.

THE PROBLEM OF PERCEPTUAL MOTOR LOAD

J. A. Michon

The invention of the wheel marks the origin of the problem of perceptual load. From this historical moment onward, man has tried to reduce his bodily involvement with his work and to exercise control instead. Gradually, and during the present century almost explosively, he has substituted transmission of information for transfer of energy. The result has been that the burden of work has been shifted from the muscles to the senses and the higher nervous centres. During the last two or three decades this burden has become so heavy that the limits of man's capacity for information processing may have been reached in several tasks, and in some cases even been exceeded. In modern traffic for instance, accidents will occur, that are nobody's fault, but simply a consequency of the complexity of the particular situations. The load placed on the perceptual-motor system by modern jobs has become an important problem and with it goes the demand for simple methods of measuring how much of the human capacity for perceiving and processing information is required in the performance of particular tasks. To date, however, no one knows exactly how to define perceptual load (or perceptual-motor load, as it might be called preferably, because fine regularity responses frequently play a large role in modern work). Too little is known about the load capacity of the human organism and the way in which it is employed: there appear to be as many definitions as there are descriptions of measuring methods. Nevertheless there is a fair consensus on the relevancy of the concept as such, and the history of intelligence testing demonstrates that devising methods of measuring something which is only defined by the measuring method, may lead to impressive results.

Some time ago we developed a method to measure perceptual-motor load (PML for short) (Michon, 1964a). Some results obtained with it recently will be discussed in this paper; two of the basic ideas underlying the method, however, must be dealt with first: the concept of 'behaviour invariants', and that of stochastic latency mechanisms.

The quest for 'behavioural invariants'

Our starting point is the assumption that there are elementary units of behaviour which remain fairly constant within the same context, but will show minor changes in appearance and temporal structure under influence of the structure and load of the task within which they are embedded. The nature and amount of these changes would then provide a basis for the measurement of PML. We shall use the concept of 'behaviour invariant' in a rather restricted sense, because in a wide sense, it is what all of psychology is after. The sense in which it is used in the present setting comes quite close to that of 'reflex'. With time the reflex has become very flexible, despite its name, and has been defined for instance by Skinner as 'a smooth predictable unit of behaviour analysis'. This can virtually mean anything and that's perhaps why many psychologists have dropped the concept (see Miller, Galanter, and Pribram (1960)).
However, 'smooth predictable units' are still good currency, even if we refuse to call them reflexes. Ethology for instance and to some extent also Time and Motion Study seek to establish hierarchies of phenotypical units to describe compound behaviour of animals in general and, it sometimes appears, of the stickleback specifically. It is clear that such phenotypical units may be produced in several ways when seen from a sufficiently molecular level. This applies even to rather basic units: simple repetitive movements may result from entirely different innervations every time (Seashore, 1951). Recent developments in computer simulation of behaviour have started a line of research which makes extensive use of the same philosophy. Especially the work of Newell and Simon (1963) and their co-workers, has shown the feasibility of explaining complex (flexible) processes in terms of hierarchical structures of relatively rigid information processing routines.
However fruitful this approach may be, it seems that at present we do not yet possess a sufficiently molecular set of observable phenotypical invariants which can be of use as a basis of measurements of PML. It

is conceivable, however, that such a set may finally be constructed for a well defined range of tasks.

Stochastic models describing temporal variation

From the work on observable units and the 'semi-observables' of the computer simulation work a thread runs to the investigations which use stochastic models to describe purely conceptual events underlying such outputs as reaction times, etc. This level of explanation increasingly gets attention from psychologists. Examples of studies which try to relate a time-varying, discrete, output to simple stochastic processes are for instance the work of Restle (1961, 1962) on reaction time and problem solving times, and that of Levelt (1965), who described the alternations of eye dominance occurring when the two eyes are stimulated differently, in terms of a gammadistribution. McGill (1963) reviewed a number of such models. The idea behind this kind of reasoning is that from the input onward there are a number of formally identical steps involved in reaching the final output. In the simplest case, a signal starting at 'neuron' 1 in Fig. 1 has in every instant Δt, a constant probability p, to pass on to the next 'neuron' and so on.

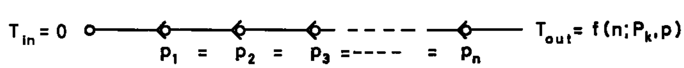

Fig. 1. The distribution of the latency times T_{out} is a function of the number of conceptual neural connections (n) and the chance P_k that an impulse will pass a node after a particular interval $k.\ \Delta\ t$. If the probability of transition in any small interval equals p, then $P_k = p\ (1\text{-}p)^{k-1}$. All nodes are assumed to have equal transitional probabilities.

From the features of the distribution function $f\ (t)$ of the output, conclusions are drawn about size and number of the hypothetical steps involved in reaching a decision, solution, alternation, etc. The usefulness of these models for our purposes is not so much the concept of neural invariants which they embody, as the idea that with increasing load on the sensori-motor system, the variance of the output may become greater, because of 'traffic-problems' in the nervous system. In terms of the model: the probability of transition, p, will change as a function of load, because the characteristics of the neural network will change. Pooling of the two foregoing considerations suggests that it should be possible to reach conclusions about the load which different tasks impose on the perceptual-motor system, from an anlysis of the temporal structure of observable invariants. However, no well defined set of invariants is currently available.

Key-tapping as a method of measuring Perceptual Motor Load

Among a number of other methods which are believed to measure PML, that of the 'secondary task' stands out for its conceptual elegance. This method starts from the assumption – proven to be tenable under many circumstances – that man acts as a one-channel information processing system. Doing two things at the same time is impossible, unless they are highly correlated by nature or by extensive overlearning (piano-playing): generally a solution of the conflict is obtained by alternating between the tasks. The basic idea of a secondary task is that it measures the difference between the 'mental capacity' consumed by the main task, and the total available capacity. The latter may in fact be subject to fluctuations (Fig. 2).

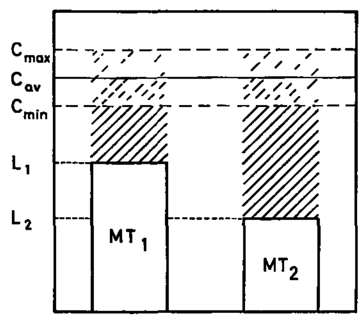

Fig. 2. The principle of measuring Perceptual Motor Load by means of a secondary task. The load capacity C is assumed to be variable, with average C_{av}. The secondary task measures the difference between the load L, of Main Tasks 1 and 2, and C_{av} (shaded areas).

The crucial point is to find a suitable secondary task, i.e. a task which is heavily influenced by the main task load, but which does not affect the main task performance. Key-tapping satisfies this requirement completely, and possesses a number of other desirable characteristics as well. The starting hypothesis is that the regularity of key-tapping at a subject's preferred rate (usually between 0.5 and 1.0 sec) will decrease as a function of PML, that is: the difference between succes-

sive intervals will on the average be greater, the heavier the load imposed by a perceptual-motor task. The relation of this assumption to the foregoing sections will be evident. The procedure followed consists in making the subject produce taps at his personal rate, as regularly as he can. A score has been developed to express the regularity, which is based on the sum of the absolute values of the relative differences between successive intervals ($\Sigma \mid \Delta t \mid / t_{av}$). This score is obtained both while the main task is performed (A) and while no other task is performed (B). The PML score then is $(A\text{-}B)/B$. This definition makes the results of different subjects easily comparable, and ensures a zero score when the main task imposes no load.
A number of experiments has been performed and reported on earlierly. Rather than describing these again, a tentative scale is presented in Fig. 3, in which the load of a number of tasks studied is plotted. The indicated scale categories are based on observations and remarks of subjects, as well as on estimates of the quality of performance (numbers of mistakes or 'blockings'); the evaluation therefore has been partly qualitative. Tasks with average PML-scores of 2.0 or more, appear to be rather strenuous to subjects, while a score of 4.0 or more indicates almost complete deterioration. On the other hand subjects generally reported boredom and even drowsiness with tasks yielding a PML-score of 0.25 or less.
One feature of all experiments done thus far, by other authors as well as by ourselves is that they were designed to measure average load rather than for continuous dynamic evaluation of the load at any moment during the execution of a particular task. This has been remedied in a recent series of experiments, from which an example will be given now.

'On line' measurements of Perceptual Motor Load

Sometimes one may want to know where the difficult or the easy points of a task lie, or whether a change in task structure, devised to spread out a peak in the load, has the effect wanted. For experimental purposes, a plotting task was chosen in which the subject listens to position reports of a number of 'ships' and plots these positions on a map such as is shown in Fig. 4. The reports were presented at intervals of exactly 11 sec, and could be varied only with respect to the number of ships involved (0-4), and the positions (consisting of two two-figure numbers or 'unchanged'). The task of the subject was to

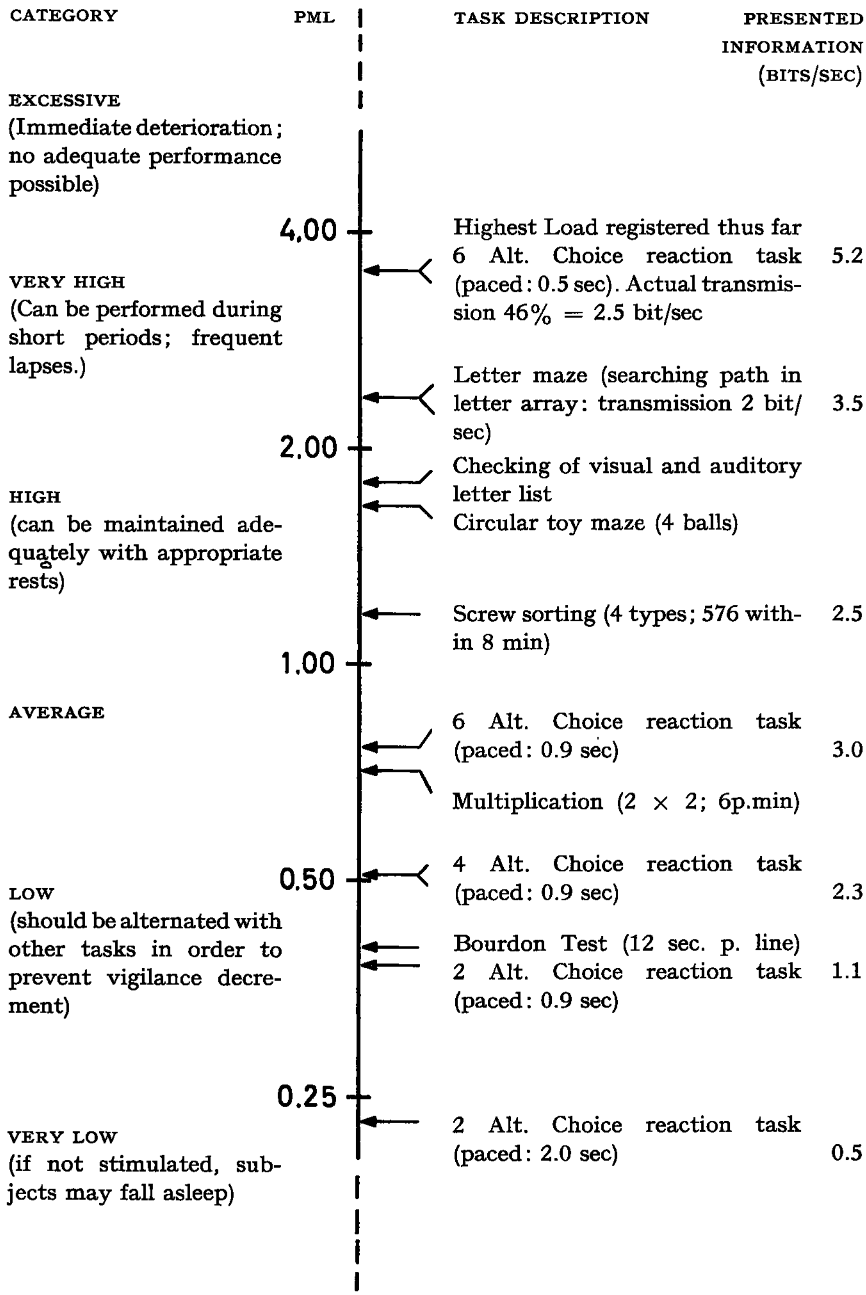

Fig. 3. Tentative classification of several tasks in order of perceptual motor load.

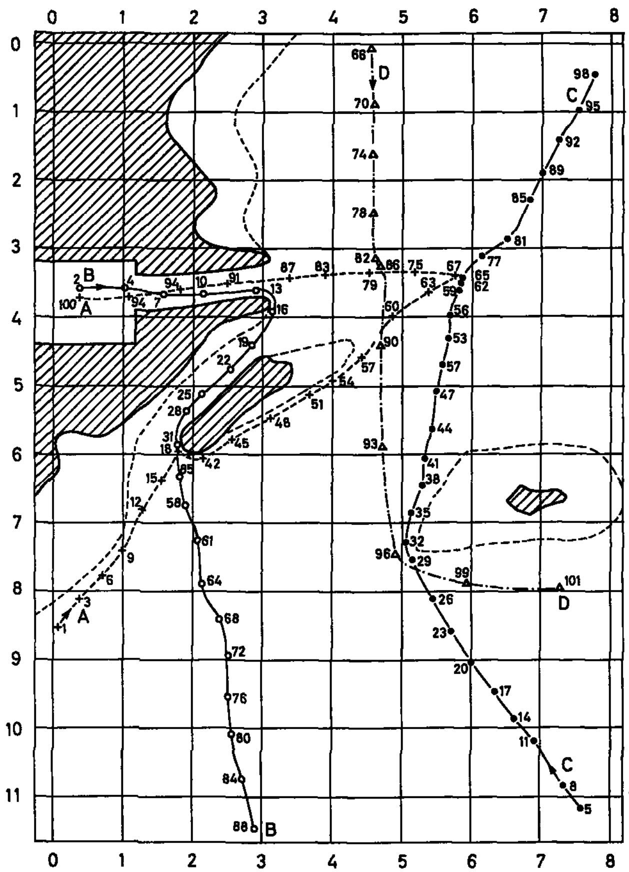

Fig. 4. Example of chart used in plotting experiment.

plot the reported positions correctly, and to write the correct rank order of each reported position next to it. These rank-order numbers were not given as an input, they had to be produced by the subjects themselves. The difficulty of the task was expected to depend upon the number of 'ships' involved and the complexity of the 'changed'/'unchanged' pattern. During this major task the subject had also to perform the key-tapping task in the prescribed way, by pressing a pedal with his foot at his personal rate. The plot of Fig. 4, which is shown as an example, consisted of 101 reports on 1 to 4 ships, for a period of 18.5 min. In the experiment proper, 4 plots were made by each of 10 subjects. The first two plots were meant to be training sessions; the last two, an easy and a moderately difficult one, were analyzed in detail with respect to the PML-scores. Part of the results of this analysis are shown in Fig. 5. The lower part of the diagram contains a synopsis of the task in terms of the number of ships moving and a few other important features of the plot concerned. The three curves represent, from top to bottom, the PML-scores, sampled at 30 sec intervals, of two different subjects (*E* and *vD*) and the average score of 10 subjects. The agreement between the three curves is fairly good, while comparison with the features of the task enables identification of several points: we find a high score between 1 and 6 min, a steep descent between 6 and 8 min, a high plateau between 10 and 16 min, with a very high peak between 14 and 15 min, coinciding with a sharply definable problem in the task. This experiment shows that our method of measuring PML can in fact identify load fluctuations of the main task quite precisely.

