Dynamic properties of human brightness perception

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Proefschrift

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus, prof. dr. F.N. Hooge, voor een commissie aangewezen door het college van dekanen in het openbaar te verdedigen op dinsdag 13 oktober 1987 te 14.00 uur

door

Huib de Ridder

geboren te Hilversum

Dit proefschrift is goedgekeurd door de promotoren:

Prof. Dr. Ir. J.A.J. Roufs

en

Prof. Dr. H. Bouma

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"Always look on the bright side of life"

(uit: Monty Python's Life of Brian, 1979)

voor Arnoud

Contents

Introduction

Light entering the eye evokes many sensations. Among the most elementary ones are hue, saturation and brightness (e.g. Hurvich, 1981). This thesis is concerned with the perception of one of these elementary sensations, viz. brightness. In particular, it focuses on the perceived brightness of rectangular incremental light flashes with variable duration, luminance and diameter. In this manner, it is hoped to gain a better insight into the dynamic properties of human brightness perception.

Recently, Shevell (1986) pointed out that "...most people are very comfortable with the meaning of the term brightness; observers readily offer judgments of it (Stevens and Stevens, 1963) and direct brightness matching of nonmetameric lights is a common psychophysical task" (p. 1195). Yet it proves difficult to give an adequate description of brightness. In general, perceived brightness is operationally defined on the basis of its relation to the physical parameter luminance. Cornsweet (1970), for instance, defined brightness as "...that aspect of the perception of a patch of light that varies most strongly when its intensity is changed" (p. 234). He admitted that such a definition is not completely satisfactory but does, nevertheless, have "...a lot of meaning" because it puts into words the subjectively experienced monotonic relation between brightness and luminance. Here, luminance at a point of a surface and in a given direction is defined as the quotient of the luminous flux by the product of the solid angle and the area of the orthogonal projection of the radiant surface on a plane perpendicular to the given direction. Luminous flux is the radiant energy passing a plane per second, weighted by the photopic luminous efficiency function (Wyszecki and Stiles, 1967).

In essence, only two descriptions of the monotonic relation between brightness and luminance have been suggested. Fechner (1860) proposed, on the basis of the constancy of the detection threshold of luminance divided by the luminance itself (the so-called Weber fraction) and some theoretical consideration, that brightness is a logarithmic function of luminance. On experimental grounds, this was opposed by Stevens (1961, 1975) who stated that brightness is related to luminance by a power function. In the last decennia, experimental evidence has accumulated in favour of the power function as the best first-order approximation of the brightness-luminance relation (for reviews, see Marks, 1974; Stevens, 1975; Warren, 1981). However, it should be pointed out that, in general, the exponent of this power function has a relatively low value (e.g. Stevens, 1975) and, hence, it may be difficult to make a definite choice between a power function and a logarithmic function (Wagenaar, 1975).

In 1885 Bloch published his results on the detectibility of rectangular incremental light flashes, showing that at short durations the detection of a flash is determined by its energy. That is, halving the duration of a flash requires a doubling of its luminance in order to be detected again. Nowadays, this reciprocity between duration and luminance is well-established (e.g. Watson, 1986) and regarded as "...probably the most fundamental relation in vision involving time" (Boynton, 1961). It has been found to hold at threshold as well as suprathreshold levels (Aiba and Stevens, 1964; le Grand, 1968). At longer durations Bloch's law does not apply and for sufficiently long durations detection may even become independent of duration. In order to give a description of the transition from Bloch's region to the constant level at long durations, several formulae have been proposed (e.g. Blondel and Rey, 1911; Projector, 1957; Schmidt-Clausen, 1968). These formulae, however, are empirical rules lacking theoretical background. As a result, parameters have to be adjusted for each new condition. For example, time constant "a" of the frequently employed Blondel-Rey relation, in which the effective intensity of a brief light flash is expressed as a function of the intensity of a stationary light, was originally determined to be 0.21 seconds for a point source at threshold (Blondel and Rey, 1911). Later on, this constant was found to depend on variables like stimulus size, background level and dark period between successive flashes (Schmidt-Clausen, 1968, 1971; Williams and Allen, 1971). Furthermore, applicability of formulae like the Blondel-Rey relation is restricted to vision at or near threshold unless the number of free parameters is increased (Schmidt-Clausen, 1968). This is mainly due to the fact that these formulae fail to approximate the rather sharp transitions that are usually observed at certain suprathreshold levels in functions such as equal-brightness curves for rectangular flashes of varying duration (Kishto, 1969; Naus, 1971). This discrepancy is enhanced by the occurrence of the Broca-Sulzer effect. This brightness phenomenon, named after A. Broca and D. Sulzer (1902), refers to the frequently reported observation that a flash of some intermediate duration may appear brighter than a flash of shorter or longer duration while the flash luminance is kept constant. In equal-brightness curves it shows up as a dip at the end of Bloch's region. Also, the Broca-Sulzer effect has been found to occur at shorter durations when flash luminance is increased (Aiba and Stevens, 1964; Mansfield, 1973). In this thesis, this phenomenon will be referred to as the shift of the Broca-Sulzer effect.

One of the main reasons these empirical rules fail at suprathreshold levels may be that they do not take into account the internal responses of the visual system evoked by flashing lights. Allard (1876) was among the first who realized that perception of flashing lights cannot be understood without assuming some internal response. He stated that after switching off a flashing light "...l'impression sur la rétine ne cesse pas de suite, mais elle diminue suivant une certaine loi" (p. 62). Similarly, after the sudden onset of a flashing light "...l'impression n'atteindra pas tout de suite sa valeur définitive" (p. 63). Subsequently, Allard (ibid) introduced an exponential function to describe mathematically the assumed gradual rise and decay of the internal response to a flash. Nowadays one would say that Allard supposed that the visual system responds as a first-order low-pass filter or leaky integrator.

In the last decennia, the kind of approach suggested by Allard (1876) has become an influential and powerful one in the investigation of the dynamic behaviour of human vision. It was initiated by the work of de Lange (1952) who showed that the principles of linear systems analysis can be applied to visual perception provided that a constant state of adaptation of the eye is warranted. At threshold, this condition is fulfilled when the luminance of the background is maintained at a constant level. Moreover, only small signals are involved near threshold and, consequently, linear processing of these signals may be assumed. This systems analysis approach has greatly improved our knowledge of visual dynamics at threshold level (for a recent review, see Watson, 1986).

At suprathreshold levels, the visual system can no longer be assumed to be linear. This can readily be inferred from the above-mentioned non-linear relation between brightness and luminance (e.g. Stevens, 1975). This non-linear behaviour is probably one of the reasons why, up to the present, little attention has been paid to the modelling of the dynamic behaviour at suprathreshold levels. Accordingly, a sufficiently general model on brightness dynamics is still lacking and a brightness phenomenon like the Broca-Sulzer effect can merely be used as an example of how complex the influence of duration seems to be on the brightness-luminance relation for rectangularly flashed lights.

The need for such a general dynamic brightness model gave rise to the psychophysical experiments described in this thesis. The starting point was formed by the suggestion by Roufs and Pellegrino van Stuyvenberg (1979) to expand Roufs' (1972b, 1974a) detection model to suprathreshold levels by adding a non-linearity to this threshold model. The main advantage of this approach is that, in this manner, the general principles of systems theory can also be applied to brightness perception. A refined version of the dynamic brightness model that was suggested by Roufs and Pellegrino van Stuyvenberg (1979) can be found in Chapter 2 of this thesis.

Methods to determine perceived brightness can be divided into two categories: matching and scaling. In a matching task, the brightnesses of different sources are subjectively equated by adjusting some physical parameter which is usually the luminance of one of the sources. In a scaling task, the subject is asked to give an estimation of the strength of the brightness impression, for instance by assigning a number to a stimulus that is in proportion to its perceived brightness (magnitude estimation).

In a series of brightness-matching and brightness-scaling experiments predictions of the dynamic brightness model are tested. These predictions refer to the brightness of rectangularly flashed one-degree (deg) fields and point sources of varying luminance and duration. In Chapters 1, 2 and 3 brightness-matching experiments are presented. Chapter 1 contains experiments on the effect of synchronization on interocular brightness matching of rectangular flashes of unequal duration. In Chapter 2 the influence of stimulus area on the Broca-Sulzer effect is investigated and compared with model predictions. Subsequently, the influence of the background on the shift of the Broca-Sulzer effect is examined (Chapter 3). From a comparison between the results of the brightness matchings and the predictions of the model, several conclusions can be drawn about the influence of stimulus area and flash duration on the exponent of the power function that is assumed to describe the relation between brightness and luminance. These conclusions are used to test the mutual consistency of three direct scaling methods, viz. magnitude estimation, category scaling and bisection (Chapter 4). Finally, the mutual consistency between brightness scaling and matching is examined (Chapter 5). In order to be able to compare the results obtained by the different methods, all measurements were carried out under the same, well-defined experimental conditions.

It has to be mentioned that the chapters are written in such a way that they can be read independently of each other. This may imply some overlap between the chapters, because sometimes it was felt necessary to repeat some of the essentials of previous chapters.

chapter 1

Effect of Stimulus Onset Asynchrony on interocular brightness matching of flashes of unequal duration

Abstract

The investigation of dynamic brightness phenomena like the Broca-Sulzer effect may require the brightness matching of rectangular incremental flashes of unequal duration. This brings up the problem of the synchronization of the flashes. The present study examined the influence of Stimulus Onset Asynchrony (SOA) on the brightness matching of rectangularly flashed point sources, projected against an extended 100 Td background. The spatial separation between the two dichoptically presented point sources was 80 min arc and the subject was explicitly instructed to match the brightness peaks. Under these conditions changes in SOA tend to have little effect on brightness matching. Small but consistent deviations were found at SOAs at which the subject reported apparent motion between the point sources. Similar "constant luminance curves" were obtained at different synchronizations of flashes. It is argued that for the investigation of phenomena like the Broca-Sulzer effect a simultaneous onset of flashes is to be preferred.

1.1 Introduction

Present models of the spatiotemporal behaviour of human vision are based mainly on threshold data. This may limit their applicability to vision at threshold. Realizing that in daily life visual perception is more than detection at threshold alone, attempts have recently been undertaken to develop quantitative models of the spatial and/or temporal properties of human vision at threshold as well as suprathreshold levels (Wilson, 1980; Swanson et al., 1984; Mandler and Makous, 1984; Roufs, 1981; de Ridder and Theelen, 1983, 1984). This has usually been accomplished by adding some nonlinearity to an already existing detection model. Swanson et al. (1984), for instance, implemented sigmoidal contrast transfer functions within each of the spatial channels of the Wilson-Bergen (1979) four mechanism model for threshold spatial vision. Roufs (1981) and de Ridder and Theelen (1983, 1984) used a compressive nonlinearity, described by a power function with an exponent less than one, to generalize Roufs' (1972b, 1974a) detection model for temporal signals to suprathreshold levels.

In order to test these models, one cannot rely on detection criteria anymore but has to make use of criteria which are considered to be more subjective. Apparent contrast in space domain and brightness of achromatic or monochromatic light in time domain are attributes that are frequently applied as criteria. Their subjective character is shown by the difficulty to define brightness. Wyszecki and

Stiles (1967), for example, state that brightness is "...the attribute of a color perception permitting it to be classed as equivalent to some member of the series of achromatic color perceptions ranging from very dim to very bright or dazzling" (p. 229). Holmes (1971) describes brightness as "...a general word, but having the particular meaning of luminosity in the USA", defining luminosity as "...subjective brightness" (p. 87). Normally it is taken for granted that such hard-to-define attributes are always used in the same manner. The correctness of this presupposition, however, may be questioned.

Recently, this problem emerged in the work of Bowen and co-workers (Bowen and Markell, 1980; Bowen et al., 1981; Bowen, 1984, 1986). They investigated a temporal brightness phenomenon known as the Broca-Sulzer effect, which refers to the observation that a rectangular incremental flash of constant luminance but variable duration appears brightest at some intermediate duration (e.g. Broca and Sulzer, 1902; Aiba and Stevens, 1964; Katz, 1964). In order to measure the duration at which this effect occurs, Bowen and Pokorny (1978) employed a method in which during each trial a subject had to compare a pair of equal-luminance flashes of different duration and judge which of the flashes appeared brighter. When the percentage of trials on which the longer one of the two flashes appeared brighter is plotted as a function of duration, the Broca-Sulzer effect will eventually emerge as a minimum. Employing this technique, Bowen and Markell (1980) found that naive observers can be classified into three categories. Type A observers showed the Broca-Sulzer effect for simultaneous onset and offset of test and comparison flash, type B observers showed this effect for simultaneous offset but not onset and type C observers did not exhibit the Broca-Sulzer effect under either asynchrony condition. After having ruled out other explanations, Bowen et al. (1981) hypothesized that the three classes of observers may relate their brightness judgments to different features of the sensory activity evoked by a flash. Type A observers, for example, are assumed to rely on the peak of this activity whereas type C observers may use the integral of the sensory activity. In addition, Bowen (1984) reported that some observers change from one type to another after a number of practice sessions. A similar phenomenon was observed during metacontrast measurements (Ventura, 1980). Both results have been interpreted as manifestations of the ability of subjects to switch from one feature of the brightness impression to another.