Two features of the main task, which reflected themselves in the

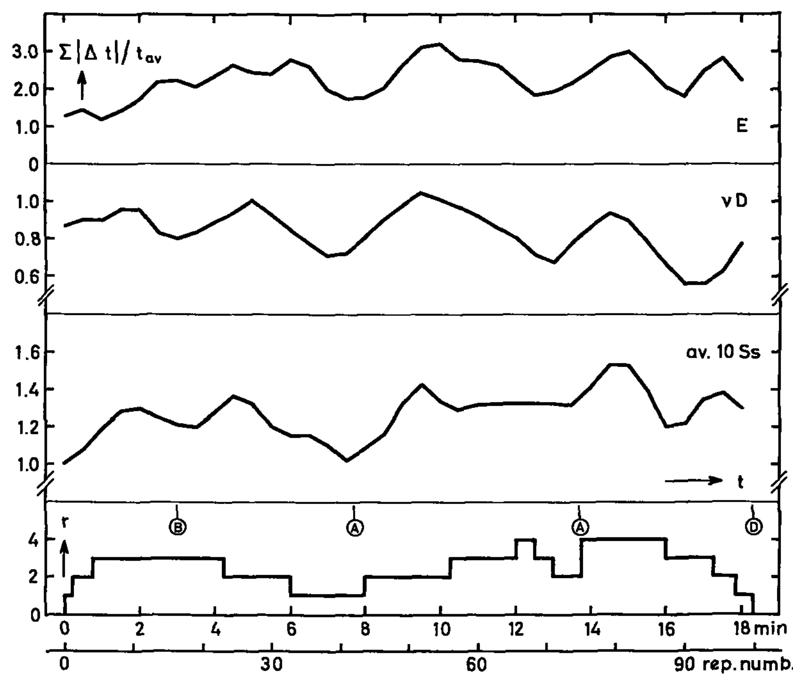

Fig. 5. On line measurement of PML during plotting task. The number of 'ships' to be tracked (r) and the occurrence of sharp turns (encircled letter) are shown in the lower part of the diagram. Along the abscissa both time and the report numbers are indicated. Shown are the PML curves of two subjects (*E* and *vD*) and the average curve for ten subjects.

records of PML were not explicitly expected before. First, deviations from the normally highly predictable paths (sharp turns etc.) frequently lead to a marked increase in PML-score: these account for the peaks at 3-4 min, partly for the large peak at 14-15 min and the one at about 17 min. This effect may be checked by using plots with different amounts of predictability: a ship executing Brownian movements will impose an excessive burden on a subject.

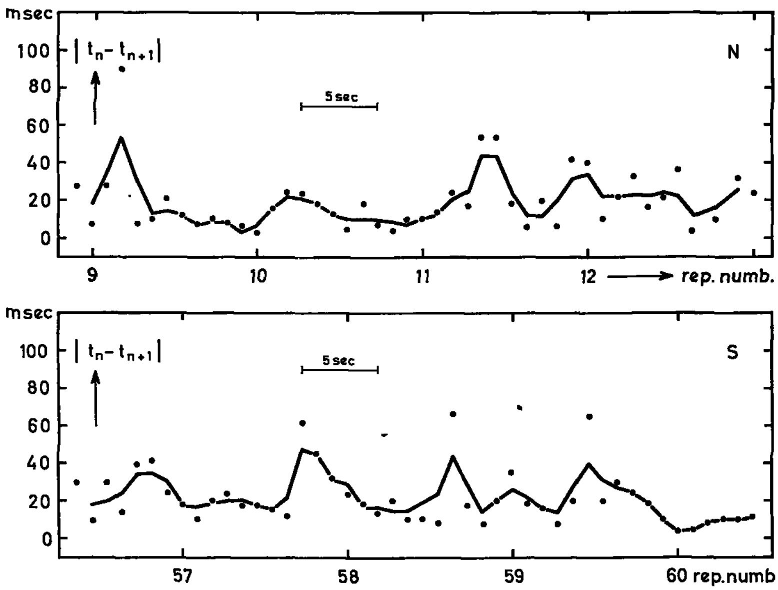

Fig. 6. Ripple shown in PML records during plotting tasks, in samples of two subjects. The 'bumps' in the smoothed curves are due to the momentary increase of information processing after each new report. There appears to be an approximately constant phase shift between report and bump.

A second unexpected results was the ripple which most subjects display quite markedly over long stretches of their records. Examples of this 'ripple', obtained from two different subjects and two different tracks are shown in Fig. 6. The ripple frequency of PML was found to be related to the rate of the position reports. Although at present we have not yet correlated the two, it is likely that the ripple is caused by a momentary increase of PML when the fresh information is processed. It can therefore be concluded that the method described in this paper is not only suited to determine the gross features of a task but is sufficiently sensitive to reveal even the 'microstructure' of the PML imposed by a task: The smallest informational units employed in the task concerned, could be traced in the records of our subjects.

Timing mechanisms in human behaviour

'The least studied and most obscure problem of nervous organisation are presented by the temporal aspects of behaviour. Every action above the level of a spinal reflex involves time factors for which there is no adequate explanation'.

These words of Karl Lashley (1937) are almost as valid today as they were in 1937. Yet there has recently been a rapidly increasing interest in this area, if not a more thorough study of it. This is for instance reflected to some extent by the work of the authors referred to in this paper. In fact, the method described in the foregoing sections quite explicitely deals with human timing mechanisms, in as much as it starts from the rather specific assumption that the regularity of timing will deteriorate as a function of available information processing capacity. The question of the structure of the mechanism, which enables a subject to produce a series of equally long intervals with remarkable precision and the way in which this mechanism is influenced by the difficulty of a task, has not been considered in the present paper. Some of the results of an extensive investigation into these problems are already available in published form elsewhere (Michon, 1964b, 1965a, 1965b).

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VIII

A COMPARISON OF TWO VISUAL THRESHOLD MODELS

P. L. Latour

Many models of the visual threshold have been proposed; prominent among these are van der Velden and Bouman's two-quantum coincidence model, and Tanner and Swets' signal detection model. In this paper, these two theories are compared, to determine which better explains the phenomena of threshold detection. The conclusion reached is that the models are often complementary rather than mutually exclusive.
A more detailed monograph about these investigations is in preparation.

A COMPARISON OF TWO VISUAL THRESHOLD MODELS

P. L. Latour

The extraction of a signal from a noisy background is a well known problem. Various techniques have been employed in attempts to solve this problem. In radar applications, for instance, delay lines are used to correlate the emitted message with the reflected signal. The delay for which the output of the correlator is maximum is related to the distance of the object scanned. The averaging technique in which a large number of responses are added to obtain an average response which has an increased signal to noise ratio, has become a common tool both in experimental physics and in the biomedical sciences.

The averaging technique depends upon, and profits from knowledge of the exact timing of the response: the electronic circuits are time-locked to this moment. In a correlator this time element has to be found by varying the delay, which costs time or, in a parallel processor, hardware. Thus, given a certain amount of computational facility, knowledge of the timing of the responses increases signal detectability.

In our sense organs signals from the surroundings are transduced into physiological events. These are transmitted to the brain where they may enter our consciousness. In a threshold experiment we ask how weak a signal can be in a given situation and still be detected, say 60% of the time. Such a threshold experiment is not a normal situation for human beings. We are not accustomed to live at the very edge of our sensory inputs, and experiments with radar operators, who have to detect small reflections on the screen have revealed that such a near threshold task is extremely fatiguing. Threshold experiments, however, may provide information about our sensory mechanisms which cannot be obtained in more normal situations. The usual approach in such a threshold experiment is to present the subject with a multitude of stimuli of different strengths, and to measure the chance of detection as a function of the signal strength. The result is a frequency of perception curve (FOP), which gives the chance of perception as a function of signal strength. One can manipulate the data from this experiment in various ways, according to the ideas one associates with the fundamental background of the phenomena under investigation. The aim of this paper is to give a short review of two different models of the visual detection problem. The mechanisms in the models are quite different, but they both give results which are in good agreement with the experimental findings. The two-quanta theory, as developed by Bouman and van der Velden states, that retinal absorption of two quanta within a summation area (about 10 minutes of arc) and within a summation time (about 20 msec) is sufficient and necessary for the perception of light in the dark adapted eye. Bouman's review (Bouman, 1961) of the quantum theory gives details about the concept and its consequences. At threshold levels the number of quanta in a test flash can be described by a Poisson chance distribution; one can calculate the energy needed for a certain chance of perception in a specific experimental arrangement from the statistical properties of this distribution. If, for instance, the energy for a 60% chance of perception of a flash is calculated as a function of the size and duration of the flash, it is found that for times which are large with respect to the summation time or for areas large with respect to the summation area, one can write for this energy: $E = ka\sqrt{t}$ in which k is a constant, a is the area defined by the visual angle and t is the duration of the flash. Threshold experiments give results which are in good agreement with this theoretical formula, although one might question whether a slightly higher quantum number would not produce a better fit (Van Elteren and Gerrits, 1961); but this does not affect the explanatory basis. When both t and a are great, however, discrepancies occur (Bouman and Van der Velden, 1947).

Another, quite different way to describe the experimental findings is with the detection theory, as applied to psycho-physical data by Tanner and Swets (Swets, 1961). Essentially this theory considers that the threshold problem is that of detecting small signals embedded in noise. The small visual signal, consisting of the transduced physical stimulus, must be detected in the presence of the noise of the visual system. It is not necessary, though, that all the noise originate in the visual system; it may also find its origin in a transduced visual background, in the case of a differential threshold experiment.

The noise has a density distribution ϱ (r), which gives the likelihood of the amplitudes, and a threshold T. The noise distribution need not to be Gaussian: the only assumption is that it is normalized in such a way that the total area is equal to one. If a physical stimulus is applied to the sense organ the transduced signal will be added to the noise present at that moment. Therefore the noise density distribution is shifted in the direction of the threshold by an amount related to the physical strength of the stimulus. The area of the resulting density distribution which is to the right of the threshold gives the chance of detection of this stimulus. This is illustrated in Fig. 1.

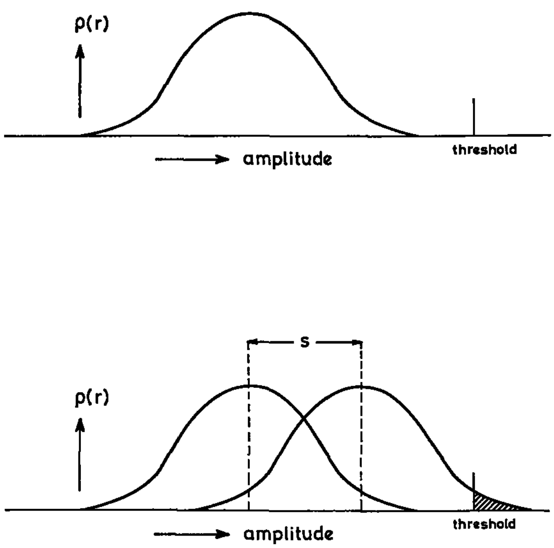

Fig. 1. The density function is shifted to the right by a stimulus S. The area at the right of the threshold gives the chance of perception.

If we now use a set of stimuli of strength I, $I + \Delta I$, $I + 2\Delta I, \ldots$ we can measure the suprathreshold area of the noise density distribution for equal increments in signal amplitude. As both I and ΔI are known it is thus possible to find the exact location of the threshold in relation to the noise density distribution, assuming that T is a constant.
In Fig. 2 some noise density distributions are given which were measured in somewhat different experiments. The visual threshold varies in relation to the onset eye movements (Latour, 1962). Presenting two

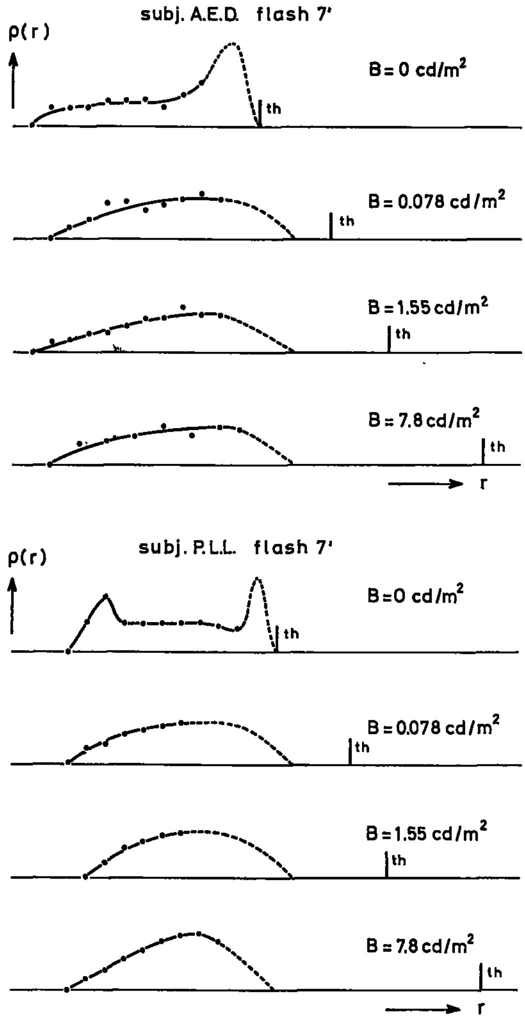

Fig. 2. The noise density distribution, ϱ (r), and threshold, *th*, as a function of background luminosity. ϱ (r) is drawn such that its width is about equal for all background luminosities.

stimuli with intensity I and $I + \Delta I$ is then already sufficient to measure both the noise density distribution and the location of the normal threshold – as the threshold itself varies during the experiment.
The result of such an experiment at different background intensities for a flash of $7'$ of arc and duration of .6 microsec is given in Fig. 2. In the figure it can be seen that at the lowest background intensities the

threshold is quite close to the density distribution, which means that even very small signals are sometimes detected. At higher background intensities the retina gives up this economy and a safe margin separates the threshold from the noise density distribution. It should be noted that the noise density distributions in Fig. 2 are drawn such that the standard deviations of these distributions are about equal for the different background intensities. The width of the noise density distribution can be measured indirectly by measuring the flash energy needed for a 60% chance of perception. This will indicate the position of the threshold in relation to the background intensity. Results from such an experiment are given in Fig. 3.

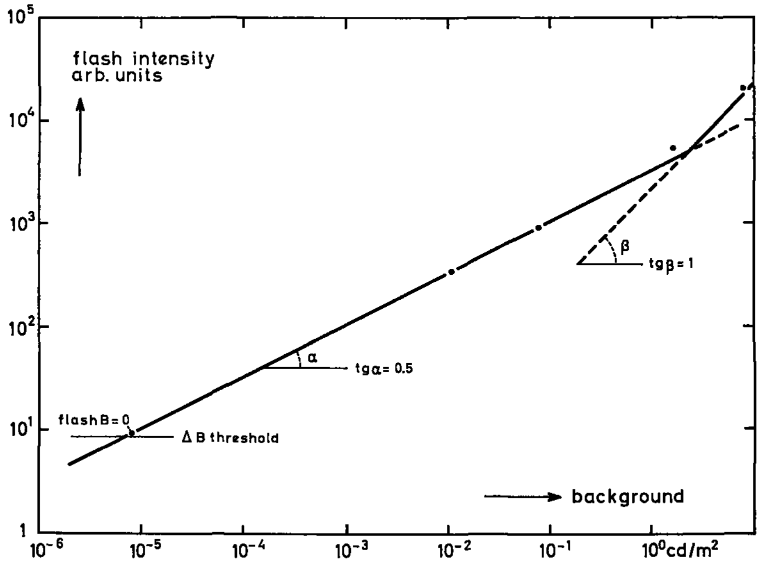

Fig. 3. Flash energy as a function of background luminosity for a fixed chance of perception.

It was found that above the absolute threshold, the flash energy for threshold detection is proportional to the square root of the background intensity over five to six log units, after which the energy tends to increase linearly with the background intensity, in agreement with the findings of Van den Brink (1957). The square root relation is known as the de Vries-Rose law, the linear relation as Weber's law. With the help of Figs. 2 and 3 we now can calculate the width of the noise density distribution in relation to the background intensity. The result of this calculation is given in Fig. 4. It appears that the width of the noise density distribution is proportional to the square root of the background intensity. It suggests that the noise results from statistical fluctuations of the background, and that the noise of the visual system itself plays an unimportant role at higher background intensities. This finding in fact justifies the treatment of colour and brightness discrimination from a fluctuation concept as Bouman and Walraven did (e.g. Bouman and Walraven, 1962). In Fig. 4 the width of the noise of the visual system is indicated also; it is clear that this noise can be neglected in differential threshold experiments.

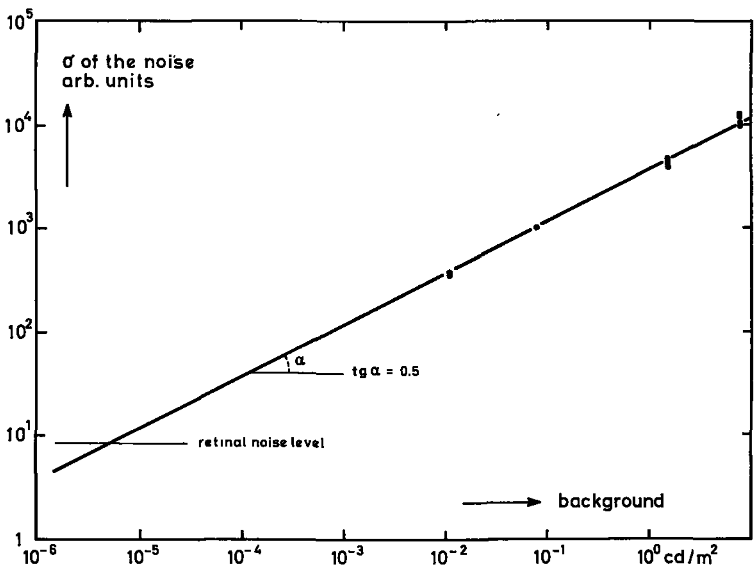

Fig. 4. Standard deviation (width) of the noise density distribution as a function of background luminosity.

The curious point is that the proportionality of the noise width to the square root of the background intensity seems to hold even beyond the de Vries-Rose region. How is one then to interpret the change in behaviour of the contrast threshold which deflects here to $\Delta B/B =$ constant, according to Weber's law? One answer to this question can be found in Figs. 2 and 3. At higher background intensities, the threshold runs away from the noise density distribution and this effect just accounts for the deviation from the de Vries-Rose Law. Such an explanation, however, is only a phenomenological description of what

happens, rather than a mechanistic description why this should happen. Bouman et al. (1963) explained the effect in terms of saturation of the nerve channels. As the stimulus strength increases, the nerve is no longer able to respond to all activations, due to its refractory period. This saturation will diminish the fluctuations but since it also affects the signalling of stimulus information, it is only natural that the threshold shifts to the right. Apparently the signal detection and fluctuation models converge in this situation to the same viewpoint.
The above results can be applied to a general calculation of how the threshold energy depends on the size and duration of the stimulus. We will assume, as Bouman and Van der Velden (1947) did, that area and time can be split into independent units, and that the chance of detection is determined by the chance that the stimulation in any of these independent sub-units is supraliminal.
The chance of detection of a stimulus can then be calculated from the chances of detection of the flashes in the sub-units, according to the formula

$$P_{det} = 1 - (1 - p)^r$$

in which p is the chance of detection of the flash in an independent time-area unit, and r is the number of independent sub-units which constitute the total flash. The above calculation is valid only if the various parts of the retina are independent rather than varying in sensitivity as a whole. In the experiments studying the relation of the threshold to eye movements it was found that only very small areas in the order of several minutes have correlated changes in sensitivity, the correlation being nil for larger areas.
Now if we present a flash of angular subtense α and duration t, the number of independent sub-units will be proportional to $\alpha^2 t$. We substitute this value for r in the formula for P_{det}:

$$P_{det} = 1 - (1 - p)^{k\alpha^2 t}$$

in which k is a constant determined both by the bandwidth of the retinal noise and by the size of the independent area. Due to the effect of facilitation, perception of one of the samples is sufficient for perception of the flash. We now want to calculate the relationship between the energy of the flash for a 60% chance of detection and the angle and the duration of the flash. First we need to express the chance of detection of an independent area as a function of the flash intensity I. Fig. 2 suggests that the density distribution of the noise increases linearly with the displacement, the first order approximation of the

area to the region is thus equal to I^2. But what must we write for the chance of detection in case where there is a small gap between the threshold and the noise density distribution? The answer is: $p = (I - I_0)^2$, in which I_0 is the width of the gap, measured in intensity units. For values $I < I_0$, p is equal to zero. We substitute this formula in P_{det} and approximate:
$P_{det} = 1 - (1 - (I - I_0)^2)^{ka^2t} = ka^2t\ (I - I_0)^2$, and require that it is constant in the threshold situation. The total energy of the flash is equal to:

$$E = Ia^2t$$

The relation above can then be written as:

$$k\ a^2t\ (\frac{E}{a^2t} - I_0)^2 = C.$$

Solving this equation in E we find:

$$E = a^2t\ I_0 + \sqrt{\frac{Ca^2t}{k}}$$

From this formula we can see that if either a or t is small, the energy is determined mainly by the second term and is therefore proportional to $a\sqrt{t}$. When both a and t are large the energy is determined by the first term, which states that E is proportional to a^2t. This sort of behaviour is what is found experimentally (Bouman and Van der Velden op. cit.) and which has always been felt as difficult to reconcile within pure two quantum theory.
The main divergence between the detection model and the two quanta theory in this respect lies in the introduction of I_0. In the two quantum theory, p is strictly proportional to I^2. In the detection model, we are less restricted in choosing our parameters and are free to assume some particular distance between the noise distribution and threshold. For high background intensities, this spacing is evident from the experimental data. In the dark adapted eye, the spacing is certainly small and could only be determined from threshold experiments with such low detection probabilities that they would take a lifetime to complete. The justification for the introduction of these concepts therefore lies in the successful predictions which can be made from the model. The conclusion one can draw from the foregoing comparison of the two models is that there are many possible ways to interprete threshold data, and that the signal detection and two-quantum coincidence models each have specific advantages and disadvantages.

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IX

PERCEPTION OF TONAL CONSONANCE

R. Plomp and W. J. M. Levelt*

Consonant chords, as used in music, are characterized by simple frequency ratios of the constituent tones. Although this relation between ratio simplicity and consonance has drawn considerable interest in the past, no unanimous opinion about its origin exists. Recent developments in hearing theory, equipment design, and measuring techniques justified a new study of the phenonenon. It appeared that the experimental results of this study were confirmed by statistical analysis of the chords of musical compositions.

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PERCEPTION OF TONAL CONSONANCE

R. Plomp and W. J. M. Levelt

One of the oldest discoveries in the field of tone perception, dating back to Pythagoras, concerns the singular character of chords produced by a string vibrating in two parts with length ratios of 1 : 1, 1 : 2, 2 : 3, and 3 : 4, respectively. These tone intervals were called *consonances* and on them the harmony of Western music has been developed, especially so since, in the Middle Ages, other intervals with ratios of 4 : 5, 3 : 5, 5 : 6, and 5 : 8 had been accepted as imperfect consonances. Nowadays we know that these consonant tone intervals are characterized by simple frequency ratios of the constituent tones. As such, however, this change in physical description does not throw more light on the phenomenon of consonance, and opinions are still divided as to its origin. Helmholtz's explanation of the difference between consonant and dissonant intervals on the basis of interference between adjacent harmonics (Helmholtz, 1863) has been opposed by many other investigators who tried to explain the phenomenon in terms of perception of the frequency ratio itself, coincidence of harmonics, difference tones or fusion (for references cf. Plomp and Levelt, 1965).

This divergence of opinions on the origin of consonance, combined with the fact that most research on it dates from before 1920, made it attractive to submit the phenomenon to a new investigation in which full use could be made of more recent developments in hearing theory, equipment design and measuring techniques. In this study, a review will be given of the most interesting results of these experiments, as far as they are available now. To avoid misunderstandings, it may be useful to emphasize that the sole concern of our investigation was why consonance is related to simple frequency ratio. Although the concept of consonance is rather vague and may be different for musicians and laymen, this relationship is always involved. In our opinion it refers to the peculiar sensorial experience associated with isolated tone pairs with simple frequency ratios. We shall use the term *tonal consonance* to indicate this characteristic experience. The study of this phenomenon was the purpose of our investigations.

Dimensions in the perception of tone intervals

One possible approach towards the question why consonance is related to simple frequency ratios is to determine in which way tone intervals are categorized or, in other words, which criteria are used in discriminating them. This means, in fact, that we are looking for the psychological dimensions in our perception of tone intervals. If frequency ratio is one of the criteria we may expect to find a corresponding dimension in the experimental results. As, after Helmholtz's conception, dissonance is related to interference, it is of interest to examine intervals consisting of simple tones (sinusoids) as well as intervals consisting of complex tones (fundamental plus harmonics).

The best way to investigate the psychological dimensions in the perception of tone intervals is to use a non-verbal technique, in which a subject is asked to compare his impressions of different intervals. Since, in this respect, the method of triadic comparisons is very attractive, it was used in the present investigation. The subject, then, can operate three pushbuttons, each corresponding with a different tone interval. By pressing these pushbuttons successively the subject has to select the two intervals which sound most similar to him and the two which sound least similar. In this investigation (Levelt, van de Geer and Plomp, 1966) 15 different tone intervals were involved, given by the frequency ratios 1 : 2, 2 : 3, 3 : 4, 2 : 5, 3 : 5, 4 : 5, 5 : 6, 4 : 7, 5 : 7, 5 : 8, 4 : 9, 8 : 9, 11 : 12, 8 : 15, 15 : 16. To avoid the influence of pitch as much as possible, all stimuli had the same mean frequency viz. 500 cycles per second (cps). The component tones of the intervals were either simple tones, or complex tones (with harmonics up to 4000 cps, all with equal loudness). The stimuli were reproduced by a loudspeaker, placed in front of the subject at a sound-pressure level of 55-60 dB (normal listening level for speech and music). Since with a set of 15 stimuli $\binom{15}{3} = 455$ different triads correspond, it was impossible to present any subject with the complete set of triads. We therefore developed an incomplete balanced design consisting of 4 blocks, each of 35 triads. Each block was presented to 4 subjects (non-musicians); they all judged one block of stimuli twice, once for simple-tone and once for complex-tone intervals.

As the blocks were so designed that all 105 possible pairs of stimuli were judged once by each subject, we obtained 16 judgements of each pair. On the basis of these responses, for each stimulus pair a 'similarity index' was computed, defined as the number of times that a specific pair was judged more similar than the other pairs. This resulted in two 15×15 matrices, one for simple-tone and one for complex-tone intervals. Any matrix element thus determines the 'psychological distance' between two intervals, a large similarity index corresponding with a small distance and a small similarity index with a large distance. The most suitable technique for further analysis of such similarity matrices is that developed recently by Kruskal (1964a, 1964b). For a better understanding of the problem, and of the way in which the data were handled, the following brief explication may be of value. Suppose that the perception of tone intervals is determined by three different psychological factors. Then, each of the 15 stimuli can be represented as a point in a three-dimensional space with orthogonal axes, the coordinates of the point corresponding to the contribution or loading of each factor in the perception of the stimulus concerned. The similarity matrix informs us about the relative distances between the 15 points. It will be clear that on the basis of this matrix the best-fitting configuration of the points can be computed. The only criterion of Kruskal's technique is that the rank order of the distances between interval points in the stimulus space must be the inverse of the rank order of the corresponding similarity indices. The degree to which this criterion is not fulfilled can be expressed in a percentage of 'stress'. In our case we do not know a priori how many independent factors are involved. Therefore, perhaps a space with more than three dimensions is required to nonviolate the data. On the other hand, 15 points can anyway be fitted in a 14-dimensional space, meeting Kruskal's criterion with zero stress. Of course, in the final solution that configuration will be taken which has the minimum number of dimensions still acceptable. The best-fitting configurations were computed in all spaces with 10 or less dimensions. This was done by means of Kruskal's MDSCAL computer programme. On the basis of what Kruskal considers as 'fair' stress (10%), it appeared that, both for simple-tone and complex-tone intervals, a three-dimensional space sufficed to fit the data.

For the interpretation of this result it is of interest to look for 'common dimensions' in both spaces. We mean by this that, in the simple-tone interval space, a direction might be found for which the projections of the interval points on an axis in that direction closely correlate with the projections on an axis of the corresponding points (same frequency ratio) in the complex-tone interval space. Computation showed that both spaces had two dimensions in common, in other words in each space a plane was found for which the projections of the corresponding interval points are near to each other (correlation coefficients of 0.935 and 0.944 for the two dimensions, respectively)*. The projections of the stimulus points on this plane are not evenly distributed over the plane but appear to be ordered along a horseshoe-like pattern with interval width (frequency difference between the constituent tones) as a parameter. Without going into further details we may conclude that this relation shows that we have in fact only one underlying dimension, common for both simple-tone and complex-tone intervals, namely interval width.

Furthermore, the question is of interest whether there is a dimension in the perception of tone intervals related to frequency ratio, for we know that consonance depends on it. For that reason in both the simple-tone and complex-tone spaces, a direction has been determined for which the projections of the interval points on an axis in that direction has a maximum correlation with ratio simplicity. Although other measures are also acceptable, the frequency of the lowest common harmonic was taken as a criterion for ratio simplicity (for instance for the interval 1 : 2 the actual frequencies were 333 and 666 cps, so 666 cps was taken; for 2 : 3 the frequencies were 400 and 600 cps, giving 1200 cps, etc.). As the distribution of these frequencies is rather skew, the logarithm was used in the computations. It appeared that there existed an a priori correlation between interval width and ratio simplicity, owing to the intervals selected; therefore, measures had to be taken to eliminate this artefact from our results. After correction for it, we found that, in the complex-tone interval space, a direction could be determined giving a high correlation ($r = 0.914$) with ratio

* We are much indebted to J. P. van de Geer for providing the techniques to compute the common dimensions and the dimension for maximum correlation with ratio simplicity described below.

simplicity, whereas in the simple-tone interval space this was not possible ($r = 0.215$).
Summarizing the results of this experiment, we may conclude that tone intervals, whether consisting of simple or complex tones, are differentiated on the basis of interval width and that, in addition, only complex tones are also differentiated on the basis of simplicity of frequency ratio. This conclusion implies that, for simple-tone intervals, tonal consonance as a sensorial experience can only be related to interval width and not to ratio simplicity. This means that all explanations of consonance in which the harmonics do not play a rôle, have to be abandoned.

Relation between consonance and interval width for simple-tone intervals

Knowing that, for simple-tone intervals, consonance is related to interval width, it is of interest to focus attention on this relation. It was investigated through experiments (Plomp and Levelt, 1965) in which subjects judged simple-tone intervals with different interval width and mean frequency on a 7-point rating scale, 1 corresponding with most dissonant and 7 with most consonant. Some subjects asked for the meaning of 'consonant'. In that case the term was circumscribed as 'beautiful' and 'euphonious'. This is justified because, as had been found earlierly (Van de Geer, Levelt and Plomp, 1962), 'consonant', 'beautiful' and 'euphonious' are highly correlated for naive subjects. The tones were reproduced by a loudspeaker at a sound-pressure level of about 65 dB.
The experiments were carried out for mean frequencies of the intervals of 125, 250, 500, 1000, and 2000 cps. Each subject participated only in one test session in which he had to judge 12 to 14 different interval widths around one of these mean frequencies. The intervals were presented five times in a random order, and only the data of those subjects were maintained who gave sufficiently consistent responses ($r > 0.5$ between the scores of first and last series). In this way, results were obtained for about ten subjects at each mean frequency.
As an example, in Fig. 1 the results for intervals around 500 cps are reproduced. At other mean frequencies similar curves were obtained, thus indicating that there is a clear minimum in the consonance score followed by a broad maximum for wider intervals. This result confirms the validity of Helmholtz's assumption that consonance is related to interference. Two tones very near to each other, give slow beats which

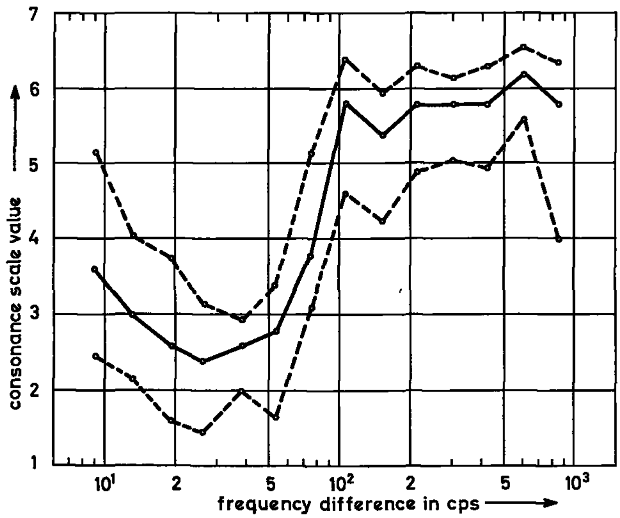

Fig. 1. Consonance rating scores of simple-tone intervals with a mean frequency of 500 cps as a function of frequency difference between the tones. The solid curve corresponds with the median, the dashed curves with the lower and upper quartiles of the scores (averaged over 11 subjects).

are evaluated as consonant. For larger interval widths, these beats are so rapid that the sound obtains a rough and dissonant character which disappears for still wider intervals. However, it was found that, contradictory to Helmholtz's view on the matter, the frequency difference for which the interval is most dissonant, depends on the mean frequency of the interval; this is also the case for the interval width for which consonance score increases no longer.

The question can now be asked whether these data can be related to other properties of hearing. They can, indeed. In recent years, many investigations have been published in which the concept of the 'critical band' plays an important rôle. This critical band, whose width is a function of frequency, can be considered as the resolving power of the hearing organ for sounds of different frequencies (for more details, see the second study). A comparison with the present results shows that tone intervals wider than critical bandwidth are judged as consonant, whereas maximum dissonance occurs for an interval width around a quarter of critical bandwidth. This supports the assumption that dissonance is due to interference.