This ability to switch from one feature to another was made explicit in an unpublished study by Roufs and Coumans (1978). In their experiments, subjects matched the brightnesses of two point sources, one being presented to the left eye, 6 min arc to the left of a black fixation dot, and the other to the right eye, 6 min arc to the right of the fixation dot. The fixation dots were positioned in the centre of 4 deg circular, "white", 1200 Td background fields which were seen superimposed after fusion. The left-eye stimulus had a Gaussian-shaped time course, lasting about 1200 ms and reaching its fixed maximum at about 590 ms after onset. The right-eye stimulus was a 20 ms flash. The onset of the latter was varied with respect to the onset of the former. In one experiment, subjects had to match the brightness peak of the right-eye flash to the brightness of the left-eye stimulus *at the moment the short right-eye flash appeared* (phase-locked brightness matching). In another experiment, subjects had to match the brightness peak of the right-eye flash to the brightness *peak* of the Gaussian stimulus of the left eye *irrespective of the onset asynchrony* (peak amplitude-locked brightness matching). The results of both experiments can be seen in Figure 1.1. It is clear that different

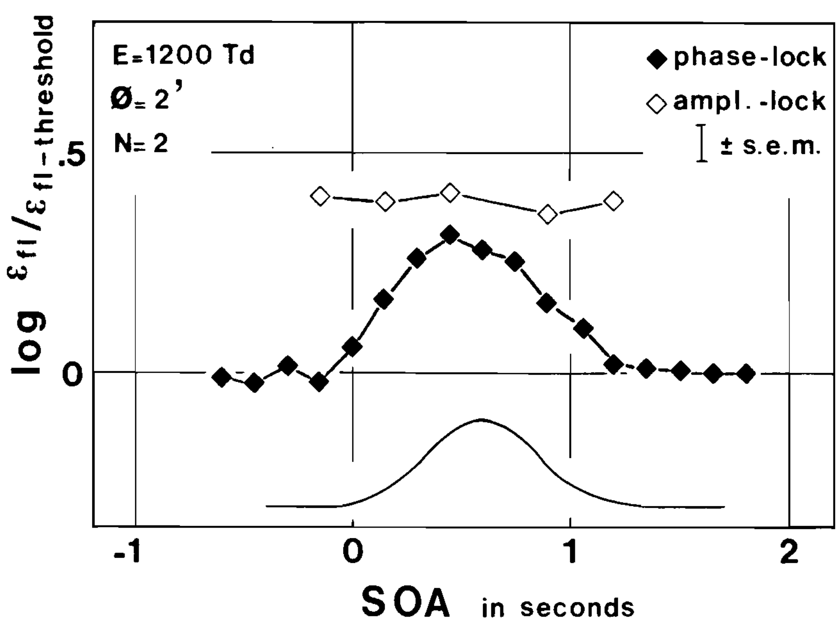


Figure 1.1: Phase- and peak amplitude-locked brightness matching between two dichoptically presented point sources, projected against an extended 1200 Td background. The right-eye stimulus was a 20 ms flash with variable luminance ε_{fl}. The left-eye stimulus had a Gaussian-shaped time course (see inserted function). Luminance ε_{fl}, required to match the brightness peak of the 20 ms flash to the brightness of the Gaussian function in either phase-locked or amplitude-locked condition, is given relative to $\varepsilon_{fl,threshold}$, being the 50% detection threshold of the 20 ms flash. The abscissa denotes the delay of the onset of the 20 ms flash with respect to the onset of the Gaussian function. Data are based on the results of two subjects (Roufs and Coumans, 1978). The data for the amplitude-locked condition have been shifted upwards for clarity of representation.

instructions lead to different results. The phase-locked brightness matching yields a function that reflects the Gaussian shape of the stimulus. The function is shifted approximately −100 ms along the time axis. This shift probably reflects a delay in response to the short flash. The instruction to match the brightness peak gives an almost flat curve. Accordingly, these results show that it is possible and perhaps necessary to direct the attention of a subject to a particular, well-defined aspect of the brightness impression evoked by a stimulus, for instance the brightness peak. Bowen (1984) never instructed his subjects in this way but let them choose their own criterion. This may, in part, explain the finding of different classes of observers.

Brightness matching techniques yield data which can easily be affected by the choice of experimental conditions (e.g. Raab and Osman, 1962; Bowen and Pokorny, 1978). The results of Roufs and Coumans (1978) and Bowen (1984) have already pointed out the necessity of giving explicit instructions to subjects about their brightness judgments. But precautions should also be taken to prevent conditions in which stimuli can exert spatial and/or temporal influences on each other. The former is usually accomplished by presenting stimuli dichoptically using a spatial separation between the stimuli (e.g. Bowen and Pokorny, 1978). The solution for the latter, however, is less obvious. For the measurement of the Broca-Sulzer effect, for example, several temporal alignments have been recommended, varying from sequential order to simultaneous offset (Aiba and Stevens, 1964; Katz, 1964; Nachmias and Steinman, 1965; Naus, 1971; Bowen and Pokorny, 1978; Di Lollo and Finley, 1986). The final choice is often based on the subject's preference (Katz, 1964; Bowen and Pokorny, 1978). The data of Bowen (1984), however, suggest that the possible role that stimulus onset asynchrony (SOA) may play in the verification of dynamic brightness phenomena like the Broca-Sulzer effect should not be neglected.

The present study addresses the question of whether interocular brightness matching of rectangular incremental flashes of unequal duration is influenced by changes in SOA when the subject is explicitly instructed to match the brightness peaks. To this end, two experiments are carried out. In the first one, the subject has to match the brightness peak of a short (16 ms) flash to that of a long (256 ms) flash and vice versa, varying the onset of the former with respect to that of the latter. In the second experiment, a flash of constant luminance but variable duration and a flash of variable luminance but constant duration are matched in brightness under two asynchrony conditions. In all cases, the subject is instructed to match the brightness peaks.

1.2 Method

Apparatus

A six-channel, binocular Maxwellian-view optical system provided the same spatial configuration for both experiments. In Figure 1.2, only the left half of the optical system is presented since the right half is an exact copy of the left one. The two halves are located on separate plateaus which move independently of each other in the horizontal plane. In this way, the optical system can be adjusted to the posi-

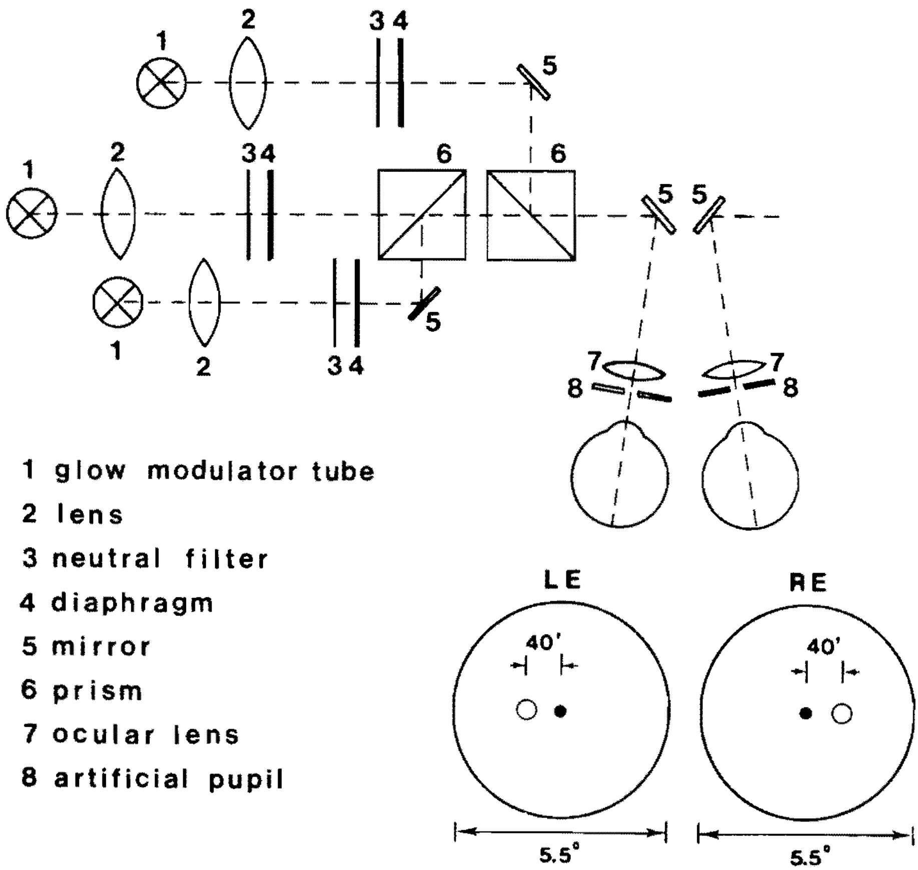


Figure 1.2: Scheme of the left half of the optical apparatus. The spatial configurations, presented to the left and right eye, are not drawn to scale. After fusion, both the backgrounds and the centrally positioned fixation points were seen superimposed.

tion of the subject's eyes, thus preventing disturbances of accommodation caused by vergence of the eyes. The light source of each channel is a glow modulator tube (Sylvania type R1131C) the light output of which is controlled electronically, special precautions being taken to prevent temperature effects. The amplitude of the light output is regulated roughly by neutral density filters and more precisely by attenuators, adjusting the intensity in one-dB steps. A one-dB step changes the intensity by 0.05 log units.

Two of the light channels, one for each eye, produced 5.5 deg circular, uniform "white" backgrounds, the retinal illuminance of which was kept constant at 100 Td. Two other channels projected small, dim, red fixation points in the centre of these fields. After fusion, both the backgrounds and the fixation points were seen superimposed. Achromatic point sources, 2 min arc in diameter, were flashed against the background by the remaining two channels. The point source projected in the left eye appeared 40 min arc to the left of the fixation point. Similarly, the point source projected in the right eye appeared 40 min arc to the right of the fixation point (Fig. 1.2). The point sources were always presented as rectangular increments, obtained by modulation of the light output using pulse generators. The subject saw the whole stimulus configuration through two eye pieces which were fitted with artificial pupils 2 mm in diameter and equipped with entoptic guiding systems (Roufs, 1963). In order to optimize fixation, the head of the subject was immobilized using a chin-and-head rest.

Before each experiment, the whole configuration was calibrated with a cooled photomultiplier tube (Philips XP 1002) placed in front of the eye pieces. The $V(\lambda)$ corrected photomultiplier tube had previously been calibrated against a standard light source (Spectra Regulated Brightness Source).

Procedure

At the beginning of each session, the subject was dark-adapted for about 10 minutes before he adapted to the 100 Td background for about 2 minutes. In the experiments following that, the subject always started a trial by pushing a tapping-key. In the first experiment, a 256 ms flash appeared in the left or right eye 500 ms after key contact. The onset delay of a 16 ms flash presented to the other eye varied between 200 and 990 ms, thus creating 13 SOA values which ranged from −300 to +490 ms. In each session, the luminance of either the 256 ms flash or the 16 ms flash was kept constant while the luminance of the other flash was varied. The method of constant stimuli was employed to determine at which luminance of the last-mentioned (variable) flash the subject judged this flash to be brighter than the constant flash in 50% of the trials. This method does not exactly produce the luminance defining the point of subjective equality since the instruction forces the subject to surpass a just noticeable brightness difference which is reflected by a just noticeable difference in luminance. However, it seems fair to assume that the Weber fraction is constant for the experimental conditions employed in the present study (e.g. Cornsweet and Pinsker, 1965; Whittle, 1986), leading to a constant shift of the data when they are expressed in log units. Furthermore, it can be shown that this effect is small, in the worst case being 0.07 log Td. During a given session, matching of the brightness peaks was performed for all SOAs, the 256 ms flash appearing continuously in the same eye.

In the second experiment, the onset of the left-eye flash had a fixed delay of 500 ms. Its luminance was kept constant but its duration varied between 4 and 975 ms. The right-eye flash always lasted 256 ms. In one condition, the left- and right-eye flashes had a simultaneous onset (SOA=0 ms). In another condition, a constant Inter Stimulus Interval (ISI) of 300 ms existed between the offset of the left-eye flash and the onset of the right-eye flash (ISI=300 ms). Again, the method of constant stimuli was employed to determine at which luminance of the right-eye flash the subject judged this flash to be brighter than the left-eye flash in 50% of the trials. A "constant luminance curve" is obtained when this luminance is plotted as a function of the duration of the left-eye flash. During a session, only one complete curve was measured for one asynchrony condition, presenting the durations of the left-eye stimulus in a random order and reversing this order in each second session.

Subject

The experiments were performed by one male subject (the author, 29 years old) who had normal, uncorrected vision. At that time, he had no previous experience with this kind of psychophysical research.