Consonance for complex-tone intervals

In practice, tones as produced by musical instruments, usually consist of a fundamental and a number of harmonics. This implies that, for intervals composed of these tones harmonics of one of them may interfere with harmonics of the other. Accordingly, the degree to which this occurs will affect the consonance value of the interval. This influence can be illustrated in the following way. From the results of the preceding experiments a standard curve was derived which represents consonance – or dissonance – of simple-tone intervals as a function of interval width with critical bandwidth as a unit (Fig. 2). Assuming that the total dissonance value of a complex-tone interval is equal to the sum of the dissonance values of each pair of adjacent harmonics, this total can be computed by using the right-hand scale of Fig. 2. Although this assumption is rather speculative, it is not unreasonable as a first approximation. Its use may be justified in illustrating how it predicts, for complex-tone intervals, the dependence of consonance on interval width and frequency ratio. On this basis the curves of Figs. 3 and 4 were computed for complex tones consisting of six harmonics. The first figure shows in which way consonance varies as a function of interval width, whereas the other graph illustrates how the consonance of some intervals, given by simple frequency ratios, depends on frequency.

The curves illustrate: (1) peaks of the curve of Fig. 3 correspond with

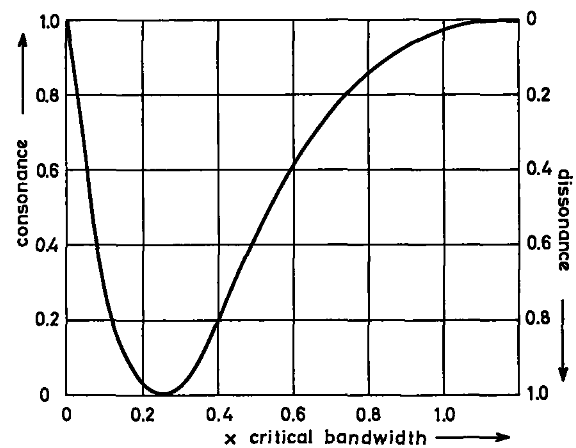

Fig. 2. Standard curve representing consonance of simple-tone intervals as a function of frequency difference with critical bandwidth as a unit. The consonance and dissonance scales are arbitrary.

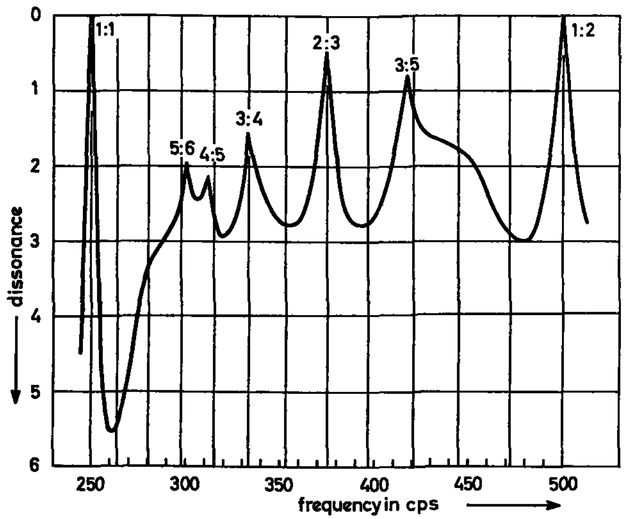

Fig. 3. Illustration of the way in which consonance of an interval with a lower complex tone ot 250 cps and a variable higher one depends on the frequency of this tone. Both complex tones consist of six harmonics. The vertical lines represent interval widths after the equally-tempered scale.

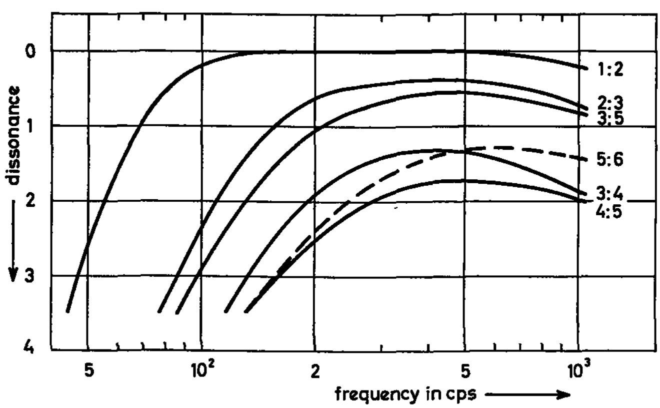

Fig. 4. Illustration of the way in which consonance of some intervals with simple frequency ratio depends on the frequency of the lower tone. Both complex tones consist of six harmonics.

simple frequency ratios of the component tones; this shows that, for complex tones, consonance is related to these simple ratios; (2) more simple ratios are represented by sharper peaks, so the octave (1 : 2) and fifth (2 : 3) are much more sensitive to a deviation from their correct ratio than are other intervals; this explains why in the equally-tempered scale (vertical lines of Fig. 4) the impure thirds (4 : 5 and 5 : 6) are much more tolerable than impure octaves and fifths would have been; (3) the relative heights of the peaks of Fig. 3 and the curves of Fig. 4 fit rather well the rank order of consonant intervals as accepted by musicians; (4) with decreasing frequency consonance is better preserved for more simple than for more complex frequency ratios (Fig. 4), reflecting the musical practice to avoid thirds (4 : 5, 5 : 6) at low frequencies.

Statistical analysis of chords in music

The close relation between consonance and critical bandwidth raised the question whether in music, too, we may find this relation. As the experiments showed, maximum dissonance corresponds with an interval width of about a quarter of the critical bandwidth, whereas consonance increases no longer for interval widths exceeding this critical value. This suggests that especially this range will be of interest in music to differentiate between more consonant and more dissonant chords. To check this assumption statistical analyses of the chords in some musical compositions, the 'vertical' dimension of music, were carried out.

An illustration may serve to explain how the analyses were done. Suppose we are interested in the occurrence of intervals with $c^2 =$ 523.2 cps as the lower tone. We then sort out all chords containing c^2 and a higher tone simultaneously and determine the fraction of time during which the nearest higher tone is separated from c^2 by a distance of 1 semitone, by 2 semitones, etc. It may appear that distances of 1 semitone as well as of 15 semitones are rare, whereas a distance of 4 semitones is rather common. Of this 'density distribution' of intervals we can determine the 50% (median)-, 25%- and 75%-points, respectively. These numbers represent a good measure of the widths of intervals with c^2 as the lower tone. By repeating the procedure for other tones over the relevant frequency range, we can find how the 50%-, 25%- and 75%-points depend on frequency.

As in practice musical tones nearly always consist of a number of harmonics with amplitudes comparable with the amplitude of the fundamental, we are also interested in density distributions in which harmonics have been taken into account. This can be done, popularly said, by plotting the notes of the first n harmonics in the score of the music and treating these additional notes in the same way as the original ones. In this way density distributions can be determined for various values of n, premising that the additional notes fit our tone scale. This is rather well the case up to $n = 10$.

Density distributions as a function of both frequency and number of harmonics were computed, using especially developed equipment, for parts of musical compositions of J. S. Bach, A. Dvořák and A. Schoenberg. In Fig. 5, some results are reproduced graphically, based on the third movement of Dvořák's String Quartet Op. 51. The density distributions of the other compositions led to similar graphs. A comparison of the solid curves with the dashed curves corresponding with critical bandwidth and a quarter of this bandwidth, respectively, shows that, for a number of harmonics representative for musical instruments, all curves have about the same shape. Moreover, the situation of the solid curves demonstrates that most intervals have a width between critical bandwidth and a quarter of it.

These results suggest that critical bandwidth plays an important rôle in music. Apparently the region over which for simple tones the consonance impression strongly depends on interval width is used for 'modulation' between more consonant and more dissonant chords. We should realize that this equally deep 'penetration' in the borderland between pronouncedly consonant and dissonant sounds is a result of many such factors as the Western tone scale, the number of simultaneous tones and the primary intervals selected by the composer. Concerning the latter factor, a comparison of the density distributions of three compositions showed that in modern music the just-mentioned borderland is penetrated more deeply than in older music.

Conclusions

The investigations strongly suggest that the relation between tonal consonance and simple frequency ratio, as it has been found in practice, is a result of interference of adjacent harmonics. The fact that the

Fig. 5. Results of a statistical analysis of the chords of the third movement of A. Dvořák's String Quartet Op. 51 in e-flat major with n (= number of harmonics taken into account) as a parameter. The solid curves represent the 25%-, 50% and 75%-points, respectively, of the cumulative density distribution of intervals, plotted as a function of frequency. The dotted curves correspond with critical bandwidth and a quarter of this bandwidth.

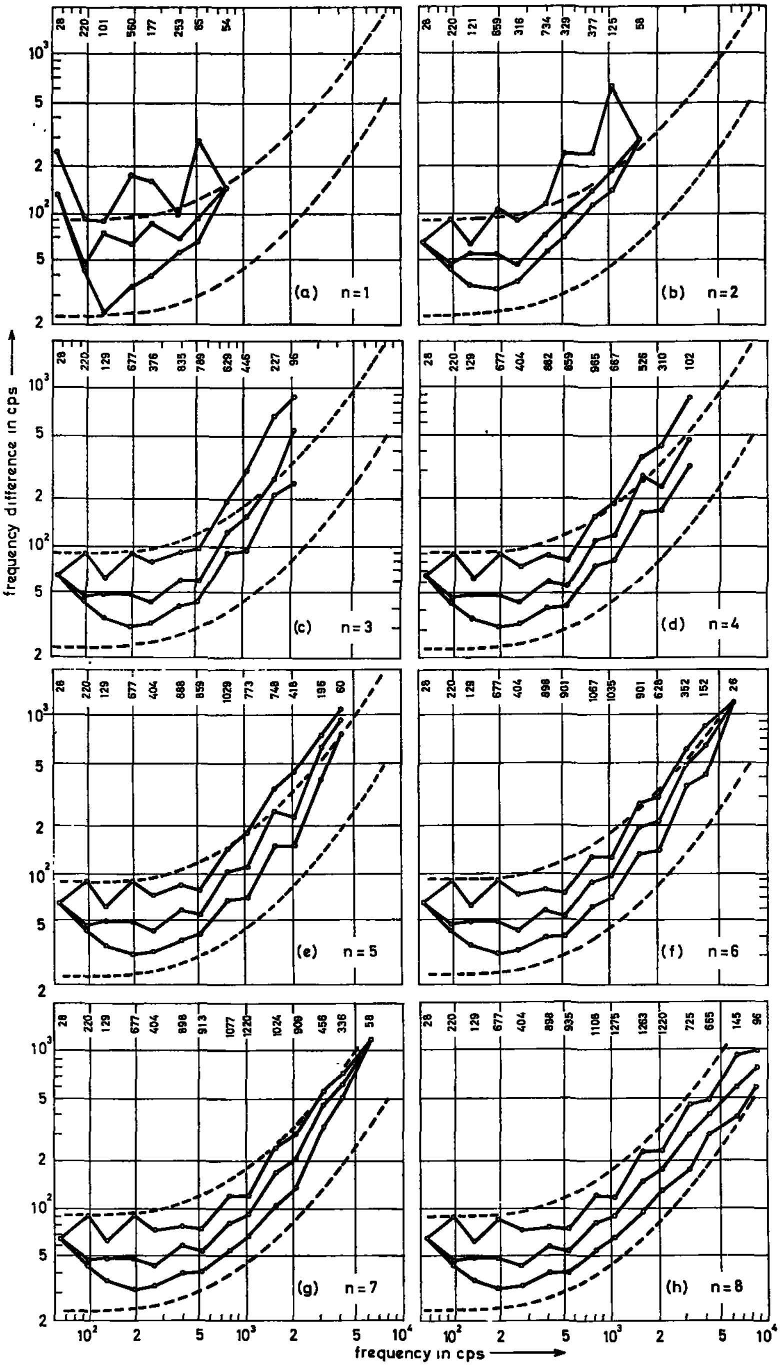
frequency difference in cps
frequency in cps
(a) n=1
(b) n=2
(c) n=3
(d) n=4
(e) n=5
(f) n=6
(g) n=7
(h) n=8

Fig. 5

perception of intervals consisting of simple tones is not governed by frequency ratio, but only by interval width, is confirmed by the finding that for naive subjects, the consonance value attached to this type of intervals is a continuous function of frequency difference. The experimental fact that frequency ratio is an important factor in discriminating complex-tone intervals can be explained by using the hypothesis that, in this case, not only the fundamentals interfere, but that adjacent harmonics do too. Moreover, the experiments showed that this interference only occurs for frequency distances within the 'critical bandwidth'; the most dissonant intervals correspond with a frequency distance of about a quarter of this bandwidth. This relevance of critical bandwidth for the perception of tonal consonance is supported by the results of statistical analyses of chords in musical compositions.

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X

THE FUNDUS AS A SOURCE OF ENTOPTIC STRAYLIGHT

J. J. Vos

When a strong light source enters the field of view it appears as though a veil of light were thrown over the world outside. Close to the light source we are almost completely blinded, but further away too, visual performance is notably hampered. The experience, well known to participants in modern traffic – and who does not participate? –, is usually called 'glare'. Straylight in the eye must be considered as the culprit. Where does this straylight come from? In the present study, one particular aspect of this entoptic scatter process is examined.
A more detailed discussion can be found in the publications 115, 118, 128, and 139 of the cumulative bibliography.

THE FUNDUS AS A SOURCE OF ENTOPTIC STRAYLIGHT

J. J. Vos

That a glaring light source in the dark is seen surrounded by an extended halo must have been known as long as man and light exist. But as a phenomenon of scientific interest these halo's were first considered and described by Goethe (1810). His characterization of them as 'subjective halos' already implies an interpretation. Goethe had realized that the halos were not really there out in space, but that the phenomenon was entoptic in some way. He thought of some kind of neural disturbance in the retina, emanating from the image of the central light source. Purkinje (1823), some twenty years later, offered an alternative explanation in terms of intra-ocular scatter.

By now we know that, though propagation of nervous inhibitive activity in the retina certainly exists, it cannot be thought responsible for the production of the subjective halos. Inhibitive processes would suppress neighbouring excitations, rather than evoke false responses. We have more direct arguments too. The roughly at least, proportional relationship between the intensity of the light source and the brightness of the halo over an intensity range of a factor of 10^5, can hardly be explained in terms of nervous processes. And objective measurements as by Boynton and co-workers (1954) have made clear that there is reason to assume that the amount of intraocular scatter suffices to explain the halo brightnesses found.

Indications about the role of the fundus

Once being so far that the conclusion seems inescapable that straylight in the eye produces the entoptic halo, we want to know where to localize the scatter processes. Slitlamp examination shows that the cornea and lens produce a lot of straylight – at least in comparison with the anterior chamber and the vitreous. But what about the role of the fundus? That we can see it in ophthalmoscopy makes that we have to take it into account as a source of straylight. On the other hand, by all experimental evidence the entoptic halo is hardly different in colour from the central light source, whereas the fundus is well known to be red in appearance. Moreover, should not the fundus act as an integrating sphere, thus giving a uniform veil all over the retina, instead of a brightness, rapidly decreasing according the Stiles-Holladay formula (Holladay, 1926; Stiles, 1929)

$$B \; (:) \; E/\vartheta^2$$

In the formula, E is the intensity of the central glare source, ϑ the angular distance to the glare source and B the halo brightness.

In our opinion these objections have kept many an author from seriously discussing a fundus component in entoptic scatter, Curiously, we can go back as far as Purkinje (l.c.) again to find indications that this ignorance is poorly motivated. Purkinje, we mentioned it already, attributed the entoptic halo to straylight in the eye and, in particular, he thought of scattering at the fundus. As a proof he described his famous experiment on the demonstration of what is now known as the Purkinje vessel figure:

'The just mentioned halos may serve to discover in the inside of the eye a picture which, because of its resemblance, I call vessel figure. When I slowly move a candlelight at a few inches from the right eye from outside the field of view to the opposite side in various directions, or move it in circles around, I perceive on the faint background of the halo a black network of vessels originating from the place of entrance of the optic nerve in two main branches upward and two downward...'.

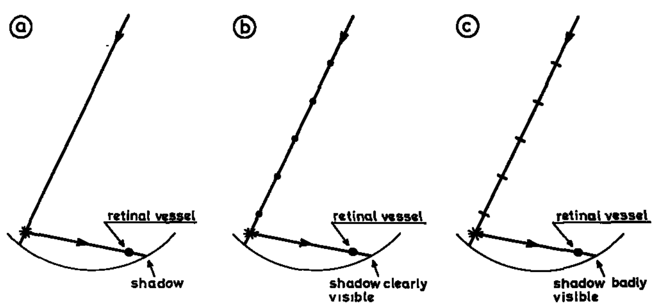

Fig. 1. The visibility of Purkinje vessel figures in natural and in polarized light.

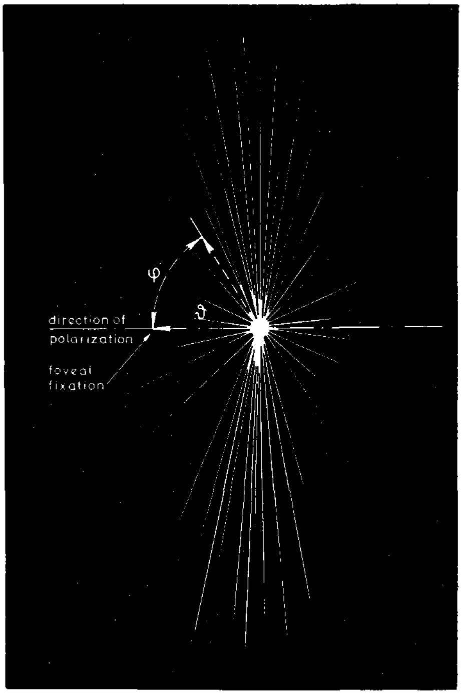

Fig. 2 Schematical indication of the brush appearance of the subjective halo, when the glare source shines in polarized light.

The optics of the experiment Purkinje described, we have tried to indicate in Fig. 1a. What makes the experiment interesting from our point of view, is that the vessel figure disappears as soon as we stop moving the 'candle light'. It proves that scattering in the cornea and lens cannot produce the effect since in moving the candle light nothing changes in the anterior part of the eye.

Now Boehm (1940) made an interesting and important refinement in Purkinje's observation technique. He polarized the light of the glare source and found that, depending on the orientation of polarization, the vessel shadows were more or less visible in the foveal region (Fig. 1b,c). It is so simple an experiment that any one can easily verify it with no other means than a screened light source and a sheet of polaroid. In terms of optics we have to attribute this effect to the presence of a not too thin single-scattering layer near the fundus. Single-scattering because of its polarization dependence, which certainly would get lost if multiple scattering would dominate; not too thin in order to get sufficient intensity notwithstanding the small scatter capacity per particle.

One would expect that the entoptic halo has a brush appearance, if the central light source is polarized. As so many entoptic phenomena, however, this brush appearance is hardly visible in stationary illumination. But it becomes clearly visible when the sheet of polaroid is rotated in front of the light source (Fig. 2). Boehm attributed these, what I should like to call 'Boehm brushes', to light scatter in the retina itself. It is the only layer of the fundus, which we can expect to produce single-scattering. Moreover, the visibility of the Boehm brushes follows the thickness of the retina. When the light source is fixated with the fovea, the pattern is hardly visible, but it is quite conspicuous with peripheral fixation.

Clearly, a study of the Boehm brushes can provide important information on at least part of the contribution of the total fundus to entoptic straylight. Boehm studied their visibility by changing the ellipticity of polarization – until, at the 'threshold ellipticity', the brushes become invisible. He has applied this method to compare clinical cases, but it cannot be used to obtain information about the absolute amounts of straylight. We have, therefore, chosen a different approach and actually followed two ways.

Experiments on the Boehm brushes

By adding to the entoptic Boehm pattern an ectoptic field with similar appearance, but rotated over 90°, we filled the dark parts with a pseudo Boehm pattern with accessible, and thus measurable, luminance distribution. When they are both offered to the eye, and rotated together, one can measure, by changing the intensity of the pseudo Boehm pattern, how much light is needed to fill the dark parts, and make the brushes disappear. By dividing the thus determined brightness difference by what is known to be the halo-brightness according to the Stiles-Holladay formula, we find the brightness modulation on the halo due to the polarization dependent retinal straylight (Fig. 3).

In this figure, we have plotted all data, measured for various wavelengths of the glare light: wavelength turned out to be a insignificant parameter. We see that the retinal share in entoptic straylight can amount to even some 40% with peripheral positions of the light source. With foveal fixation this is reduced to less than 20%, due to the reduced thickness of the retina in this region.

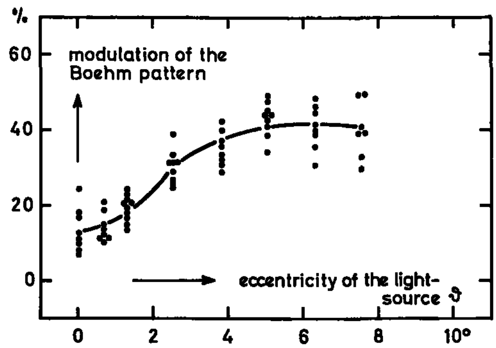

Fig. 3. The modulation of the Boehm pattern as a function of the position of the light source in the field of view. The results for various wavelengths are plotted together.

Of course, this overall method to determine the brightness distribution in the Boehm pattern cannot be but rough, since complete equivalence of the real and the pseudo Boehm pattern, at all distances from the central light source, can hardly be attained. A more refined approach therefore, is to determine the halo brightness using the 'equivalent veil' technique. Otherwise visible objects are obscured by the veiling effect of the halo. With threshold determinations, one can compare this obscuring effect with that of an ectoptic light veil and thus determine, quite locally, the equivalent veiling brightness.

We have applied this technique on the Boehm pattern. The light source was offered to the subject in the near periphery at angles ϑ between 2° and 8° to the temporal side. The determination of the thresholds, and thus of the equivalent brightness was done with foveal vision. With vertical polarization of the glare light, the fovea is covered by the bright parts of the Boehm pattern ($\varphi = 90°$), with horizontal orientation by the dark parts ($\varphi = 0°$). As a matter of fact, the equivalent veiling brightness was found to change by about 20% between both extreme orientations of the polarization plane (Fig. 4). The difference is small, smaller than might be expected from Fig. 3, but significant. That it is smaller by a factor of 2 than the difference found earlierly need not bother us. The conditions were different. In the earlier experiments the whole parafoveal region was active in some way and, due to the low light level, rods will have played a predominant role in the production of a brightness sensation. In the second, better controlable, experiment, only cones could be active. And cones, directionally sensitive as they are towards the pupil, suppress fundus

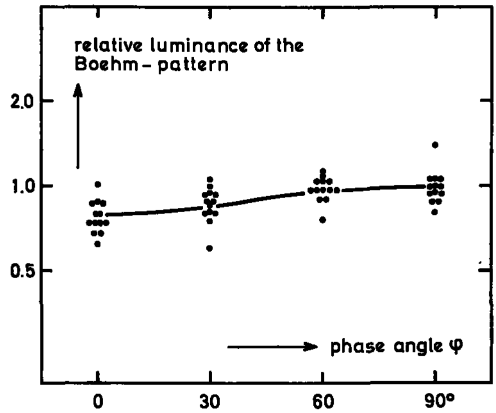

Fig. 4. The relative luminance of the entoptic halo in foveal perception as a function of the orientation of the polarization of the central light source. The results for various eccentricities of the glare source in the field of view are plotted together.

to fundus straylight. On the ground of the experiments described we may thus conclude:

a. There is a measurable and not negligible component in the entoptic halo, which is due to scattering in the retina.
b. Within the limits of accuracy, this component is independent of wavelength.

Experiments on the Stiles-Crawford Effect in glare

Of course, from this experiment we have only learned something about the retinal share – which does not say all about the fundus as a whole. However, encouraged by the findings on the retinal component, we did another experiment, and this time on the whole fundus component (Fig. 5).

Let us for the moment assume, as a simplification, that there are only two notable scatter centres: the anterior centre, composed of cornea and lens; and the posterior centre: the fundus layers. The simplification is not unmotivated in view of the relative optical emptiness of the vitreous, as evident from slitlamp photographs. Let us now consider what will happen to the halo, if the light of the central glare source enters the eye as a narrow light beam, and we vary the point of entry of this beam in the pupil. Nothing should change in first appearance. The scatter angles in the anterior eyemedia hardly change, and it seems

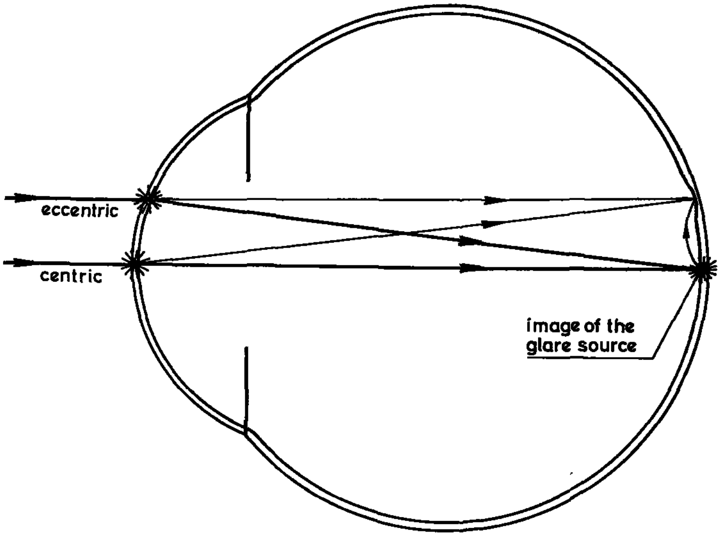

Fig. 5. The optics of the eye, as to direct light and straylight, when the light beam enters the eye in a centric, or eccentric, position.

improbable that the sideward scattering at the fundus is so sensitive to a small variation in the angle of incidence that we should find a measurable difference in its contribution to the halo brightness.

In fact, when we looked for variations in the halo brightness, we could not find any such effect, when rod vision could be assumed. In this experiment, the light source, focussed on the fovea, was blue (450 nm) and the equivalent brightness of the halo was determined in the periphery at 5° off the fovea – experimental conditions which guarantee rod vision only.

With foveal determinations of the halo brightness, however, where only cones are active, we found a distinct decrease in the equivalent brightness with increasing eccentricity of the glare light (Fig. 6). What happens is this: the fundus to fundus contribution does not change, but the component from the anterior media is subject to the Stiles-Crawford effect, and thus follows the normal reduction in luminous efficiency with increasing eccentricity of incidence of the glare beam! Therefore, if the fundus would have been the only contribution to entoptic straylight, a straight horizontal line could be expected (the 100% line); if the cornea and lens would have been the only sources of entoptic straylight, the experimental data should have followed the

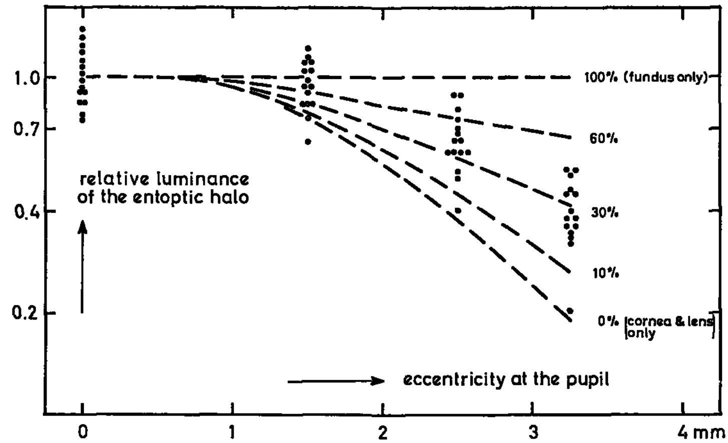

Fig. 6. The decrease in luminance of the entoptic halo with increasing eccentricity of incidence of the glare light at the pupil. The rate of decrease is an indication of the share of fundus straylight in entoptic scatter.

lowest curve (the 0% line), which represents the subject's Stiles-Crawford behaviour. In fact, the experimental data lie between both limiting curves and indicate that the share of the fundus in entoptic straylight is of the order of 30%.

From the experimental data presented we derived that, in foveal observation of the entoptic halo, the share of the total fundus is of the order of 30%, and the share of the retina some 20%. For neither fraction can we claim high accuracy, but it becomes probable that the contribution of the total fundus is mainly due to the retina. When we found that this retinal component was independent of wavelength we obtained a first answer to the question why the entoptic halo has the same colour as the light source and yet is substantially due to fundus straylight.

Theoretical interpretation

The above explanation of the 'colourless' appearance of the entoptic halo is only experimental, and hardly meets the objections raised in the introduction: why the fundus should look red in ophthalmoscopy and yet neutral in endoscopy; and why the entoptic halo should fall in brightness to 50% instead of levelling off – because of its fundus share – to a constant value due to the integrating sphere effect. Some theoretical considerations will be appropriate at this side. Of course, we cannot go into details here, and must refer to other publications. However, qualitatively we may indicate the acting mechanisms.

We have used the word fundus a number of times, without actually defining it. In fact it is a collective noun for a number of layers in the back of the eye: retina, pigment epithelium, choroid and sclera. Together these constitute the ophthalmoscopic fundus image, and together they produce the fundus component of the entoptic halo. Their shape is spherical in good approximation, but their resemblance with an integrating sphere is only superficial. In the integrating sphere (Fig. 7a), the reduction in light intensity by the increase in distance (d) is just compensated by the effect of a better mutual angular position of emitting and receiving surfaces (φ). Essential conditions, however, are that E and R lie on the same sphere, and that both the reflection at E and the reception at R obey Lambert's cosine-law.

One can easily demonstrate the importance of these conditions with a spherical opal glass ceiling luminaire (Fig. 7b) within which a small piece of white paper is glued. When we project a small light spot suc-

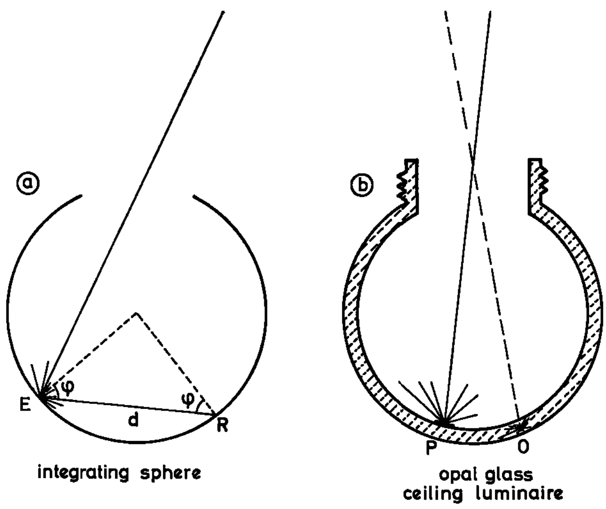

Fig. 7. a. In an integrating sphere, an increase in mutual distance d is compensated in its effect by a decrease in φ, so that the sphere is uniformly bright all over its surface.

b. An opal glass luminance – just like the fundus – does not meet the integrating sphere requirements. This can be demonstrated by alternatingly projecting a light spot at O, and on a piece of paper glued at P, and studying the change in halo pattern.

cessively on the piece of paper, P, and beside it, at O, a dramatic contraction of the halo is noticed.

It will be clear that the actual fundus departs from the diffusing sphere model in many respects:

a. The various layers do not lie on the same sphere, but one behind the other. At large distances along the retina the effect will be small, but radical changes in the picture occur at small angular distances.
b. None of these layers obeys Lambert's cosine-law, which only holds for a simple, smooth, opaque reflector. The retina is not opaque, the pigment layer is not smooth, and the other layers cannot be considered as simply reflecting, because their effective reflectivity is complicated by the absorbing pigmentation in front of them.
c. Finally, the angular receptive properties of the retinal receptors do not obey the cosine-law either. Again: the retina is not opaque – in its receptive function no more than as a scatter medium – and besides, the cone system is directionally sensitive towards the pupil according to the Stiles-Crawford effect.

We have thus to consider the contributions of the various fundus layers separately and with more detailed attention to their scatter mechanisms. The retina, which we saw was the main constituent of the fundus component, is optically thin both as emitter and as receiver and therefore the compensation mechanism between 'd' and 'φ' (Fig. 7a) does not work. As a result, the halo brightness, due to retinal scatter, can be expected to fall with $1/\vartheta^2$, and even sharper yet for small angles of glare because the scatter pattern of the retinal tissue will doubtlessly be directed strongly forward. The pigment epithelium does not reflect much light ,but it is so closely adjacent to the photosensitive outer segments of the receptors that it may nevertheless have a considerable influence. However, this does not play a role any more at angular distances beyond 1°, for which our investigations were done. And in this domain, between 1° and 10° distance to the light source, the rays reflected from the pigment to the receptors should pass so closely along the intermediate parts of the pigment layer that even a small granularity of the surface would suffice to almost completely suppress this scatter component. And a reflection against the sclera through the blood rich choroïd, which should give the fundus component its red colour is even in a worse position. It is always yet subject to two times absorption in the intermediate pigment layer, but at large glare angles the second passage through the pigment is in an oblique direction, so that almost nothing comes through. And straight backward, where the passage is shortest, its 300 micron distance to the outer segments prevents it from adequately competing with the retinal or pigment components.