1.3 Results

1.3.1 SOA and brightness matching of flashes of unequal duration

The results of the first experiment are shown in Figure 1.3. The four experimental conditions, symbolized by the pictograms at the right side of the curves, were: (a) 256 ms flash with fixed retinal illuminance (3.05 log Td) presented to the left eye; (b) 16 ms flash with fixed retinal illuminance (3.84 log Td) presented to the right eye; (c) 256 ms flash with fixed retinal illuminance (3.02 log Td) presented to the right eye; (d) 16 ms flash with fixed retinal illuminance (3.35 log Td) presented to the left eye. The data are the average of six measurements. During a session, only one complete curve was measured, presenting the SOA values in a random order. Each second session was a repetition of the previous one, the SOA values appearing in the reversed order. Although there are some small fluctuations, the curves of Figure 1.3 tend to suggest in view of the extended scale that changes in SOA have little effect on the matching of the brightness peaks of the 256 ms and 16 ms flashes. This is supported by the fact that averaging the results of the four conditions yields a function independent of SOA (Fig. 1.4, curve a). This function was obtained after having normalized each curve of Figure 1.3 with regard to the retinal illuminance measured at SOA equal to 0 ms.

A closer look at the curves of Figure 1.3, however, reveals a small but systematic variation in the data. The functions, obtained when the luminance of the 256 ms flash is kept constant (curves a and c), are a more or less mirrored version of the functions, obtained when the luminance of the 16 ms flash is kept constant (curves b and d). For example, curves a and c show a minimum around the offset of the 256 ms flash while curves b and d show a maximum for the same SOA values. In order to prove the existence of such systematic deviations, the averaging procedure was repeated, but in this case the data of the normalized curves of conditions b and d were reversed in sign before the averaging occurred. The resulting function is curve b of Figure 1.4. Two deviations can be observed,

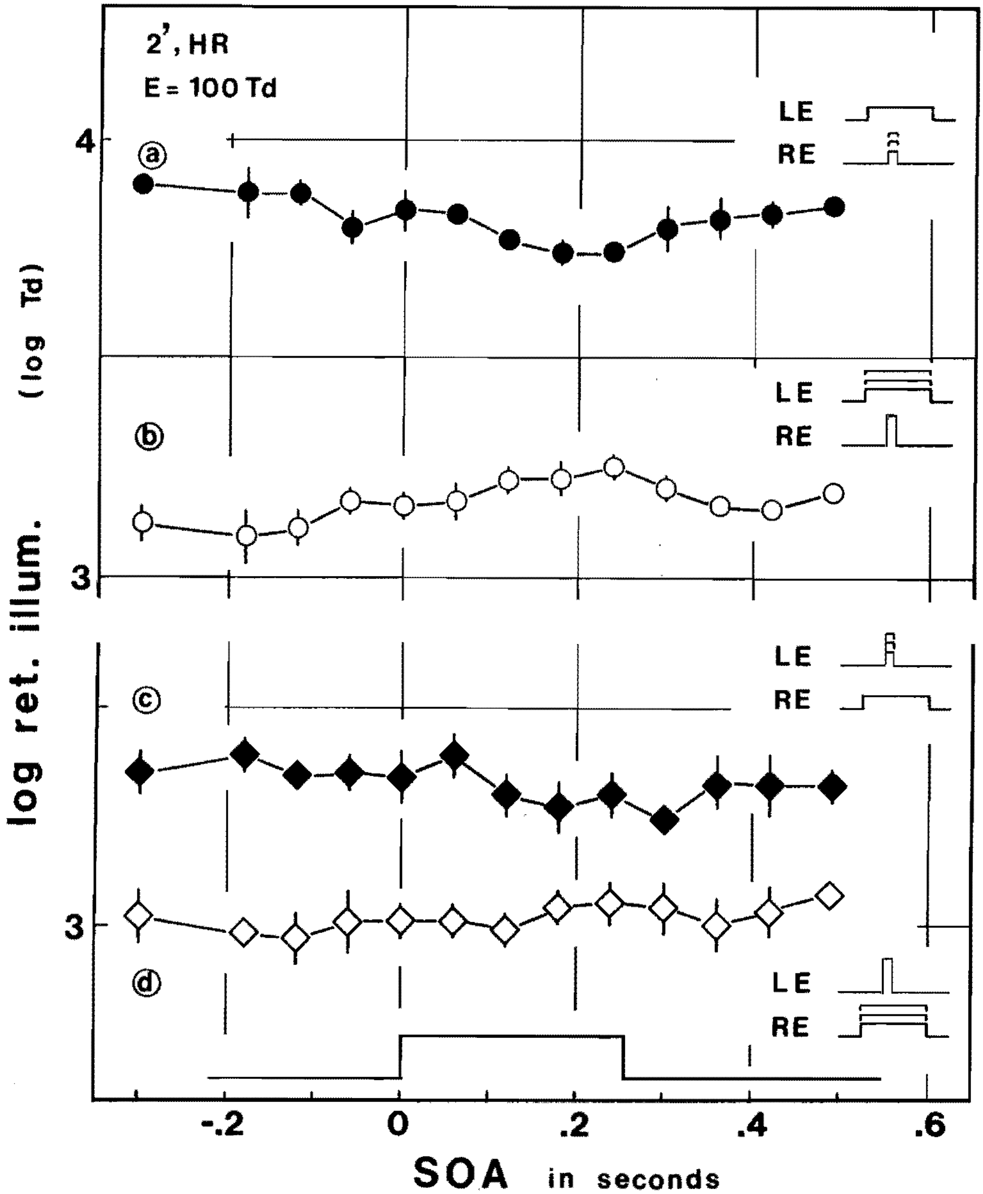


Figure 1.3: Brightness matching between two rectangularly flashed point sources, projected against an extended 100 Td background. The flashes lasted 16 and 256 ms respectively. The abscissa denotes the delay of the onset of the 16 ms flash with respect to the onset of the 256 ms flash. The four conditions were: (a) 256 ms flash with fixed retinal illuminance (3.05 log Td) presented to the left eye; (b) 16 ms flash with fixed retinal illuminance (3.84 log Td) presented to the right eye; (c) 256 ms flash with fixed retinal illuminance (3.02 log Td) presented to the right eye; (d) 16 ms flash with fixed retinal illuminance (3.35 log Td) presented to the left eye. For each condition the ordinate gives the retinal illuminance of the remaining flash which appears in the other eye and which is required to match the brightness peaks of the two flashes at a given SOA. Vertical bars: ± s.e.m.

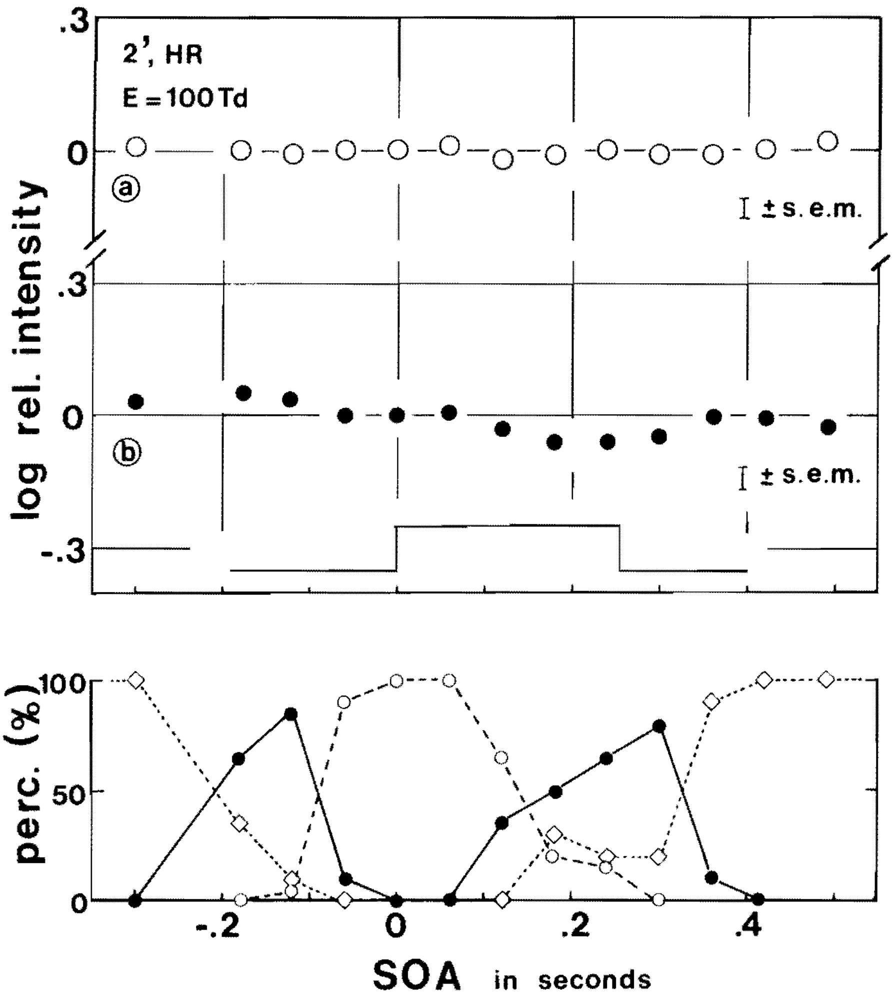


Figure 1.4: Curve "a" represents the average of the four conditions of Figure 1.3 after normalization of each function with respect to the retinal illuminance measured at SOA=0 ms. Curve "b" is the same but for an additional reversal of normalized functions b and d of Figure 1.3 (see text). The lower panel denotes, as a function of SOA, the percentage of trials in which the subject perceived the two point sources sequentially (open diamonds), in apparent motion (filled circles) or simultaneously (open circles).

viz. a hunch around SOA equal to −200 ms and a dip around SOA equal to +200 ms. The deviations were 0.06 log units at most.

During the brightness matchings, the subject sometimes observed an illusion of movement between the two point sources. An additional experiment was performed to determine at which SOAs this apparent motion was perceived. To this end, a 16 ms flash, presented to the left eye, and a 256 ms flash, presented to the right eye, were matched in brightness at SOA equal to 0 ms. Subsequently, the two flashes were shown to the subject at all SOAs, the order of SOA-values being randomized. At every trial, the subject indicated whether he saw the two point sources separated in time (sequential order), simultaneously or in motion. Results after twenty of these sessions can be seen in the lower panel of Figure 1.4. Apparent motion was perceived at SOAs equal to −120 and −180 ms and at SOAs between +120 and +360 ms, i.e. around the offset of the 256 ms flash. A simultaneous appearance was reported around the onset of the 256 ms flash. At the remaining SOAs, the point sources always appeared in a sequential order. A replication of this experiment with a 512 ms flash instead of the 256 ms flash gave similar results since apparent motion was seen at SOAs equal to −120 and −180 ms and at SOAs between +420 and +660 ms, which is again around the offset of the long flash. Figure 1.4 also shows a correspondence between the occurrence of apparent motion and the small deviations in the brightness matching function (upper panel, curve b). This suggests that there might be a close relation between these phenomena, at least for the spatial configuration used in these experiments. The practical implication of this suggestion is that during brightness matching SOAs should be avoided at which apparent motion occurs.

1.3.2 SOA and "constant luminance curves"

A frequently applied method to measure the influence of flash duration on perceived brightness is to vary the duration of a flash of constant luminance and to determine, for each duration, the luminance of a second flash that is required to match the flashes in brightness. The duration of this second flash is kept constant. The construction of these so-called "constant luminance curves" implies the brightness matching of two flashes of unequal duration and, consequently, a choice has to be made about the synchronization of the two flashes. From the results of the first experiment it is predicted that a simultaneous onset and a sequential order will yield the same unbiased results, provided that SOAs are avoided at which apparent motion is seen. Figure 1.5 shows two "constant luminance curves", obtained at SOA equal to 0 ms (circles) and ISI equal to 300 ms (diamonds). In the last-mentioned condition, the flash of variable duration always preceded the flash of constant (256 ms) duration. All data were normalized with respect to the average level, obtained at the long durations in the simultaneous onset condition. The curves have the same shape. They increase monotonically with duration, approaching a horizontal asymptote without showing the Broca-Sulzer effect. The absence of this effect can be attributed to the fact that the stimuli were point sources (Roufs, 1981; de Ridder and Theelen, 1983, 1984; see also Chapter 2).

The data of Figure 1.5 were subjected to a two-way analysis of variance. As expected, the flash duration has a significant effect ($F(11,46)=77.55$, $p < 0.001$). The temporal order, on the contrary, has no influence on the results ($F(1,46)=3.57$, $0.05 < p < 0.10$) nor does the interaction between duration and temporal order

($F(11,46)=0.17$, $p > 0.5$). From this, it is concluded that similar results were obtained for the two conditions that were examined in this experiment.

1.4 Discussion

A number of precautions have to be taken before brightness matching of flashes of unequal duration can be employed in the investigation of dynamic brightness phenomena like the Broca-Sulzer effect. From the literature (e.g. Bowen and Pokorny, 1978) it is known that even dichoptically presented stimuli need a spatial separation to avoid mutual influences. In the present study, the separation between the point sources was 80 min arc. Furthermore, the subjects must receive clear instructions about what feature of the brightness impression they should relate their brightness judgment to in order to obtain unambiguous results (Roufs and Coumans, 1978; Bowen, 1984). In our case, the subject was explicitly instructed to match the brightness peaks. The results of Figures 1.3, 1.4 and 1.5 show that a third parameter, the SOA, has little effect on the brightness matching of flashes of unequal duration when the above-mentioned conditions are fulfilled. This relative insensitivity to variations in SOA is consistent with results from other studies.