Much of which we have written above needs quantitative argumentation. We have indicated where the reader can find that. Accepting, for the moment, that the retinal component of fundus scatter is the only component of any significance, he can understand why the entoptic halo does not look red, and why it does not level off to a value of constant brightness. He might ask now, however, in return why, then, the fundus should look red in ophthalmoscopy. Well ,here the situation is quite different. The proximity of the layers to the receptors is of no importance any more, and in back scatter the blood coloured scleral reflexion can play its role. Moreover, now the retina cannot compete adequately, because its scatter pattern was so typically forward. An important, if not dominant, role of the red chorioscleral reflections may thus be expected.

That is why the fundus looks red, and can yet give a 'colourless' contribution to the entoptic halo.

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XI

THE MOON ILLUSION, A MATHEMATICAL RECREATION

J. P. van de Geer and E. J. Zwaan*

In pre-astronautic proverbs the moon usually acts as summit of inaccessibility. How even more detracted from real life the term 'moon illusion' should sound. The authors of the present study have nevertheless tried to make it more abstract a phenomenon yet by a process of mathematical recreation. The curious thing though is that this mathematical play of generalization has direct bearing on such very real problems as that of mediated motion-control – via TV screens in particular. The moon illusion is real – for terrestrial objects as well –, and in situations of 'artificial vision' it may dangerously lead to a disturbed visual-motor feedback.

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J. P. van de Geer and E. J. Zwaan

The large size of the horizon moon seems to have been noticed by attentive observers since antiquity, and many outstanding philosophers have payed attention to the interesting phenomenon. The history of its tentative explanation was written by Reimann (1902). In his article we find among other illustrious names those of Aristotle, Ptolemay, Alhazen, Vitello, Bacon, Kepler, Descartes, Huyghens, Malebranche, Helmholtz, and Gauss. Aristotle thought the phenomenon to be related to nebulae at the horizon. Ever since, these nebulae have played a part in the attempted explanations. Some centuries ago, it was erroneously supposed that the visual angle of objects at the horizon was enlarged, by refraction of light. Then, light absorption, also due to the nebulae, has been considered as a relevant factor up till recent times. Other concomitant factors, like ground texture, perspective and the presence of terrestrial objects between the observer and the horizon moon, which trace back to Ptolemay and Arabian scholars, still have a honorary place in moon illusion theories.

Nebulae, terrestrial objects, and ground texture tend to give the observer an impression of distance which is lacking in the vertical direction. This view is in accordance with the finding that the sky gives the impression of being a flattened dome. Since the days of Ptolemay this principle has been used in explanations of the moon illusion. It states that, if angular size is constant, the perceived size of the moon must be a function of its perceived distance. The same principle would hold for after-images, in which context it is referred to as Emmert's law.

The only difficulty here is the fact that most observers judge the horizon moon to be closer than the zenith moon in stead of being farther away. Two recent advocates of the apparent distance-theory, however, Kaufman and Rock (1962) argue that there is a difference between perceived distance and registered distance, and that only the latter defines perceived size. In the case of the moon, the larger distance is registered in the horizontal direction, resulting in a larger size for the horizon moon. If now the observer is asked whether the moon at the horizon seems to be near or far as compared to the moon in culmination, he might judge the horizon moon to be nearer because of its larger size. This idea, already suggested by Boring, is supported by the authors with experimental evidence.

According to Holway and Boring (1940) the moon illusion is largely dependent upon the angle of regard. The influence of this factor was confirmed by Van de Geer and Zwaan (1964), who also found that the spatial direction of the stimulus object appeared to be a relevant factor. In view of these divergent findings, another approach to the moon illusion is proposed in the following.

A parameter for rate of loss of size constancy

A more sophisticated flattened dome-theory emerges if we assume that a particular spatial direction of viewing is characterized by a parameter for the rate of loss of size constancy. The idea is that at near distances size constancy may be approximated, but at far distances (like that of the moon) angular constancy becomes the rule. We assume then that, with increasing distance of the stimulus object there is a continuous change from size constancy towards angular constancy. To grasp the idea one may imagine a circular disk travelling away from us and of which the objective size is adjusted in such a way that the apparent size remains the same. Let us assume that the disk travels in a space which is somewhat structured by the presence of visible objects or texture, so that at least for near distances size constancy is approximated. This implies that, as long as the disk remains in this nearer region, its objective size needs hardly any correction to suggest constant apparent size. But with increasing distance the objective disk must be increased, and, finally, it has to be enlarged proportionally to the distance from the observer for the disk to retain constant apparent size. If for such a travelling disk we plot objective size against distance we shall obtain what may be called an equimagnitude curve. Such a curve is sketched in Fig. 1.

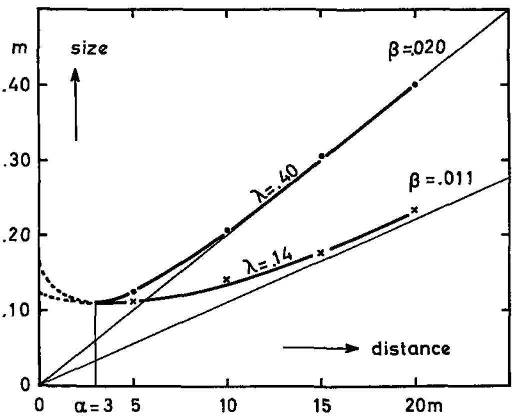

Fig. 1. Two equimagnitude curves matched to empirical data for one subject (Van de Geer and Zwaan, 1964). **x**: horizontal direction, eyes in primary position. • : vertical direction, elevated eyes.

Let this curve be described by some function $y = f(x)$, where y is objective size and x is distance from the observer. Then the foregoing can be expressed in terms of the first derivative of the function. Essentially, dy/dx should be a monotonically increasing function which has zero value at some some value $x = \alpha$, and which tends towards an asymptote at $y' = \beta$. Size constancy and angular constancy would be limiting cases for $dy/dx = o$, and $dy/dx = \beta$, respectively.

A simple function which satisfies our requirements is $y' = \beta\,(1 - e^{-\lambda(x-\alpha)})$, in which λ can be looked upon as a parameter for the rate of loss of size constancy. By integration we obtain $y = \beta\,(x + 1/\lambda \cdot e^{-\lambda(x-\alpha)}) + C$. Since we may safely assume that $f\,(x)$ has asymptote at $y = \beta\,x$, the integration constant C may be set equal to zero (for $\lambda \neq 0$). This implies that if we have two objects seen from the same visual angle, one nearer than the other, the farther one will never appear smaller than the nearer one.

Our function implies that for distances smaller than α an object must be made larger again in order to retain constant apparent size. Although there is evidence that this is true (Blumenfeld, 1913) it should be admitted that for small distances perceived size depends in some intricate manner upon the fixation distance and the particular characteristics of binocular viewing. For the present paper we want to disregard such complications and therefore we shall not attach any meaning to the part of an equimagnitude curve for distances smaller than a.

In Fig. 1 the above function has been roughly fitted to a few empirical measurements obtained in an earlier study (Van de Geer and Zwaan, 1964). Of course, since we have three parameters in our function it is not too difficult to obtain a reasonable fit. Fig. 1, therefore, merely serves to give at least some impression of the effect of variation in λ on the course of the curve. Let us add that the measurements resulted from an experiment which was done in a dark room in which size constancy was already substantially reduced. With smaller values of λ we find a curve which is a good approximation of a size constancy curve for a considerable range of distances. For instance, with $\lambda = .01$, the objective size of an object which travels away from $a = 3$ m to a distance of 20 m, has to be increased with hardly more than one percent in order to retain constant apparent size.

The concept of perceived size

Given an equimagnitude curve as described above one may wonder what might be the 'perceived size' associated to the constant size suggested by the curve. Psychological theories do diverge as to the meaning of 'perceived size'. On the one hand we have theories which deny that 'perceived size' can have any absolute value: perceived size would always be relative (Taylor and Boring, 1942). This means that objects can be ordered as to their apparent size, but the unit of measurement is arbitrary and one cannot say what the perceived size of a single object is. On the other hand we have the phenomenological assumption that an object is perceived as having some size of its own which the observer cannot change at will by simply altering his mental yard stick. A matchbox on my table appears to have a specific size which I cannot manage to make twice as large by just trying hard to multiply the whole space with a factor two.

However, the idea that objects have some absolute perceived size seems to hold only for spaces which are characterized by a fair amount of size constancy. The counterexample is a photograph of a ping pong ball against a uniform background: such a photograph suggests a space without any size constancy and in this case we can perceive the ping pong ball with any size we want it to have.

Let us now attempt to relate such considerations to our parameter a. a is the distance for which size constancy is optimal, in the sense that variations in observation distance near a do not affect perceived size very much; we simply assume that the perceived size associated to an equimagnitude curve is the value of y at distance a. This is $k = \beta\ (a + 1/\lambda)$. We then are able to combine the phenomenological view and the relativistic position. For objects at viewing distance a, size is immediately perceived; such objects have apparent size k. However, objects at a far distance are not perceived as having a specific size of their own; we can say only that their apparent size is equal to that of some other reference object at distance a with size k. The far object then is judged to have size k by virtue of such a comparison with a reference object.

So far we have silently assumed that a is a constant parameter. If a can be interpreted as an optimal viewing distance, however, phenomenological considerations suggest that it is not constant. In fact, to appreciate the size of a large object one would prefer a larger viewing distance than for a small object. Then a would be an increasing function of k. In the following we shall for the sake of simplicity avoid this additional assumption where it does not affect the main argument.

The moon illusion

Let us now see what our equimagnitude curves have to offer as an explanation of the moon illusion. We shall assume, then, that for the horizontal direction of viewing, λ is smaller than for the vertical direction. Why this might be true is another matter to which we shall come back later. Suffice it to remark here that the difference may result from the fact that the horizontal direction is more richly supplied with visible objects or texture so that better distance cues are available and that, as a result, size perception is more veridical than in the vertical direction. Or it may be that the difference in λ results from the fact that in the horizontal direction we look at the moon with eyes in primary position whereas the zenith moon is looked at with deviated eyes.

The equimagnitude curve for the horizon moon will have the same asymptote as the one, valid for the zenith moon. This asymptote is $y = .0087\ x$, where the value of $\beta = .0087$ conforms to the visual angle of 30′ subtended by the moon. In Fig. 2 the situation is illustrated by using the same two values for λ as applied in Fig. 1. It follows immediately that the perceived size k_H of the horizon moon will be larger than the perceived size k_V of the overhead moon. Given the two parameter values, a moon illusion of 1.84 will be obtained.

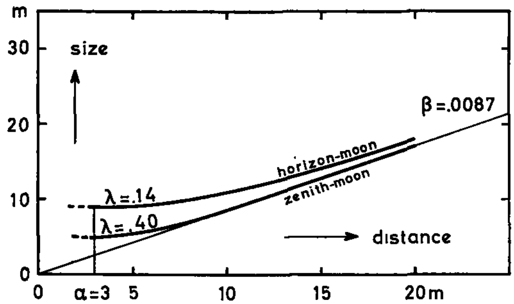

Fig. 2. The moon illusion explained in terms of equimagnitude curves with identical asymptote. The curves are those of Fig. 1, reduced to the angular size of the moon. Magnitude of the illusion for comparison object at $a = 3$ m is 1.84.

The Taylor-Boring paradox

Our curves can also be related to a paradox mentioned by Taylor and Boring (1942, p. 198). In their experiment subjects were instructed to match the size of a comparison disk with the apparent size of the moon. It was incidentally noticed that a match which was valid for the comparison disk at a 3 m-distance appeared much too small when the observer looked at it from a greater distance, and much too large when the observer came nearer. However, as long as the comparison disk wat not related to the moon, its perceived size appeared not to change much when the observer came nearer or moved away. The paradox, then, is that a disk which has approximately the same apparent size for different observation distances nevertheless matches the size of the moon for only one particular observation distance.

The Taylor and Boring experiment was done on the top platform of a large building. In the near space, therefore, visible surroundings were present. The fact that the size of the comparison disk is approximately constant under variation of observation distance shows that in the near space, size constancy was approximated. In our terms, in the near space λ had a small value.

On the other hand, the fact that the matched size of the comparison disk, if it is related to the moon, does depend upon the observation distance, shows that a subject does not compare absolute perceived sizes (i.e., the value of k associated to the equimagnitude curves). The subject rather seems to give the comparison disk that size which the moon would have had if, following its equimagnitude curve, it would

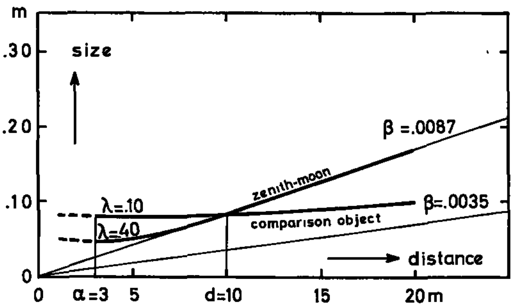

Fig. 3. Explanation of the Boring-Taylor paradox.

approach to an observation distance equal to that of the comparison object.

The explanation of the Taylor-Boring paradox is illustrated in Fig. 3. Given a comparison disk at distance *d*, its matched size will conform to the value of y for the equimagnitude curve of the moon at distance $x = d$. If the comparison disk is looked at in its own right, apart from any reference to the moon, it comes to belong to the near space which has a smaller λ so that the pertinent equimagnitude curve has a much flatter slope. At a distance smaller than *d*, the comparison disk therefore would come to look larger than the moon, and at a distance greater than *d* it would appear too small to match the moon.

The effect of angle or regard

There is considerable controversy in the recent experimental literature about the effect of angle of regard upon the perceived size of the moon. Holway and Boring argued that the moon illusion can be largely attributed to this factor. Its effect was also found by Van de Geer and Zwaan. Kaufman and Rock, however, in a crucial test of this effect did not find any substantial effect of angle of regard. They had their subjects match artificial moons projected on the wall or ceiling of the Hayden Planetarium which was otherwise completely dark; the moon illusion obtained under these conditions was not larger than 1.03 which is far below the values usually found. Kaufman and Rock therefore reject the idea that angle of regard can explain the moon illusion and prefer an explanation in terms of the apparent distance hypothesis.

We do not want to argue with Kaufman and Rock as to the role of distance cues; actually, their experiments are admirable demonstrations of the effectiveness of this factor. However, it might just be possible that apparent distance and angle of regard are both effective and that the two factors interact in some manner. Intuitively, our idea is the following: for a structured space, with many distance and size cues, size constancy will be approximated and it will not matter very much whether the observer looks with eyes in primary position or with elevated eyes. For a less structured space, however, the effect of angle of regard may become substantial. But in the limit the effect vanishes again if the space approximates angular constancy even for an observer who looks with eyes in primary position.

Such a state of affairs can be easily expressed in terms of our parameter λ. We would have to assume only that the ratio λ_D/λ_P (D for deviated eyes, P for eyes in primary position) will tend to unity for small values of λ_P and will increase with increasing λ_P. Under these conditions the moon illusion, defined as $(a + 1/\lambda_P) / (a + 1/\lambda_D)$ will have a maximum for some finite value of λ_P. For instance, if $\lambda_D/\lambda_P = 1 + q\lambda_P$, the illusion will be maximal for $\lambda p = 1/\sqrt{aq}$.

Does our reasoning agree with experimental evidence? First, Kaufman and Rock demonstrated absence of effect of angle of regard for completely dark surroundings where λ may be supposed to be larger, resulting in an illusion which is not optimal. Holway and Boring, however, demonstrated the effect of angle of regard for the actual moon; i.e. they worked during moonlight nights so that much of the surroundings was visible. Therefore, their basic λ may have been smaller than the one valid for Kaufman and Rock's completely dark environment. Van de Geer and Zwaan did their experiments on the top floor of a large building. In their report it is summarily said that this space was 'a long dark room'. Let us admit that this is a not quite adaquate description. In fact, the space was immediately underneath the roof of the building, and this roof appeared to have some leakage of light. Holes in the roof that were at once visible were filled, but the point was, of course, that with increasing dark adaptation more and more leakages became apparent, so that the process of filling them was stopped at some compromise which looked reasonable at the time. Moreover, we may assume that, since the vertical direction was suggested by using a slanted mirror, any visibility that might have remained would be similar in both directions.

Our experiments were done in 1959 and it is impossible at the present to reconstruct the exact visibility of the space during the time of the experiments. Anyway, the space was not completely dark for dark adapted subjects, and our value for λ must have been smaller than that one valid for the Kaufman and Rock experiment.

Depth perception

As a final speculation we might attempt to explain our equimagnitude curves by assuming that distance perception is nonveridical. Actually, if we assume that far away objects are as it were projected on a transparent screen at some finite distance, and that nearer distances are interscaled between this screen and the observer, size constancy can be artificially re-established. One requirement is that the screen should be placed at the distance where $y = k$ intersects the asymptote $y = \beta x$. This distance is $x = \alpha + 1/\lambda$. Let us call this distance η; it is a sort of absolute horizon of viewing.

Our considerations above imply some consequences for η. First, for spaces with low λ, η will be large. On the other hand, a space with angular constance will appear flat as a plane. Further, if it were true that α increases with object size, large objects would have a larger η associated to them than small objects. Said otherwise, behind a large object there is more space available than behind a small object that is at the same objective distance. This might be related to the fact that the large object, in such circumstances, often appears nearer than the small one.

The classical difficulty with such an apparent distance theory is that it implies that the zenith moon, projected at a nearer 'horizon screen', should look nearer than the horizon moon, whereas the majority of observers will agree that in fact the horizon moon looks nearer than the zenith moon. It is our speculation, however, that η is not located at determinate distance. In fact, η means absolute remoteness to the observer; there can be no object farther away than η. Therefore, it seems somewhat contradictory to say that η has determinate distance; if it had one could always imagine an object even farther away.

Let us suppose therefore that η has not a specifiable distance but that it serves as a reference limit: the observer has some amount of space available to him and objects are ordered in depth with reference to their relative position to both the observer and the limiting distance η. The consequence would be that in fact a large object should be located nearer than a small one, as was already suggested above.

Difficulties arise if we asks observers for a comparison between two objects both at a distance η, as in the case of the moon. Actually the question whether the horizon moon is nearer or farther than the zenith moon ought to be meaningless to the observer. But it would require an incredible amount of sophistication for an observer to be immediately aware of the trap that is set for him. Therefore, we may safely assume that what the observer does is to answer the question in the same spirit as he would have done for a comparable question related to objects at a nearer distance: he would say that the larger object is nearer.

Conclusion

Our approach to the problem of the moon illusion can be looked upon as a mathematical recreation. Of course, it is possible to produce further specifications of the mathematical functions we have suggested. But, given the lack of empirical data, there are so many degrees of freedom for further specification that at the present it is a sheer waste of effort to make such an attempt. Let us therefore conclude by emphasizing that experimentation is needed in which there should be much more systematic variation than is usually found in studies of the moon illusion or other size constancy phenomena. For one thing, size comparisons should be made for all kinds of pairs of stimuli, at varied distances, with varied sizes, under different conditions of cue availability, and only then it would be possible to see what kind of mathematical functions would reveal consistency among comparisons for individual observers.

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XII

THE STILES-CRAWFORD EFFECT AS INSTRUMENT OF RESEARCH

P. L. Walraven, J. J. Vos, and C. J. W. Dunnewold*

Research in vision is mostly characterized by laboriously exploring old fields with new experimental and theoretical techniques. Seldom it is marked by discovery of really new phenomena. One such a discovery was that of the Stiles-Crawford effect in the thirties. Though neither its origin, nor its significance for vision are fully understood, it has proved to be a tool of significance, anyway, in vision research.
For details about the investigations mentioned, we refer to nrs. 86, 111, 115, 128 and 136 *of the cumulative bibliography.*

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Until 1933 it had been implicitly assumed that it did not matter as far as the luminous effect was concerned, through which part of the pupil light entered the eye, just as is the case with a camera. However, Stiles and Crawford (1933) discovered that this is far from true, and that the sensitivity of the retina is dependent upon the direction of incidence of the light. Light passing through the border of the pupil, which produces oblique incidence on the receptors, may easily be some five times less effective in eliciting a visual response than light passing through the centre of the pupil. (Fig. 1).

Absorption by the eye media only plays a minor role in the effect, (Weale, 1961). Numerous investigations have established the effect and have made it clear that the effect is principally of retinal origin. It has been convincingly shown that the effect occurs only in photopic vision and not under scotopic conditions.

A completely satisfactory explanation of the Stiles-Crawford effect has not been given. The most promising explanation was put forward by Wright and Nelson (1936). They based their interpretation on the well known fact that the receptors have a refractive index which is higher than the fluid surrounding them. This should make them act as light conductors and, if they are suitably shaped, as light traps for perpendicularly incident light. Obliquely incident light, however, should partly leak out of the receptors and then only partly reach the visual pigments. This explanation nonetheless leaves a number of questions unanswered. Why should central and peripheral cones, with their difference in shape, show identical Stiles-Crawford patterns? Or

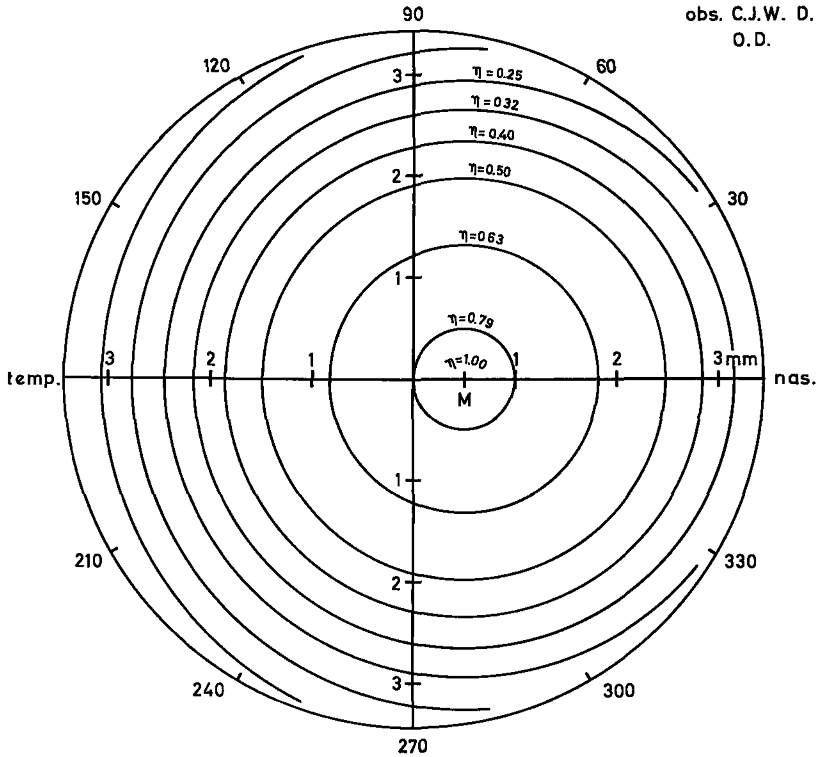


Fig. 1. Normal Stiles-Crawford pattern. The lines of equal luminous efficiency are concentric around a, slightly nasal, centre. Red light.

is this shape difference only an artefact, as suggested by Dowling (1965) on the basis of electronmicroscopic studies of cones? May the directional sensitivity of the individual receptor be much more pronounced than the eye as a whole, as suggested by Enoch (1960), the fact being obscured by a certain degree of disorder in the orientation of the receptors? But, as peripheral rods can hardly be distinguished from central cones, this would imply that rods show less alignment than cones. At the present time there is no reason to believe that this is so.

There are not only many unsolved problems as to the explanation of the Stiles-Crawford effect, but also many areas of ignorance about the role the Stiles-Crawford effect plays in visual performance. In daytime it can not play a role because of the narrowness of the pupil; at night it is of little importance because it is purely a photopic effect. Perhaps its major function is the suppression of entoptic stray light

– which is only another way of saying that light incident through the pupil is favoured. As students of vision, however, we have learned to attribute to the Stiles-Crawford effect quite another kind of significance: that of a powerful tool in visual research. To illustrate this – perhaps teleologically unacceptable – significance we will now give a couple of examples.

A clue to the mechanism of colour vision

Phenomena of colour vision have long been explained on the basis of the existence of three types of cones containing visual pigments absorbing at different spectral bands. A number of psychophysical studies has provided the basis for this assumption. Recent microspectrophotometric studies of cones have provided independent support for this assumption (Marks and McNichol, 1963, Brown and Wald, 1964). These objective measurements provide far less accurate information about cone pigments, however, than do psychophysical experiments. One example of the way psychophysical experiments can give quantitative information on the visual pigments is the determination of the pigment densities from the interrelation between colour vision and Stiles-Crawford effect.

How is the Stiles-Crawford effect related to colour vision? In the first place, it has been shown that the Stiles-Crawford effect is dependent upon wavelength. In the second place a shift in the entrance point on the pupil produces a hue shift as well as a decrease in luminous efficiency. Thirdly, the colour mixture functions change with increasing obliquity of light incidence. Following up suggestions by Stiles (1939) and Brindley (1953), Walraven and Bouman (1960) explored the possibility of relating this whole set of phenomena to certain aspects of absorption of light by the visual pigments. It is in particular the third effect, the break down of the colour match, which directs our attention to the visual pigments. It is hard to imagine how a nervous effect could affect a colour match. Once signals starting from the receptors are equal, the oblique incidence of the light cannot cause any change in the nervous transmission.

It is well known in colorimetry that a colour match cannot be upset unless the shapes of the colour mixture functions change. One possible set of colour mixture functions is the set of absorption curves of the visual pigments themselves. And a change in the shape of the absorption curves can be produced by a change in the optical density of the visual pigment. It follows directly from the exponential law of absorption that the absorption curve of a filter (to which the outer segment of a cone can be compared) broadens with increasing density. This effect starts to be of significance when the absorption in the top of the curve is more than 20%. Now perpendicular versus oblique incidence of the light can be compared with passage of the light through a thick versus a thin filter, respectively. With oblique incidence, the pathway of the light through the visual pigment in the outer segment is shorter than for perpendicular light, due to the light leakage. Thus the change in shape of the pigment absorption as manifest in the breakdown of the colour match is directly coupled to the loss in luminous efficiency as manifest in the Stiles-Crawford effect. This relation is complicated, however, by the fact that only that part of the light loss which occurs in the pigment-containing receptor outer segments is related to the hue effects, whereas the loss of luminous efficiency may be due to loss of light from either the inner or the outer segment. The extent to which the Stiles-Crawford effect is due to light loss in the outer vs the inner segments is not known; thus a direct relationship between the absolute size of the Stiles-Crawford effect proper and the breakdown of the colour match cannot be expected.

If the absorption curves become more narrow with oblique light incidence, this could particularly affect the luminous efficiency at the

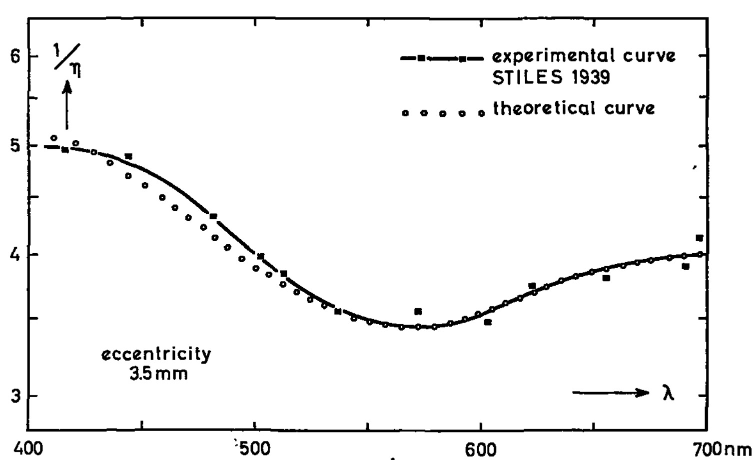


Fig. 2. Dependence of the Stiles-Crawford effect upon wavelength. The dip is attributed to the narrowing of the pigment absorption curves; the asymmetry should be attributed to an inherently stronger Stiles-Crawford effect in the blue cone system. Theoretical curve after Walraven and Bouman (1960).

ends of the visible spectrum with the result that the Stiles-Crawford effect should be smaller in the middle of the spectrum than at either spectral extreme. Such is actually the case, as is shown in Fig. 2. All of the variation of the Stiles-Crawford effect with wavelength cannot be accounted for by a narrowing of cone pigment absorption curves: There is in addition a rise of the Stiles-Crawford effect at the blue end of the spectrum. Stiles (1939) has accounted for this by hypothesing that the blue cones show a larger Stiles-Crawford effect than do the red or the green cones.

The theory that the wavelength dependence of the Stiles-Crawford effect is due to narrowing of the photopigment absorbing curves with oblique light incidence can be tested as follows. If the photopigments are bleached with a bright adaptation light, all pigment concentrations will be reduced to low values, so that the dip in Fig. 2 should disappear. This test has been made by testing the effects of bleaching on the Stiles-Crawford effect at 590 and 650 nm. The pigments have high effective density for light of 590 nm, but not of 650 nm. Bleaching should thus produce little change in the Stiles-Crawford effect at 650, but should produce an increase in the Stiles-Crawford effect at 590 nm. The change in the Stiles-Crawford effect at 590 nm during recovery from bleaching with a 650 nm light, is shown in Fig. 3.

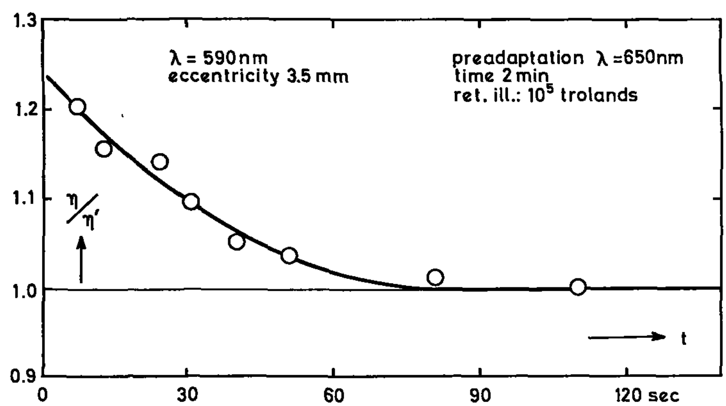


Fig. 3. Recovery of the normal Stiles-Crawford effect at 590 nm after offset of bleaching adaptation light. The Stiles-Crawford factor before and after bleaching is indicated with η and η' respectively.

The recovery rate compares well with the values found by Brindley (1953), who measured the recovery of the breakdown of the colour match. This agreement points again to a common, non-neural origin. At 650 nm, no change in the Stiles-Crawford effect produced by bleaching could be detected. The size of the effect of bleaching, as can be seen from the $t = 0$ value in Fig. 3, is just large enough to make the dip in Fig. 2 fully disappear. In other words, the dip can be completely accounted for by the high pigment concentration.

The absolute value of the pigment concentration cannot be completely specified by these experiments. There remains a certain freedom of choice due to the fact that we do not know to what extent the Stiles-Crawford effect proper is due to leakage from the outer versus the inner segment of the receptors. If the whole process takes place in the outer segments, then a pigment density of 0.3 (corresponding to 50% absorption) is sufficient to explain the phenomena observed. The more the Stiles-Crawford effect takes place in the inner segments, the higher the pigment density must be to account for the phenomena. We can thus specify a minimum density value of 0.3 for the cone pigments at their absorptive peak.

A clue to entoptic scatter

As mentioned before, the significance of the Stiles-Crawford effect in vision might be its suppressive effect on intra-ocular stray light. The receptors are orientated towards the pupil, and thus the normally incident light is accepted with preference to stray light which comes from all directions, scattered as it is by inhomogeneities in the ocular media and at the fundus itself.

With a slight shift in accent one may reformulate the above in the following way. Light scattered at the ocular fundus is, as far as cone vision is concerned, relatively ineffective, and it is independent of the way the primary incident light beam has entered the eye. Stray light from cornea and lens, on the other hand, will be more and more suppressed with increasing eccentricity of incidence, simply because it is subject to the normal Stiles-Crawford effect. Hence we have a means to distinguish between stray light produced in the anterior eye media, and that produced near or at the fundus .We will not go deeper into this subject here, as it is discussed already in more detail in the tenth study, on light scatter at the fundus. We would not fail to mention this aspect, however, within the present context.

As the Stiles-Crawford effect is typically a cone phenomenon, one would expect that the suppressive effects would disappear at scotopic light levels. In fact, indications of this were found (Vos and Bouman, 1959) in measurements of the 'glare capacity' as a function of glare intensity. A difficulty in discussing these data (Vos, 1963) is that we are largely ignorant of the behaviour of the Stiles-Crawford effect – of both rods and cones! – in directions which are obscured by the iris. Our knowledge about the suppression of entoptic stray light rests mainly on guesses, extrapolations, and vague experimental indications. Therefore, any indication about the continuation of the Stiles-Crawford effect outside the pupillar area will be welcome.