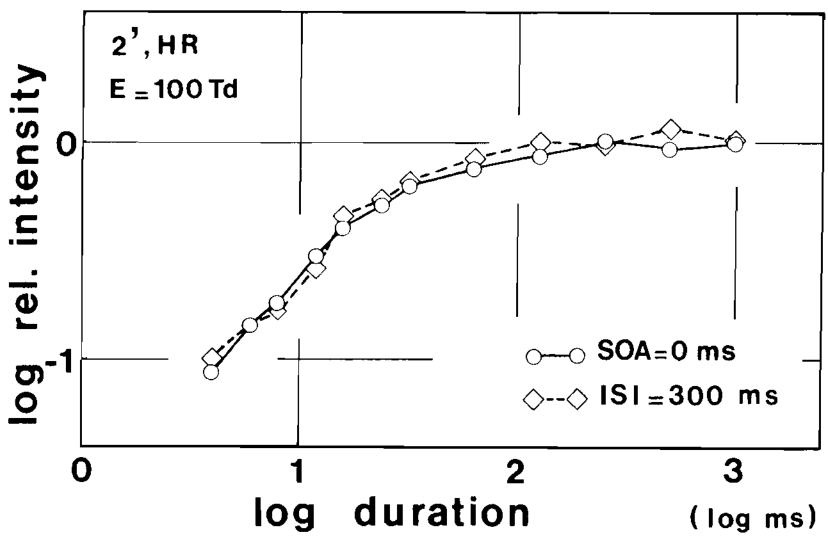


Figure 1.5: Interocular brightness matching between two point sources under two asynchrony conditions. The luminance of the right-eye flash, lasting 256 ms, is given as a function of the duration of the left-eye flash. The luminance of the latter was kept constant. The retinal illuminance of the background was 100 Td. All data are normalized with respect to the average level, obtained at the long durations in the simultaneous onset (SOA=0 ms) condition.

Table 1.1: Number of trials in which the subject perceived the point sources in motion, sequentially or simultaneously as a function of deviation in brightness matching (curve b of Figure 1.4). Deviations are given in log units.

deviation in	perceived temporal order		
brightness matching	in motion	sequentially	simultaneously
0 - 0.02	11	58	71
0.03 - 0.04	16	24	0
≥0.05	53	19	8

Katz (1964) and Bowen and Pokorny (1978), for example, obtained the same results for simultaneous onset and offset of test and comparison flashes. Similarly, Servière et al. (1977) reported no significant differences when the flashes appeared simultaneously or with an ISI of 400 ms.

Figure 1.4 also indicates that small but consistent deviations occurred at SOAs around −200 and +200 ms and that at these SOAs the subject perceived apparent motion. It is well-known that apparent motion between two dots can be perceived dichoptically across large separations and for SOAs up to 500 ms or more (e.g. Kolers, 1972; Larsen et al., 1983; Anstis, 1986). Our data are within this range. The correlation between apparent motion and brightness reduction, however, is less clear (Kahneman, 1967; Weisstein and Growney, 1969; Didner and Sperling, 1980). On the other hand, the results of Figure 1.4 suggest a close correspondence between apparent motion and small changes in perceived brightness or changes in matching criteria of perceived brightness. In order to test the significance of this correspondence, the data of curve b of Figure 1.4 were split up into three categories, based on the increasing deviation from the zero level. Subsequently, for each category the number of trials was determined at which the subject perceived the point sources in apparent motion, sequentially or simultaneously. Table 1.1 summarizes the resulting frequency data. At SOAs with deviations of 0.05 log units or more, apparent motion was seen for 53 out of 80 trials (66%). At SOAs with deviations of 0.02 log units or less, a sequential or a simultaneous order was mentioned for 129 out of 140 trials (92%). A chi-square test of variance was conducted on the frequency data of Table 1.1. The resulting chi-square value was equal to 109.66 (df=4), significant at the 0.001 level. Consequently, a significant statistical association exists between deviations in brightness matching and the perceived temporal order.

1.4.1 Conclusions

Brightness matching of flashes of unequal duration is hardly affected by variations in SOA if dichoptically presented point sources have a large spatial separation and subjects are requested to match the brightness peaks. Deviations have been found to correlate with the perception of apparent motion. It should be remembered, however, that the deviations were small, 0.06 log units at most. Finally, a simultaneous onset and a sequential order yield the same "constant luminance curves". As the last-mentioned condition requires relatively prolonged trials, it is concluded that the simultaneous onset configuration is to be preferred for the examination of dynamic brightness phenomena like the Broca-Sulzer effect.

chapter 2

Broca-Sulzer effect and the sustained-transient dichotomy [1]

Abstract

The influence of stimulus area on the Broca-Sulzer effect has been investigated in a series of interocular brightness matching experiments in which circular one-deg fields and point sources were flashed against an extended photopic background. The results show that the Broca-Sulzer effect is present with one-deg fields but not with point sources. Contrary to what is usually found, it did not shift to shorter durations with increasing flash luminance. The observed relation between the Broca-Sulzer effect and stimulus area is correctly predicted from impulse responses, measured at threshold. These responses were determined for the same stimulus configurations used in the brightness matching experiments except that for the one-deg fields the background was reduced to a circular one-deg field. Based on these results, it is argued that the Broca-Sulzer effect is generated by one of the two temporal channels that are assumed to operate in the visual system, viz. the transient one. A dynamic brightness model, which enables results of threshold and suprathreshold measurements to be unified, was applied to the brightness matching data. The good fit between model predictions and experimental results suggests that (1) the initial part of the visual system is linear even for large amplitude changes, (2) the exponent of the power function relating brightness to luminance is independent of flash duration and (3) the brightness impression of a flash is determined by its effective luminance, i.e. luminance above threshold.

2.1 Introduction

At the beginning of this century, A. Broca and D. Sulzer published a series of papers in which a curious brightness phenomenon is described (Broca and Sulzer, 1902, 1903, 1904). Using a brightness-matching technique, they determined the dependence of perceived brightness upon duration for single rectangular pulses of fixed luminance. Provided the luminance was not too low, the resulting curve consisted of two parts. For short durations, perceived brightness increased monotonically with duration but at longer durations, after having reached a maximum, it declined to a constant level which implies that the brightness had become independent of flash duration. The remarkable consequence is that a flash of some intermediate duration will appear brighter than a flash of any other (shorter or longer) duration. Since then, the existence of this bright-

[1] Part of this research was presented at the Eighth European Conference on Visual Perception, Peñiscola, Spain, 18–21 September 1985. An abstract has already been published (de Ridder et al., 1985).

ness "overshoot" has repeatedly been confirmed, not only in brightness-matching experiments (e.g. Stainton, 1928; Alpern, 1963; Nachmias and Steinman, 1965; Arend, 1973; White et al., 1980; Bowen, 1984) but also, after the pioneering work of Raab (1962), in brightness-scaling experiments (Stevens and Hall, 1966; Corwin and Green, 1978; Osaka, 1977; Bowen et al., 1981). Nowadays, it is known as the temporal brightness enhancement or Broca-Sulzer effect. Its general occurrence is shown by the fact that it can be seen under scotopic and photopic viewing conditions (Aiba and Stevens, 1964; White et al., 1976), during monoptic and dichoptic stimulation (Katz, 1964), in the fovea and periphery (Baumgardt, 1963; Corwin, 1978; Osaka, 1981, 1982), with stimuli of different size, ranging from small fields to a Ganzfeld (Naus, 1971; Rinalducci and Higgins, 1971; Mansfield, 1973; Osaka, 1977; Corwin and Green, 1978) and with sharp and blurred images (Bowen and Pokorny, 1978).

Although the Broca-Sulzer effect has already been known for a long time, there is still no general consensus about its origin. Consequently, many qualitative explanations have been offered for this phenomenon, varying from experimental artifacts like mutual masking of test and reference flash in a brightness-matching experiment (Raab et al., 1961; Lewis, 1965) to physiological explanations like the interaction between excitatory and delayed inhibitory neural processes (Le Grand, 1968; Arend, 1973; Corwin and Green, 1978). It has often been interpreted as reflecting the transient activity of the neural response to a stimulus onset (Le Grand, 1968; Kitterle, 1984). This correlation, however, may be illusory: in psychophysical experiments, the independent variable is *duration*, in neurophysiological ones *time after stimulus onset* (Wasserman and Kong, 1974). For the same reason, it seems unlikely that the Broca-Sulzer effect will reflect the time course of the sensation of brightness, resulting from a step of luminance (Roufs and Pellegrino van Stuyvenberg, 1979).

In most recent theories on the brightness of time-dependent stimuli, it is implicitly or explicitly assumed that a relatively fast change in luminance is a necessary condition for obtaining the Broca-Sulzer effect (e.g. Bowen, 1984; Kitterle, 1984). This assumption is directly supported by the finding of Bowen and Nissen (1979) that fast luminance changes, rather than hue changes, determine the occurrence of the Broca-Sulzer effect for coloured stimuli. It is also in agreement with the fact that the temporal enhancement of the apparent contrast of a pulsed sinusoidal grating is abolished if the grating is turned on gradually instead of abruptly (Kitterle and Corwin, 1983). This suggests that both the temporal contrast enhancement and the Broca-Sulzer effect are generated by a system that is sensitive to relatively fast temporal changes. Such a system is the transient temporal channel which is known to be sensitive to high temporal and low spatial frequencies (e.g. Breitmeyer and Ganz, 1976; Lennie, 1980; Green, 1984). This suggestion is supported by the fact that the temporal contrast enhancement effect can only be found at low spatial frequencies (Kitterle and Corwin, 1979; Georgeson, 1987) and disappears after 6 Hz flicker adaptation (Kitterle and Beard, 1983).

Individual differences in brightness perception indicate that not one, but two more or less independent systems are contributing to the brightness of pulsed achromatic light (Drum, 1980, 1984; Bowen et al., 1981; Bowen, 1984). According to Drum (1980, 1984), this second system is optimally sensitive to high spatial and low temporal frequencies and, thus, resembles the other temporal channel that is assumed to exist in the visual system, viz. the sustained channel (e.g. Green, 1984).

At threshold, the temporal impulse response of the visual system has been found to change with stimulus configuration (Roufs and Blommaert, 1981). For point sources projected on an extended photopic background, this response is monophasic, resembling the impulse response of a fourth order low-pass filter. For a one-deg field with dark surround, the impulse response is triphasic, indicating a band-pass type of filtering. This influence of stimulus size on the shape of the impulse response suggests again that the visual system comprises two distinct channels operating in parallel, viz. a low-pass filter associated with the physiologically defined "sustained" cells (Cleland et al., 1971) and a band-pass filter associated with the "transient" cells (Roufs, 1974a; Roufs and Blommaert, 1981; Watson, 1986). Furthermore, it shows that point sources are effective stimuli for the sustained channel whereas large fields are optimal stimuli for the transient channel. The assumption of two channels operating in parallel is also supported by the existence of two different percepts in the case of temporal sinusoidal modulation, viz. "swell" at low frequencies and "agitation" at high frequencies (Roufs, 1972a).

If it is assumed that (1) the transient and sustained channel are both working at suprathreshold levels and (2) the transient channel generates the Broca-Sulzer effect, then it should, in principle, be possible to manipulate the occurrence of this effect by varying the size of the stimulus field. Almost all experiments which demonstrate the Broca-Sulzer effect have been performed with circular fields, having a diameter of 0.5 deg or larger (e.g. Raab, 1962; Aiba and Stevens, 1964; Bowen et al., 1981). This is to be expected as the transient channel is maximally sensitive to large fields. Point sources are predominantly stimulating the sustained channel and, consequently, the Broca-Sulzer effect should be absent. Experimental support for this hypothesis, however, is scarce and not conclusive. On the one hand, it has been reported that the "...Broca-Sulzer effect is significantly reduced for targets of small radius..." (Berman and Stewart, 1979) and that it even disappears for point sources (Roufs and Pellegrino van Stuyvenberg, 1979; Roufs, 1980, 1981). On the other hand, Naus (1971) and Rinalducci and Higgins (1971) have presented evidence that the Broca-Sulzer effect will reappear with point sources if not a co-beginning or co-midpoint sequence of test and reference flash is used but a co-terminating one.

The purpose of the present study is to investigate the relationship between the Broca-Sulzer effect and the sustained-transient dichotomy, represented by the different impulse responses at threshold level. Based on the results of Roufs and Blommaert (1981), the choice of stimuli was restricted to point sources and one-deg fields, being optimal stimuli for the sustained and transient channel respectively.

For the point source as well as the one-deg field, two sets of experiments have been performed, viz. interocular brightness matchings with flashes of variable luminance and duration and threshold measurements. The former are meant to determine the effect of stimulus area on the Broca-Sulzer phenomenon, the latter to measure the impulse responses of the visual system for the same areas used in the brightness-matching experiments. In order to facilitate comparison of experimental data, each subject participated in both kinds of experiments. Furthermore, the threshold and suprathreshold measurements were performed at the same 100 Td background level.

Apart from the correlation between the shape of the impulse response and the occurrence of the Broca-Sulzer effect, the present study is also concerned with the possibility to predict the results of the brightness-matching experiments from the measured impulse responses. In this connection, a recently proposed model to describe the brightness of time-dependent stimuli (Roufs and Pellegrino van Stuyvenberg, 1979; Roufs, 1980, 1981; de Ridder and Theelen, 1983, 1984) will be discussed. This model predicts, among other things, that individual differences in the size of the Broca-Sulzer effect and/or the duration at which this effect occurs can be traced back to individual differences in the shape of the impulse response.

2.2 Section I : Interocular brightness matching

2.2.1 Introduction

There are two ways to measure the Broca-Sulzer effect when a brightness-matching technique is used. One possibility is to obtain "equal-brightness curves" by matching the brightness of a test flash with varying luminance and duration to that of a constant reference flash. The Broca-Sulzer effect will appear as a minimum when the luminance of the test flash, required to obtain constant brightness, is plotted as a function of its duration. A second possibility, which was originally used by Broca and Sulzer (1902), is to vary the duration of the test flash while keeping its luminance constant and determine the luminance of the reference flash that is required to match both flashes in brightness. The duration of the reference flash remains fixed. In this case, the Broca-Sulzer effect will look like an overshoot when the luminance of the reference flash is plotted against the duration of the test flash. The determination of equal-brightness curves is sometimes considered to be superior to the other method (Boynton, 1961). The extensive study of Aiba and Stevens (1964), however, has demonstrated that the results of the two methods are in agreement with each other. In the present study, both methods have been employed.

As already noted in the Introduction, only two stimulus sizes were used to determine the effect of stimulus area on the Broca-Sulzer phenomenon, viz. point sources and one-deg fields. It was predicted that the Broca-Sulzer effect would only occur in the last-mentioned condition.

2.2.2 Method

Apparatus

A six-channel, binocular Maxwellian-view optical system was used to generate the stimulus configuration shown in Figure 2.1. A scheme of the optical apparatus has already been presented in Chapter 1. Two of the channels, one for

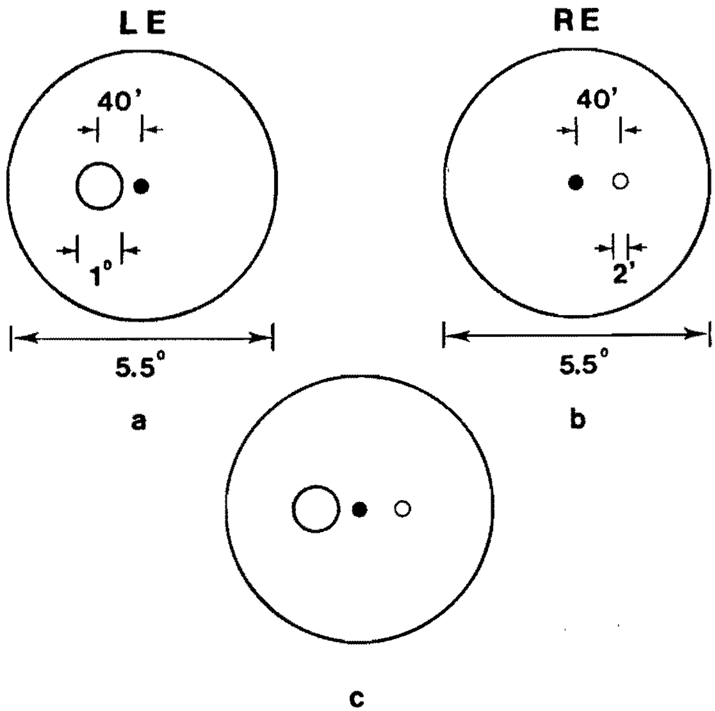


Figure 2.1: Schematic representation of the spatial configurations, presented to (a) left and (b) right eye. The configurations are not drawn to scale. After fusion, both the backgrounds and the centrally positioned fixation points (filled circles) were seen superimposed (c).

each eye, produced circular, 5.5 deg, uniform "white" backgrounds, the retinal illuminance of which was kept constant at 100 Td. Two other channels projected small, dim, red fixation points in the centre of these fields. After fusion, both the backgrounds and the fixation points were seen superimposed (Fig. 2.1c). Circular "white" test fields were flashed against the background by the remaining two channels. The centre of the left-eye test field appeared 40 min arc to the left of the fixation point (Fig. 2.1a). Similarly, the centre of the right-eye test field appeared 40 min arc to the right of the fixation point (Fig. 2.1b). The diameter of these fields was either 2 min arc (point source) or one degree, depending on the diaphragm placed in the light beam. The subject saw the whole stimulus configuration through two eye pieces which were fitted with artificial pupils 2 mm in diameter and equipped with entoptic guiding systems (Roufs, 1963). In order to optimize fixation, the head of the subject was immobilized using a chin-and-head rest.

The light source of each channel was a glow modulator tube (Sylvania type R1131C or the equivalent type EEV XL670). A beam splitter reflected part of the light output on a photodiode (Siemens SFH203), properly corrected with respect to spectral sensitivity. The output signal of this diode fed back to the current source of the glow modulator tube in order to linearize and stabilize its light output. Rectangular incremental flashes were generated electronically by modulating the light output using pulse generators. The amplitude of the flashes was set roughly by neutral density filters and more precisely by attenuators, adjusting the intensity in one-dB steps. A one-dB step changed the intensity by 0.05 log units. As a result of the fact that the lamps were driven from the zero point, the flashes became reddish when the current pulses were weak. In order to minimize this colour shift, neutral density filters were applied to keep the working range of the current pulses as small as possible.

Before each series of experiments, the whole configuration was calibrated with a cooled photomultiplier tube (Philips XP1002), placed in front of the eye pieces. The $V(\lambda)$ corrected photomultiplier tube had previously been calibrated against a standard light source (Spectra Regulated Brightness Source).

Procedure

At the beginning of each session, the subject was dark-adapted for about 10 minutes before he adapted to the 100 Td background level. The subject started a trial by pushing a tapping-key, thus releasing two flashes after a delay of 300 ms. The flashes, one appearing in the left eye and the other in the right eye, had a synchronous onset. In Chapter 1 it was shown that this configuration gives the same, unbiased results as using a sequential order. During the experiments, this was repeatedly confirmed. Furthermore, no effect of rivalry between the two eyes was ever observed under the present conditions. After each trial, the subject answered whether the right-eye flash appeared brighter or darker than the left-eye flash by pressing one of two buttons. The subject was explicitly instructed to compare the brightness peaks of the two flashes. Previous experiments, briefly described in the Introduction of Chapter 1, have shown that subjects are able to follow this instruction. By pressing a third button, the subject indicated if a trial had to be rejected because he did not see the flashes, for instance due to eye blinks.

The method of constant stimuli was employed in all experiments to determine the retinal illuminance of the right-eye flash at which the subject judged this flash to be brighter than the left-eye flash in 50% of the trials. This procedure does not exactly give the retinal illluminance defining the point of subjective equality since the instruction forces the subject to surpass a just noticeable brightness difference which is reflected by a just noticeable difference in retinal illuminance. However, it seems fair to assume that the Weber fraction is constant for the experimental conditions employed in the present study (e.g. Cornsweet and Pinsker, 1965; Whittle, 1986), leading to a constant and small shift of the data when they are expressed in log units. The flash which served as the reference flash lasted either 8 or 256 ms, while the duration of the test flash varied from 2 to 1000 ms. In order to measure an equal-brightness curve, the experimenter set the luminance of the reference flash at a constant level and varied the duration of the test flash. The luminance of the test flash was the dependent variable. The reference flash was presented to the left eye and the test flash to the right eye. Both test and reference flash were either one-deg fields or point sources. For the second experiment, described in the introduction of this section, the reference flash was a point source, presented to the right eye. Consequently, the test flash, being a one-deg field or a point source, appeared in the left eye. In this experiment, the duration of the test flash was varied while its luminance remained fixed at a certain level. Contrary to the first experiment, the luminance of the reference flash was the dependent variable. In a third experiment, the conditions were the same as in the second one with the exception that not the duration but the luminance of the test flash was varied. Its duration was kept constant at either 4, 8 or 32 ms.

Subjects

Two male subjects participated in the experiments. Subject HR, aged 29 years at the beginning of the experiments, had some experience in psychophysical work. Subject KS, aged 35 years, was well-trained. Both subjects have normal vision.

2.2.3 Results

The data presented in this section are the average of six measurements. During a session, only one complete curve was measured, presenting the stimuli in a random order. Each second session was a repetition of the previous one, the stimuli appearing in the reversed order. For both subjects, the standard error of the mean was about 8% of the mean. This percentage proved to be independent of stimulus size, flash duration or flash luminance.

Equal-brightness curves, determined for a one-deg field, are shown in Figures 2.2 and 2.3. For subject HR, the curves are isomorphous up to more than 3 log units above threshold (Fig. 2.2). At short durations, the data lie on straight lines with a slope −1. This implies that Bloch's law holds at suprathreshold levels. At long durations, the curves are independent of the flash duration. A small dip of approximately 0.1 log Td can be seen around 80 ms, indicating that the Broca-Sulzer effect is present for one deg fields. As was found by Katz (1964), the dip does not shift to shorter durations as the luminance of the reference flash, represented by the filled diamonds in Figure 2.2, is increased. This result is con-

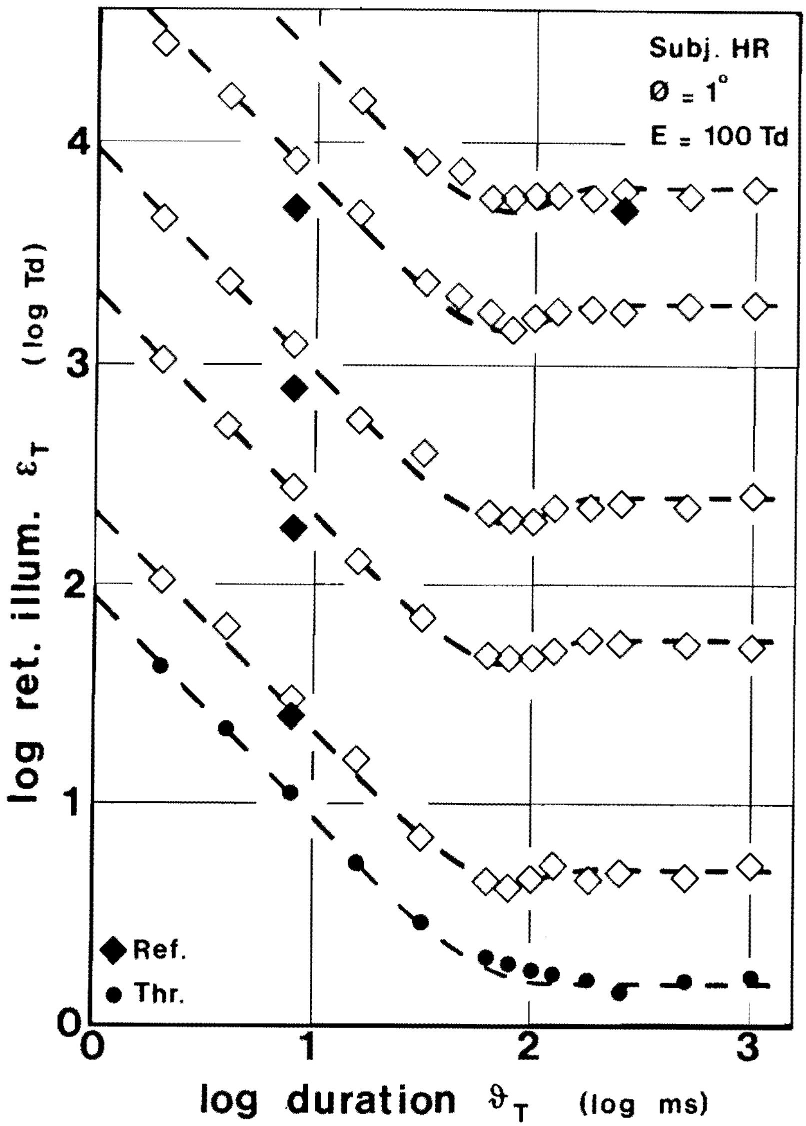


Figure 2.2: Equal-brightness curves for a flashed one-deg field with variable duration ϑ_T for various reference flashes, indicated for each curve by a filled diamond. Both test and reference flashes were presented against an extended 100 Td background. The diameter of the reference field was one degree. The dashed lines fitted to the equal-brightness curves are curves predicted according to eq. (2.13). Exponent β_T in eq. (2.13) was assumed to be constant. The function represented by the dashed line fitted to the threshold data (filled circles) has been used to determine ε_{0T} in eq. (2.13). Subject: HR.