One of the sources of information lies in the occurrence of strongly asymmetrical Stiles-Crawford patterns. They suggest, that, in fact, the reduction of the luminous efficiency continues behind the pupil border, so that it reaches values of 0.05 or less. We will return to this problem in the next and last section. Quite another, and as yet unexplored source, might lie in the hue shift of diascleral light. Schouten (1934), who as a first investigated the intensity and spectral distribution of light which enters the eye through the externally visible part of the sclera, noticed a curious hue difference between a light seen through the sclera and the same light when it enters normally through the pupil. His qualitative discription leads one to suspect that he actually noticed a Stiles-Crawford hue shift 'avant la lettre'. More detailed exploration of this Stiles-Crawford effect outside the pupillar area via its hue shift might give a more solid basis for evaluating its suppressive effect on entoptic stray light.

An aid in ophthalmological diagnosis

A third and last example which we will give of possible uses of the Stiles-Crawford effect is in making diagnoses of retinal anomalies, and in following recovery after treatment. Let us make clear, though, that this area is still in an exploratory state; it is far from sure that this application will ever be realized in ophthalmological practice.

We can approach our subject from two sides. The first approach is via the 'Campbell Effect'. In 1958 Campbell found that in looking through a circular aperture of 1 mm diameter placed close to the cornea, visual acuity is maximum when the aperture is over the approximate centre of the pupil. If the aperture is displaced from the centre towards the periphery of the pupil, visual acuity decreases at right angles to the meridian of displacement. It does not decrease, however, in the meridian of displacement. Bypassing the confusion – not the least due to Campbell himself (Campbell, 1960) – about the size and origin of the effect, we can state that a reduction, with increasing eccentricity, of the 'tangential' grating acuity by some 30% must be attributed to causes associated with the Stiles-Crawford effect. An example of this reduction is given in Fig. 4.

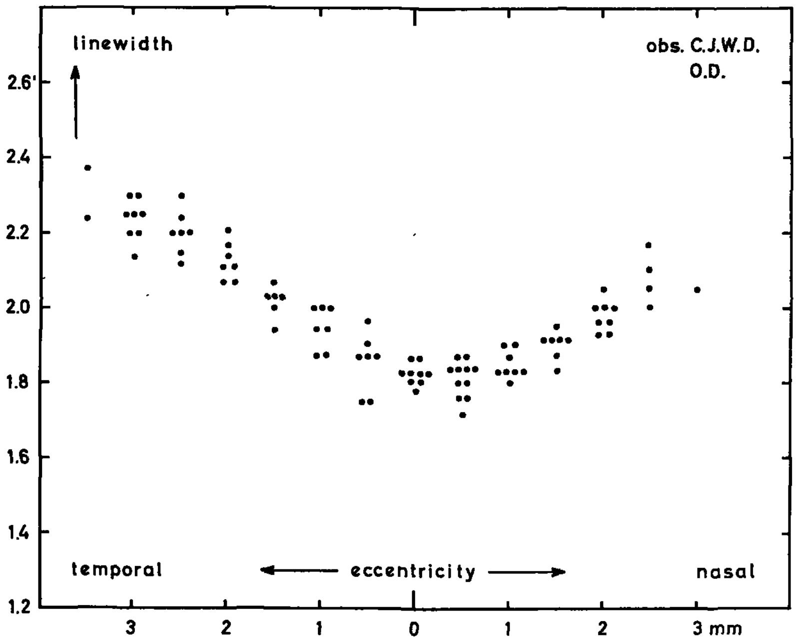
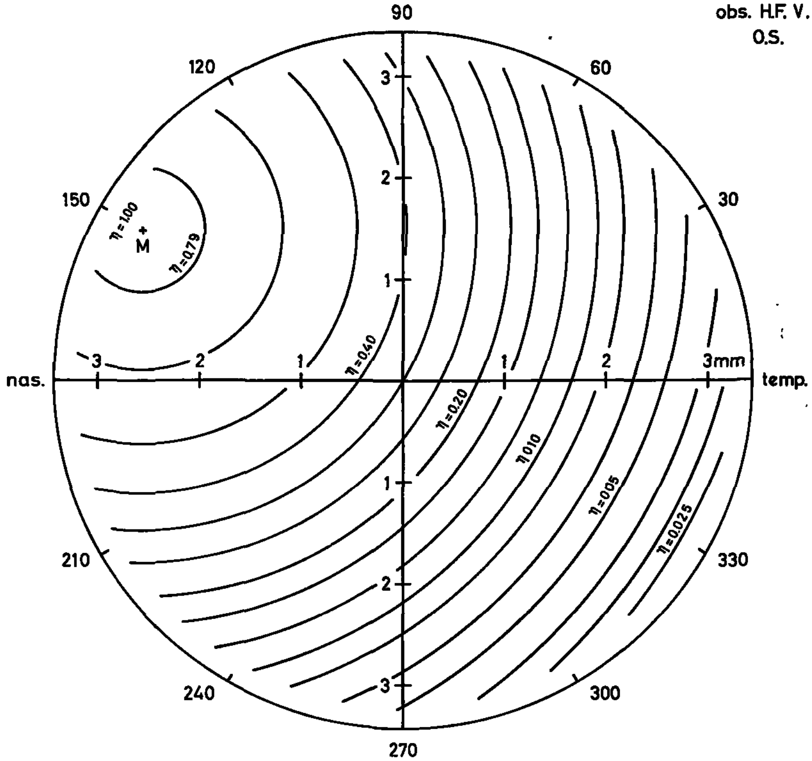


Fig. 4. The just perceptible linewidth as a function of eccentricity of entry of the light beam at the pupil. Same eye, same wavelength as in Fig. 1. Retinal illuminance 5 troland.

The main argument against this effect being due to dioptrical processes, such as spherical aberration, is the coincidence of the maxima of both the visual acuity and luminous efficiency curves in relation to the pupil. This is not only in the normal situation and with such slightly eccentric positions as in the case illustrated in Fig. 4, but also in more anomalous situations where the maximum lies as far as 3 mm off centre (Fig. 5a and b; from Dunnewold, 1964). Qualitatively, this reduction of visual acuity can be interpreted in terms of an increasing leakage of light from one receptor to another, with increasing obliquity of light incidence. But if this is true, one might expect a reduction of visual acuity in such anomalous cases as the just mentioned; the usual



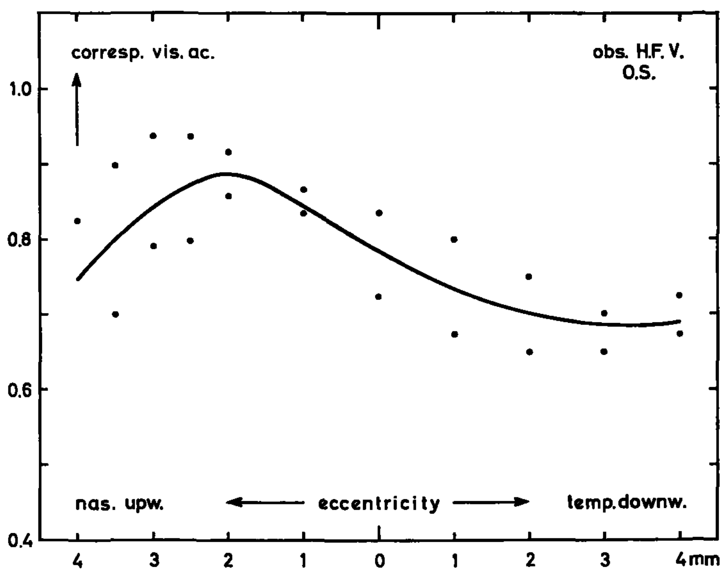


Fig. 5a. Stiles-Crawford pattern of the amblyopic eye of obs. H.F.V.

Fig. 5b. Visual acuity as a function of the point of entry of the light beam in the same eye, along the meridian through the maximum.

clinical test methods are too rough, though, to reveal any such effect in normal cases. For an amblyopic eye with abnormally eccentric position of the Stiles-Crawford top, however, we could measure an acuity effect with Landolt rings (Fig. 5b).

And with that, we have come to the second approach to our subject. In 1957 Enoch described a case of non-squinting amblyopia with abnormally flat Stiles-Crawford effect. Enoch gave an interpretation based on a disturbance of the otherwise orderly receptor orientation and it will be clear that this explanation falls well in line with the reasoning about the origin of the – later discovered – Campbell Effect. Since then, Enoch and coworkers (Enoch, 1959a, 1959b; Fankhauser, Enoch and Cibis, 1961), and Dunnewold (1964) have investigated a number of clinical cases of possible interest, to evaluate the significance of the Stiles-Crawford effect for diagnosis, follow up, and prognosis. Fankhauser, for instance, followed the recovery of retinal strain after light coagulation. Other cases investigated were cases of central serous retinopathy, central retinal oedema, congenital coloboma of the uvea, and prepapillar toxoplasmotic inflammation.

Let us try to summarize the confusing findings.

a. The coincidence of a number of cases of anomalous Stiles-Crawford patterns and ocular disfunction seems to point to a relation. This relation is unclear, however, and only statistical in nature. Typically asymmetric Stiles-Crawford patterns have been found, for instance, without any abnormality in visual performance. Certainly the number of cases investigated is too small to draw definite conclusions.

b. Since the procedure of measuring the Stiles-Crawford effect is time consuming, notwithstanding the development of instruments for clinical measurements of the Stiles-Crawford effect (Vos and Huigen, 1959), further research is called for.

c. The position of the top of the Stiles-Crawford curve with relation to the pupil varies so much from subject to subject, that it is difficult to decide on that basis whether a Stiles-Crawford pattern is anomalous or not. Moreover, the correlation between the positions of the maxima in the left and right eyes of one subject is hardly better than that between the eyes of different subjects. Thus the 'normal' eye can not be used in clinical practice. It is possible, however, that in future it will play a role, notably to diagnose differentially cases of amblyopia, since the Stiles-Crawford effect is the only means of access to problems of receptor orientation. A great deal of laborious research has to be done, however, before we can admit a Stiles-Crawford check into clinical test procedures.

Concluding remarks

We have mentioned three types of application of the Stiles-Crawford effect to other fields. One field is that of colour vision. Here it proved a useful means of obtaining more knowledge, in particular about pigment densities. A second field was that of entoptic light scatter. Here the Stiles-Crawford effect opened the way to being able to distinguish between light scattered in the anterior eye media and at the fundus. Finally its relevance to ophthalmology was discussed. It is not excluded that at some future time the Stiles-Crawford effect will find application in the diagnosis and prognosis of cases of retinal disfunctions.

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XIII

PERCEPTION RESEARCH AND HUMAN ENGINEERING

P. L. Walraven and A. Lazet

To apply the knowledge and know-how, obtained in perception research, the human engineering department fulfills an important role as a link between laboratory and practice. Some aspects of this activity of human engineering may be illustrated with examples taken from the departments record.

PERCEPTION RESEARCH AND HUMAN ENGINEERING

P. L. Walraven and A. Lazet

The studies brought together here bear upon fundamental problems of perception. Does this mean that the application of the results is outside the competence of the authors? This certainly is not the case; we would therefore like to discuss the relationship between these studies and practice.

It is curious to see that a field of science such as perception research which is so close to daily life does not contain striking examples of direct applications. The key to understanding this is the complexity of the relation between theory and practice in this field.

The application of perception research has two aspects, a medical-psychological and a technical aspect, because the object of study is the human being in his environment. An illustration of this can be found in traffic safety research. Perception is a key-factor in traffic. In order to keep traffic safe, one has to banish from the highways those whose perception is inadequate and advise those with hampered perception how they can overcome their difficulties while driving. Development of selection procedures, indication of selection criteria, prescription of glasses, medical treatment, training, all this belongs to the medical-psychological aspect mentioned.

It is obvious that a thorough understanding of perception is necessary to give adequate advice. The reader can correctly assume that the Institute has often given advice of this kind, in connection with many kinds of jobs, such as colour vision selection procedures, ear damage protection etc.

The technical aspect of perception research is that the driver's environment should be adapted to his perception capabilities. The perceptual load of a driver is heavy and one has to do what is possible to shape the environment in such a way as to reduce the perceptual load as much as possible, so that the vehicle is more likely to arrive at its destination without being involved in an accident. A moderate perceptual load means more opportunity to face unexpected happenings. The shape of the roads, highway markers, signs, the interior design of vehicles etc.; all this belongs to this technical aspect, which is called human engineering. We will look at this in more detail, and leave now the example of traffic safety research.

The human engineering department at an Institute for Perception has an indispensable part to perform in such an institute. The practical problems which arise have to be translated into scientific language in order to be handled by the staff. Afterwards the answer has to be translated for the user, and one has to consider how the task can be accomplished technically. The latter situation is often complicated by such restrictions as limited amounts of money. And more has to be considered than just the technical realization of the advice: the future user must also be convinced of its usefulness. Although this no longer concerns research work proper, it is an essential part of the effort of bringing perception research into practice.

Human engineering, defined as shaping the environment in such a way that the human capabilities are handled most effectively, can be divided in many areas, for example: *a.* interior design, the arrangement of groups of men and machines; *b.* display design, the visual presentation of information; and *c.* illumination. These three facets are often combined in a particular project.

We will illustrate, with an example, human engineering work in which these facts can be easily recognized, notably the design of a navigation bridge. When designing a bridge for a vessel the designer faces a number of apparently contradictory requirements. The officer of the watch needs to have a good view and yet requires near by him instruments for determining direction and distance or speed, position finding instruments and other electronic aids, and the means of communicating with the helmsman or engine room, and finally some check on these communications.

If one considers these requirements, it would appear that a suitable solution would be a cockpit arrangement of the instruments (Besnard, 1960). On the other hand, one might ask whether the officer of the watch can remain alert for long periods while stitting in an enclosed compartment. Moreover, the duties of the officer of the watch extend beyond those of simply directing the ship; these sometimes require him to leave the centre of the bridge. This requirement demands a considerable amount of space to walk around in particularly along the windows (Van Rees, 1962). The concept we have put forward (Walraven and Lazet, 1964) is essentially that of recognizing that these two different requirements complement each other, rather than being contradictory.

The men and instruments can be so arranged that all instruments are at hand in the central position. This central position in the fore part of the bridge behind the compass is, in most people's view, the required position of the officer of the watch. Grouping the instruments in front of the officer of the watch, with the principal instruments above the windows, gives all the advantages of a cockpit, but also allows sufficient space in which to walk about and discuss things with other people. The scales on the instruments should be large enough to be read from the wings of the bridge, and symbols of optimal shape should be used (Lazet, 1960). This is necessary because in some cases, such as when entering a harbour, one directs the ship from the wings. The less important remaining dials must be mounted on panels which prevent the disorderly appearance of separate meters. Chart table, compass and radar display should be placed as close to each other as possible. There is a limit, however, because a too close grouping blocks the passage close to the window which is useful as look-out position, as well as for viewing the ship itself. This suggests an arrangement where the chart table and radar display, respectively, are placed on either side of the compass and slightly behind it, so that the officer of the watch has only to take a step backwards to look at either. The radar display must be rotatable.

So as not to loose dark adaptation, deep red light should be used for the illumination of the scales at night time. The appropriate choice of red has been discussed elsewhere (Leebeek, 1955; Vos and Lazet, 1965). Nevertheless the amount of light should be kept as low as possible, and a good method of achieving legibility with a minimum amount of light is to use transparant scales with the light source behind the scale. So as to keep white markers to indicate starboard and red for port, the paint used should be translucent enough for nighttime and reflective enough for daytime. This can be achieved by using a transparent scale-plate and a screening technique.

The chart is best lit by means of a few small bulbs in the chart cover.

A compromise between red and white light should be looked for, because the Decca lines are drawn with different colours. A light-shield, which can be folded up in the daytime, may be placed over the chart table so that the light does not shine out at night. In daytime, this shield may be sunk into the table and the gap remaining at the sides covered with flaps.
If the radar display is screened off from the bridge or is kept quite separated, one can use a broad-band blue illumination system, as developed by Kraft (1958) and Walraven, Lazet and Leebeek (1964), rather than having to keep the radar room dark.
Building a mock-up on a scale of 1 : 1 has proved to be a big help in convincing people of the advantages of a navigation-bridge constructed according the directions as outlined above. In such a case everybody involved can convince themselves that this arrangement is a better solution than the traditional bridge design. Moreover, such a mock-up is a firm base for discussion, not only with the builders, but in particular with the future user. He can suggest modifications before the final construction starts. During the development of a design a regular exchange of thoughts has to take place between the designer and the user, and such a mock-up has turned out to be nearly an indispensable help in accomplishing this efficiently.
Looking back at this sketch of an example of human engineering one savours in nearly every sentence the dependence upon the fundamental research program at the Institute. Suffice to mention the relationship of the display design to the functional visual field, the relation between the advice to use red illumination and studies of dark adaptation, etc. On a base of cooperation between scientists in perception, human engineers and the user, perception research and human engineering complement each other in a fruitful way.

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