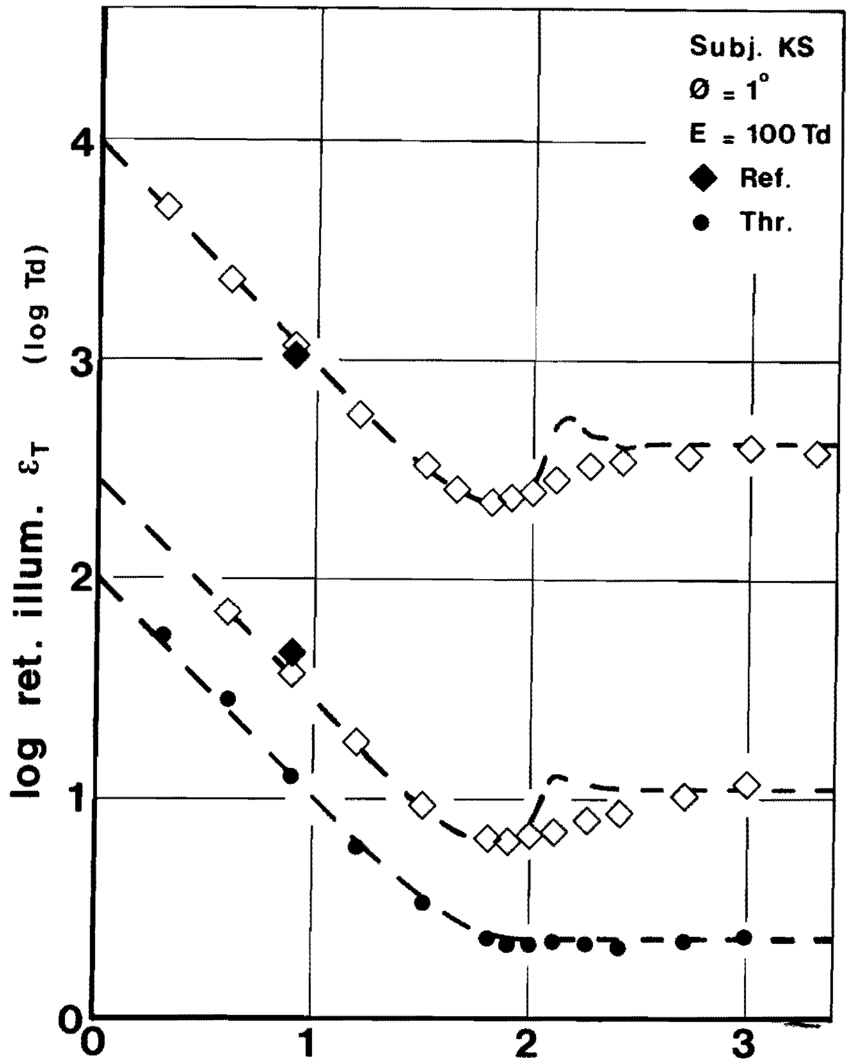


Figure 2.3: Same as Figure 2.2. Subject: KS.

trary to what Aiba and Stevens (1964) have found. In Chapter 3, it will be shown that this discrepancy is due to procedural differences concerning the presence or absence of a background.

The results obtained for subject KS (Fig. 2.3) are in general agreement with those obtained for subject HR. In particular, they confirm the conclusions about Bloch's law and the Broca-Sulzer effect. At the same time, however, individual differences can be observed. The most significant one is the size of the dip, being about 0.25 log Td for subject KS and 0.10 log Td for subject HR. The size of the dip is defined relative to the asymptotic level at long durations. The Broca-Sulzer

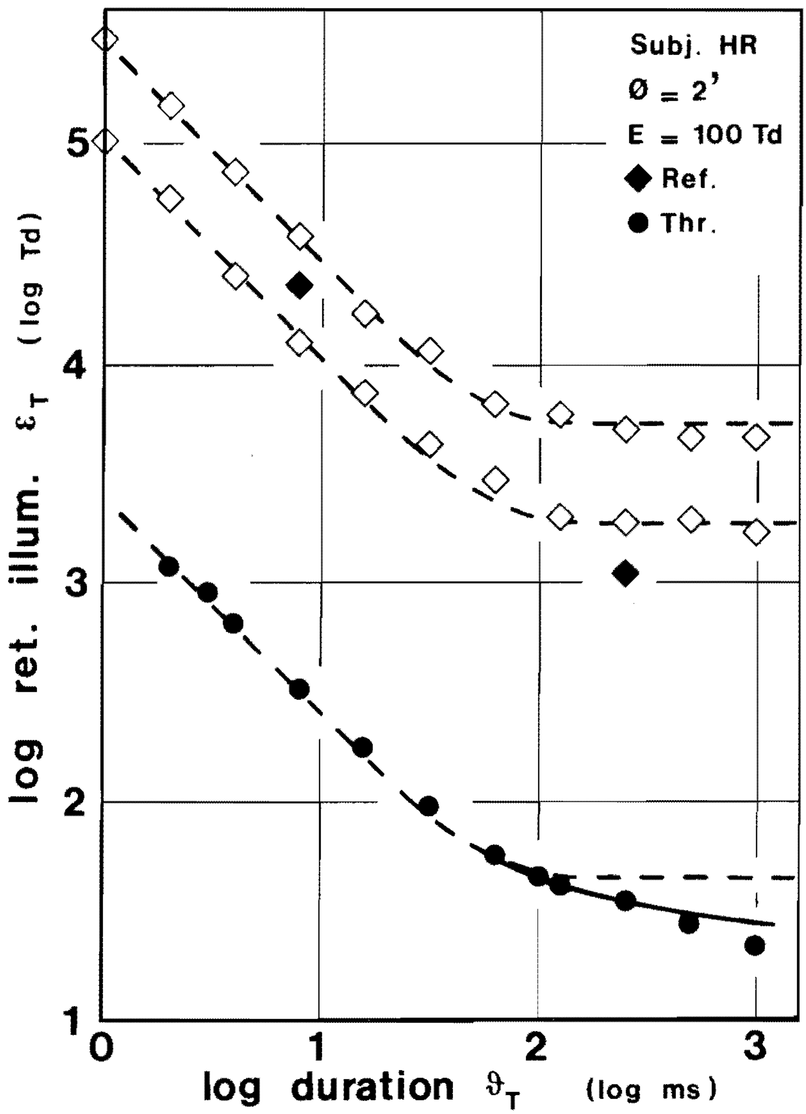


Figure 2.4: Equal-brightness curves as a function of duration ϑ_T for a point source, 2 min arc in visual angle, flashed against an extended 100 Td background. The filled diamonds denote the reference flashes, lasting 8 and 256 ms. The diameter of the reference field was also 2 min arc. The upper curve has been shifted 0.5 log units upwards. The dashed lines fitted to the brightness and threshold data (filled circles) are model predictions derived from eqs (2.13) and (2.15) respectively. Exponent β_T in eq. (2.13) remained constant. The solid line indicates a correction for probability summation.

effect also occurs at different durations: around 65 ms for subject KS and around 80 ms for subject HR. At threshold level, the dip has vanished for both subjects (Figs 2.2, 2.3, filled circles).

The upper two curves of Figure 2.4 are equal-brightness curves measured for a point source. The only difference between these two curves is the duration of the reference flash: 256 ms for the lower curve and 8 ms for the upper one. The last-mentioned curve has been shifted 0.5 log units upwards for clarity of representation. The duration of the reference flash proves to have no influence on the shape of the equal-brightness curve. At short durations, the data lie again on straight lines with slope -1, while at long durations the data approach a horizontal line. Unlike the equal-brightness curve for a one-deg field, no dip can be observed and, consequently, the curves change smoothly from an asymptote having slope -1 to a horizontal one. This suggests that the Broca-Sulzer effect is absent with point sources.

In order to provide further evidence for this last suggestion, brightness matchings have been performed between flashed point sources of variable duration but

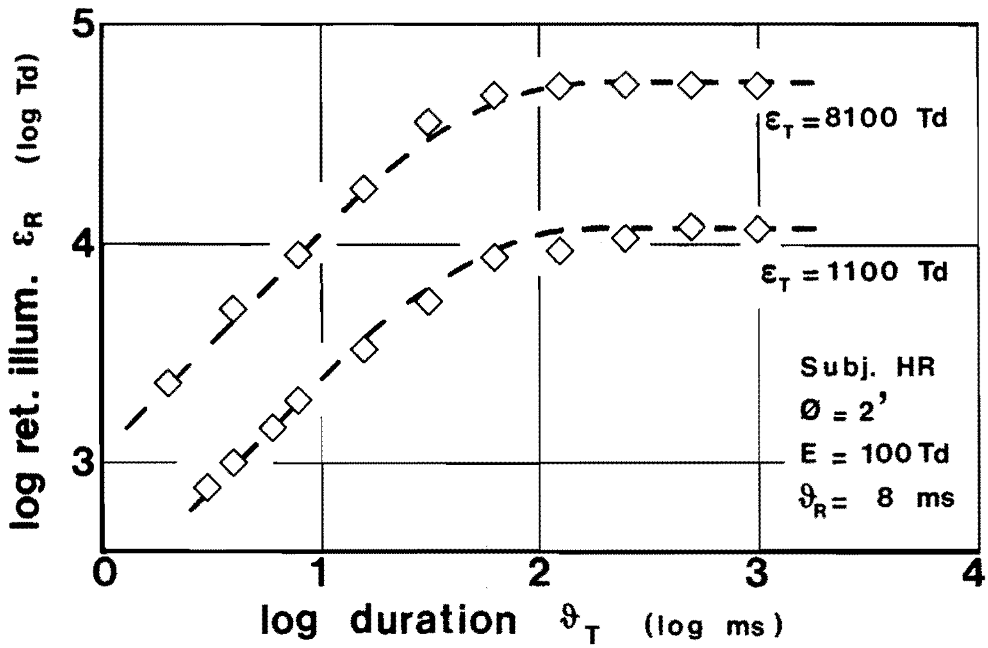


Figure 2.5: Brightness matching between a flashed point source of constant luminance but variable duration (test flash T) and a flashed point source of constant duration (reference flash R). The reference flash lasted 8 ms. The luminance of the test flash was set at two levels. The dashed lines are curves predicted according to eq. (2.16). Exponents β_T and β_R were assumed to be independent of flash duration.

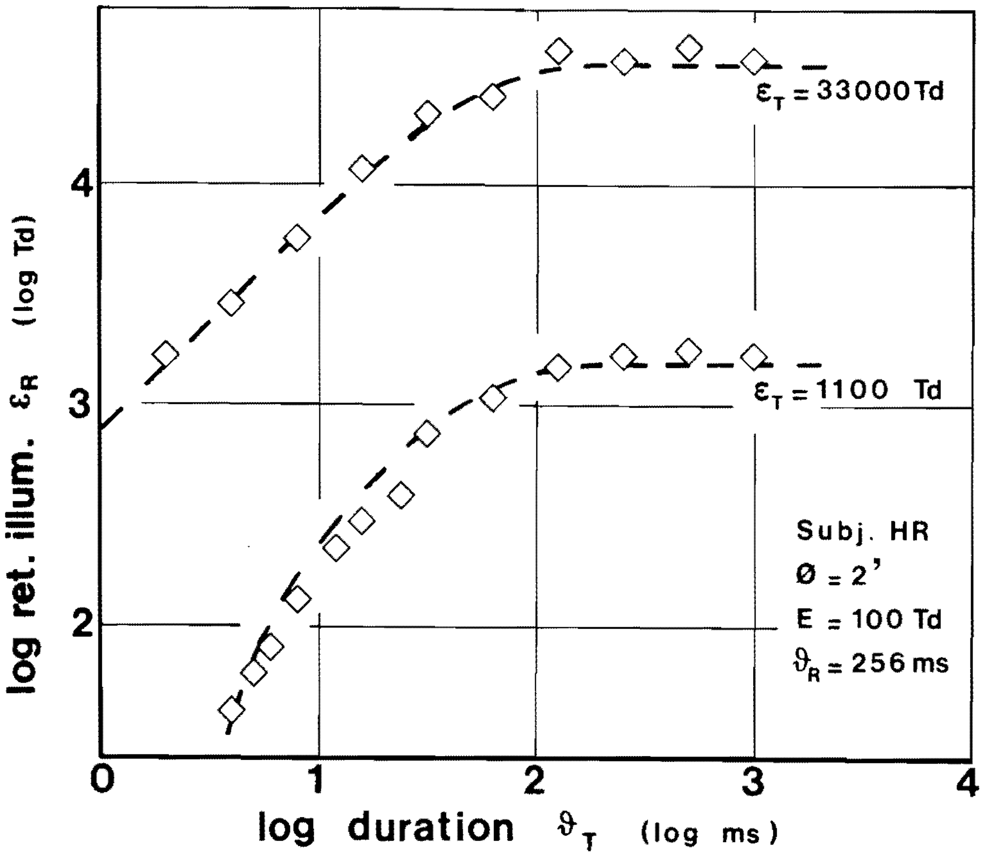


Figure 2.6: Same as Figure 2.5, except that the reference flash lasted 256 ms.

fixed luminance and flashed point sources of fixed duration but variable luminance. The results can be seen in Figures 2.5 and 2.6, where the retinal illuminance of the reference flash is plotted as a function of the duration of the test flash. The reference flash lasted either 8 ms (Fig. 2.5) or 256 ms (Fig. 2.6). If the Broca-Sulzer effect is present with point sources, then an "overshoot" should appear around 80 ms. This is not the case and, consequently, these data are in agreement with those of Figure 2.4. At short test flash durations, the data lie on straight lines with a slope of about +1. A clear deviation from this slope is observed only if both the reference flash lasts 256 ms and the luminance of the test flash is low so that the detection threshold is approached at short durations (Fig. 2.6, lower curve). Under these conditions, the curve becomes steeper. For instance, the data at durations shorter than 10 ms can be fitted by a line with slope 1.67. A similar deviation near threshold seems to be absent when the reference flash lasts 8 ms (Fig. 2.5, lower curve).

The equal-brightness curves of a one-deg field and a point source (Figs 2.2, 2.3, 2.4) indicate that the Broca-Sulzer effect occurs for large fields. Consequently, the Broca-Sulzer effect can be measured with experiments like the ones described in the last paragraph if the test stimulus is changed from a point source to a one-deg field. Figure 2.7 shows the results of such an experiment. Three luminance

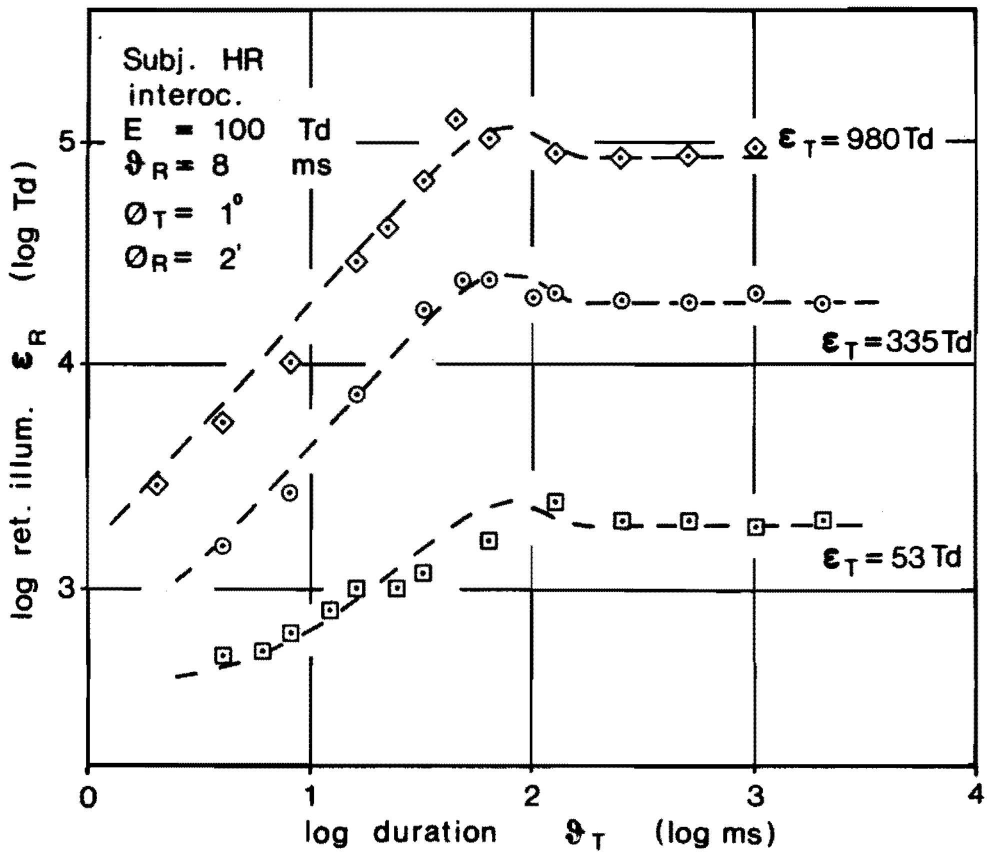


Figure 2.7: Brightness matching between a test flash of constant luminance but variable duration and a reference flash of constant duration (8 ms). Test stimulus T is a one-deg field and reference flash R a point source. The dashed lines are curves predicted according to eq. (2.16). The ratio of the exponents (β_T/β_R) was assumed to be 1.18. This value has been derived from the data in Figure 2.8.

levels of the test flash were used. For the two upper levels, the curves have the same shape. At short durations, the data lie on straight lines with a 1.2 slope and at long durations the data are independent of the duration. All three curves show a maximum in the mid-range, around 90 ms. There are some deviations near threshold. The most significant one is that at short durations the data lie on a line with slope 0.5 (Fig. 2.7, lower curve). Both the occurrence of the Broca-Sulzer effect and the lowering of the slope near threshold were found to be independent of the duration of the reference flash.

A third kind of experiment was performed to examine in more detail the change of the slope as was observed in the last experiment (Fig. 2.7). The same configuration was used, but now the experimenter varied the luminance instead of the duration of the test flash. The test stimulus remained a one-deg field and the reference flash a point source. The duration of the test flash was kept constant at either 4, 8 or 32 ms while the reference flash always lasted 8 ms. Besides matching the brightness peaks of test and reference flashes, the detection threshold was measured for both test and reference flash. The resulting three curves are shown in Figure 2.8. They have the same shape. At high luminance levels of the test flash, the data lie on three parallel straight lines. The best fit, obtained with the

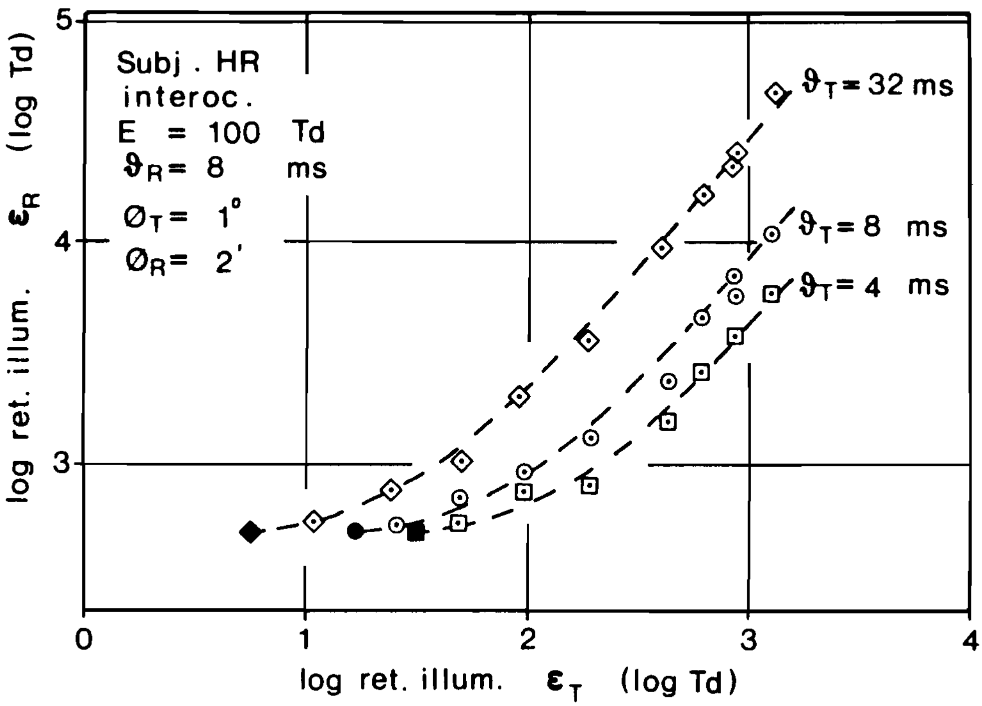


Figure 2.8: Brightness matching between a test flash of constant duration (4, 8 or 32 ms) but variable luminance and a reference flash of constant duration (8 ms). The stimulus configuration is the same as described in Figure 2.7. The broken lines are curves predicted according to eq. (2.16). They were simultaneously fitted to the data. The filled symbols represent the threshold data.

method of least squares, is a line with slope 1.18. Approaching the threshold, the curves start to bend towards the threshold (Fig. 2.8, filled symbols) in such a way that the point source seems to decrease faster in brightness than the one-deg field. This bending of the curves implies that, at low luminance levels of the test flash, the luminance of the reference flash has to increase more slowly with test flash duration than at high luminance levels of the test flash. This implication is confirmed by the changing slope of the curves in Figure 2.7.

2.2.4 Discussion

It can be concluded from our results that the occurrence of the Broca-Sulzer effect depends on the size of the stimulus field, the effect being absent with point sources. This conclusion is based on the fact that (1) the dip in the equal-brightness curves is observed with one-deg fields but not with point sources (Figs 2.2, 2.3, 2.4) and (2) an overshoot will appear if the test stimulus is changed from a point source to a one-deg field (Figs 2.5, 2.6, 2.7). The latter may be the most convincing argument as during those experiments only the area of the test stimulus was changed whereas during the determination of the equal-brightness curves the reference and test stimulus simultaneously changed from a one-deg field to a point source. The dependence of the brightness overshoot on the area of the test stimulus has also been found in earlier studies (Roufs and Pellegrino van Stuyvenberg, 1979; Roufs, 1980, 1981).

Naus (1971) reported that no dip is observed in equal-brightness curves of point sources if a co-beginning or a co-midpoint sequence of test and reference flash is used. He regarded this result as an experimental artifact since a dip can be observed during a co-terminating presentation. A similar result was found by Rinalducci and Higgins (1971). Plotted in log-log coordinates, the shape of their dip changed systematically with flash luminance. For large fields, on the contrary, the dip remains almost the same over a large range of flash luminances (Aiba and Stevens, 1964), as is confirmed in the present study (Fig. 2.2). Using 4 deg semicircular fields, Aiba and Stevens (1964) found the size of the dip to vary between 0.2 and 0.3 log units. This is consistent with the values we have obtained, viz. 0.10 and 0.25 log units (Fig. 2.2, 2.3; see also Roufs and Pellegrino van Stuyvenberg, 1979). In our opinion, this suggests that the dip measured by Naus (1971) and Rinalducci and Higgins (1971) may not be the Broca-Sulzer effect. An alternative explanation for their results may be the following. Both Naus (1971) and Rinalducci and Higgins (1971) used relatively long flashes as reference flashes. If it is assumed that the perceived brightness of a long flash gradually decreases as a function of time after flash onset (Bowen, 1984) *and* that in the co-terminating condition the subjects make their brightness judgments at the time of the onset of the test flash, then the brightness of the reference flash will be less for short than for long test flashes. This will result in a relative shift downwards of the equal-brightness curve at short durations. As a consequence of this shift, a dip will appear in the midrange of equal-brightness curves. In our experiments, the subjects were always instructed to compare the brightness peaks of two flashes. In combination with a simultaneous onset of test and reference flash, this probably eliminates temporal influences on the brightness matchings as described above (see also Chapter 1).

Below a certain critical duration, the brightness of a flash is determined by its energy. This suprathreshold version of Bloch's law has been confirmed in brightness scaling (Raab, 1962; Lewis, 1965; Stevens and Hall, 1966; Mansfield, 1973; Osaka, 1978) as well as brightness matching experiments (Aiba and Stevens, 1964; Rinalducci and Higgins, 1971; White et al., 1976; Roufs and Pellegrino van Stuyvenberg, 1979; Roufs, 1981). In the present study, it is demonstrated by the equal-brightness curves where the data for short durations lie on straight lines with slope -1 (Figs 2.2, 2.3, 2.4). This reciprocity between luminance and duration implies that, in Bloch's region, the growth of brightness with duration has to follow the same power function as the one that is assumed to describe the relationship between brightness and luminance (e.g. Marks, 1974). It also implies that, in Bloch's region, the matching data of Figures 2.5, 2.6 and 2.7 have to lie on parallel lines. The same holds for the curves of Figure 2.8. At high luminance levels, the data are consistent with this implication. Near threshold, however, a deviation can be observed towards the stimulus that has the highest detection threshold. A similar bending of matching curves has been obtained by Greenstein and Hood (1981). The observed deviations in Figure 2.8 disappear when the luminances of both test and reference flashes are corrected for their thresholds by subtracting the luminances at which the flashes are detected. This is in accordance with the notion of Onley (1961) that, in the case of flashes projected on a background, the luminance has to be "...expressed as luminance above psychological zero brightness (that is, as luminance above threshold for each specific condition)" (p. 667). The change of the slope that is shown in Figures 2.6 and 2.7 can be explained in the same way (see also Section III).

2.3 Section II : Threshold measurements

2.3.1 Introduction

The results of the brightness matching experiments indicate that the existence of the Broca-Sulzer effect depends on the size of the stimulus field. The fact that this brightness phenomenon occurs only with the one-deg field endorses the hypothesis that the Broca-Sulzer effect is generated by the transient channel. In order to elaborate this point, a quantitative description of the dynamic behaviour of both the transient and sustained system is required. The threshold measurements presented in this section are aimed at finding such a description. Their main purpose is to determine the temporal impulse response of both systems.

At threshold the visual system can be linearized by keeping the luminance of the background constant (e.g. Roufs, 1972b, 1974a). In that case, the dynamic behaviour of the visual system is fully defined by its temporal impulse response, the chosen background being the working point. This implies that the response to any arbitrary temporal signal can be calculated by convolution with the impulse response. Roufs and Blommaert (1981) introduced a drift-correcting perturbation technique to measure psychophysically the impulse response of the visual system for various stimulus configurations. This technique evolved from a model that Roufs (1972b, 1974a) constructed in two steps of refinement to describe the relation between the detection thresholds of various periodic and aperiodic signals (Roufs, 1972a, 1973, 1974a, b). The model consists of a quasi-linear filter that is followed by a noisy peak detector. The quasi-linearity means that the visual system behaves linearly for sufficiently small amplitude changes in a sufficiently small time. According to the model, a signal is detected as soon as the output of the filter exceeds a certain internal (positive or negative) threshold value d.

The drift-correcting perturbation technique of Roufs and Blommaert (1981) comprises the determination of the 50% detection threshold of (1) a combination of a short probe flash of duration ϑ and a much weaker test flash of the same duration ϑ that has a variable delay τ with respect to the probe flash and (2) the probe flash alone. Since the test flash is relatively weak with respect to the probe flash, the internal response to the combination will always have only one maximum at approximately the extreme value of the response to the probe flash. When this maximum reaches the internal (positive or negative) threshold d at time t_{ex} and duration ϑ is small compared to the time-constants of the system, one obtains

$$\varepsilon_p \vartheta U_\delta(t_{ex}) + q\varepsilon_p \vartheta U_\delta(t_{ex} - \tau) = d \tag{2.1}$$

where ε_p is the luminance of the probe flash, q the fixed ratio of the luminances of the test and probe flash, $q \ll 1$, and $U_\delta(t_{ex})$ the value of the unit impulse response at time t_{ex}. Similarly, the determination of the threshold of the probe flash alone is described by

$$\varepsilon_0 \vartheta U_\delta(t_{ex}) = d \tag{2.2}$$

In these expressions the effect of noise on the detection of the nondominant phases of the probe response and of the perturbing response is neglected (see also Blommaert and Roufs, 1987). From eqs (2.1) and (2.2) it follows that

$$\frac{U_\delta(t_{ex} - \tau)}{d} = \frac{1}{\vartheta q}\left(\frac{1}{\varepsilon_p} - \frac{1}{\varepsilon_0}\right) \tag{2.3}$$

The normalized impulse response $U_\delta^*(t_{ex} - \tau)$ is obtained by combining eqs (2.2) and (2.3) and is given by

$$U_\delta^*(t_{ex} - \tau) = \frac{1}{q}\left(\frac{\varepsilon_0}{\varepsilon_p} - 1\right) \tag{2.4}$$

Consequently, the absolute impulse response, expressed in d-values, is given by

$$\frac{U_\delta(t_{ex} - \tau)}{d} = \frac{1}{\varepsilon_0 \vartheta} U_\delta^*(t_{ex} - \tau) \tag{2.5}$$

where $1/(\varepsilon_0\vartheta)$ is the norm factor NF, expressed in $Td^{-1}.s^{-1}$. Time t_{ex} is not known on basis of these measurements alone. For the present purpose, however, it does not have to be known. Consequently, it can be taken as the zero of the $-\tau$-axis, the impulse response being defined on this time axis with respect to t_{ex}.

The drift-correcting perturbation technique was employed to measure the impulse response of the visual system for the same stimuli that were used in the brightness-matching experiments, viz. one-deg fields and point sources. In doing so, we have replicated the experiments of Roufs and Blommaert (1981). The main difference was the retinal illuminance of the background, being 100 Td instead of 1200 Td. Since one deg fields and point sources are thought to be effective stimulus configurations for the transient and sustained system respectively, the resulting functions are, by definition, the impulse responses of these systems. Additional experiments have been performed to test the assumptions of linearity and peak detection.

2.3.2 Method

Eqs (2.3) and (2.4) are valid if threshold d remains constant. However, this threshold is a stochastic variable, subject to non-stationary fluctuations like a slow drift (Roufs and Blommaert, 1981). In order to correct for these disturbances, ε_p and ε_0 were always measured in pairs. Furthermore, the time to determine the 50% detection threshold was shortened by applying the "constant slope" method. This method is based on the finding that the psychometric function is a cumulative normal distribution that, between 20 and 80%, can be approximated by a straight line, provided that the retinal illuminance is expressed in dB values (Roufs, 1974b). The slope of this line has been found to be independent of background level and flash duration (Roufs, 1974b). It has to be determined in advance by averaging over an adequate number of psychometric functions which have to be determined fast in counterbalanced sequences over a limited number of intensities. In conjunction with the percentage "seen" at just one dB value, the 50% detection threshold can be derived from this slope. Only 10 successive trials were used to determine the percentage "seen" at one dB value. Correction for order effects within a pair was obtained by repeating each pair an even number of times in counterbalanced order. These repetitions appeared in different sessions, because during one session the whole stimulus set, containing all values of τ, was presented only once. The subject saw these stimuli in a random order that was reversed in each second session.

The right part of the Maxwellian-view system generated the stimulus configuration for the determination of the impulse responses. The point source appeared in the centre of the background. Four small, dim, red fixation points, positioned at the corners of an imaginary square having 0.5 deg sides, were centered around the point source. During the measurements of the impulse response for the one-deg field, the background was reduced to a circular one-deg field. This was done because a dark surround enhances the opportunity to perceive "agitation". This percept is associated with the activity of the transient system (Roufs, 1974a; Roufs and Blommaert, 1981). Subject KS fixated a small red light that was positioned 40 min arc to the left of the centre of the one-deg field. Subject HR, on the contrary, fixated directly the one deg field and no fixation system had to be used in that condition.

In all experiments, the subject started a trial by pushing a tapping-key. The probe flash appeared after 300 ms. Both test and probe flash lasted 4 ms. The value of q, being the ratio between the luminances of the test and probe flash, was set at either 0.1, 0.2 or 0.3. Throughout the experiments, however, it became clear that differences in this ratio have no effect on the results as long as it is smaller than or equal to 0.3. Consequently, results obtained with different values of q could be averaged. The electronic circuitry to set the value of q and to vary the delay between test and probe flash has already been described elsewhere (Roufs and Blommaert, 1981).

The drift-correcting perturbation technique was also used to measure the step response. In order to create a step, the duration of the test flash changed from 4 to 700 ms. In a preliminary experiment the value of q was determined by measuring the thresholds of the probe and test flash and, subsequently, putting the luminance of the test flash at 30% of its threshold. Finally, threshold curves as a function of flash duration have been determined for point sources as well as one-deg fields. The duration varied between 1 and 2000 ms.

2.3.3 Results

The normalized impulse response for a point source is shown in Figure 2.9. This function was determined for subject HR. The data are the averages of 24 threshold pairs. Ratio q remained 0.2. The slope of the psychometric function at the 50% point proved to be -0.31 dB^{-1}, corresponding to a Crozier quotient of 0.15. This Crozier quotient represents the ratio between the standard deviation of the normal distribution underlying the psychometric function and the luminance at the 50% point (Roufs, 1974b). Roufs and Blommaert (1981) reported a Crozier quotient of 0.14 for their subject FB. The function drawn through the data of Figure 2.9 is the impulse response of a fourth order low-pass filter and is given by

$$h(t) = \left\{0.744\,(t/11.87)^3 \exp(-t/11.87)\right\} H(t) \tag{2.6}$$

$$H(t) = \begin{cases} 0, & t < 0 \text{ ms} \\ 1, & t \geq 0 \text{ ms} \end{cases}$$

In order to locate the extremum of this function on the origin of the $-\tau$-axis, time t of eq. (2.6) has to be replaced by "$t_{ex} - \tau$" with $t_{ex} = 35.61$ ms if no transport time has to be assumed. To fit their data, Roufs and Blommaert (1981) used

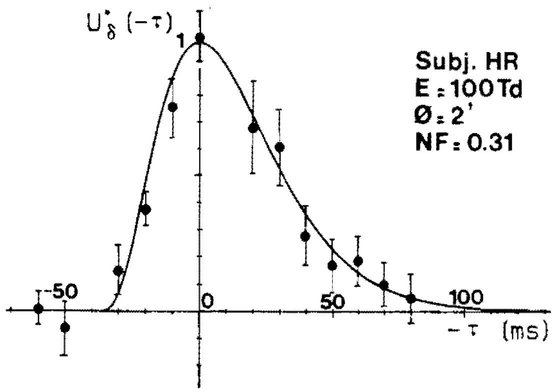


Figure 2.9: Normalized impulse response for a point source projected against an extended 100 Td background. The solid line drawn through the data is the normalized impulse response of a fourth order low-pass filter described by eq. (2.6). The vertical bars represent twice the standard error of the mean.

a fourth order low-pass filter with about the same time constant, viz. 12.66 ms instead of 11.87 ms. Since Roufs and Blommaert (1981) have measured against a

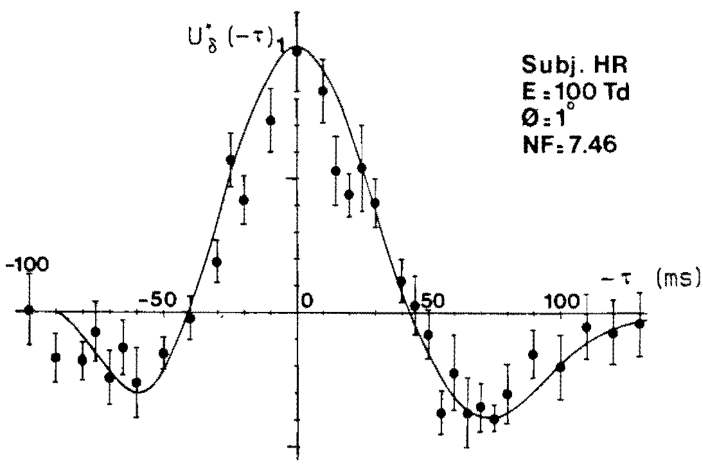


Figure 2.10: Normalized impulse response for a circular one-deg field with dark surround. The retinal illuminance of the background was 100 Td. The function drawn through the data is described by eq. (2.7). The corresponding values of the parameters can be found in Table 2.1, subject HR. Vertical bars indicate twice the standard error of the mean.

background of 1200 Td instead of 100 Td, this correspondence suggests that in the case of point sources the temporal properties of the visual system hardly change as a function of background luminance.

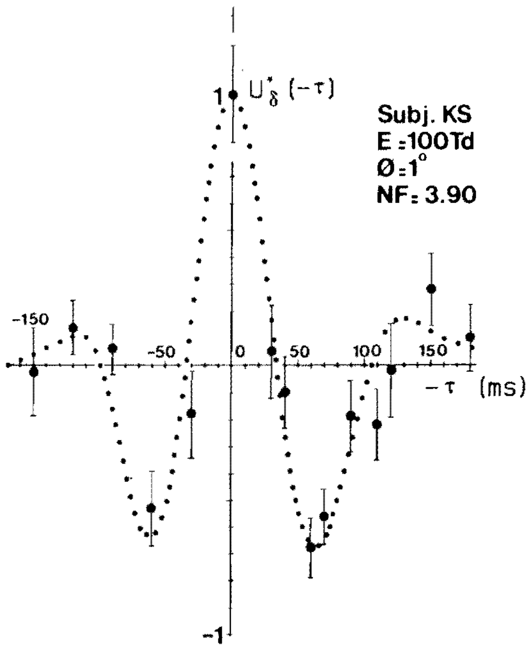
Going from a point source to a one-deg field, the time course of the impulse response will change from a monophasic to a more oscillatory one (Roufs and Blommaert, 1981). This is confirmed by our results. The normalized impulse response has now become triphasic for subject HR (Fig. 2.10) and the impulse response for subject KS appears to contain at least five alternately positive and negative phases (Fig. 2.11a). The data of Figure 2.10 are based on 12 threshold pairs whereas 22 sessions were used to obtain the curve of Figure 11a. The value of q was 0.3 and 0.1 respectively. For both subjects, the Crozier quotient proved to be 0.16. In order to find an analytical expression for both impulse responses, the data of Figures 2.10 and 2.11a were, at first, fitted by a linear combination of at least three Gaussian functions. This, however, has the disadvantage that it will never give a causal description. Later, this problem was solved by using the impulse response of an n^{th} order linear filter with complex conjugated poles (den Brinker and Roufs, 1987). This impulse response consists of linearly summated damped cosines and is given by

$$h(t) = \left\{ \sum_{i=1}^{m} A_i \exp(-b_i t) \cos(\omega_i t + \varphi_i) \right\} H(t) \tag{2.7}$$

$$H(t) = \begin{cases} 0, & t < 0 \text{ s} \\ 1, & t \geq 0 \text{ s} \end{cases}$$

The lowest order that still gives a reasonable approximation proved to be 4 for subject HR and 6 for subject KS. These functions have been drawn through the data of Figures 2.10 and 2.11a. The corresponding values of the parameters can be found in Table 2.1. Again, time t of eq. (2.7) has to be replaced by "$t_{ex} - \tau$" with t_{ex} is 87 ms for subject HR and 168 ms for subject KS if no transport time has to be assumed.

Figure 2.11b shows the normalized step response for a one-deg field with dark surround. It was measured with the perturbation technique under the same conditions that were used to determine the impulse response of Figure 2.11a. Ratio q was approximately 0.03. This small value is needed in order to end up with a ratio of a few tenths for the extrema of the step response and the impulse response of the probe. The data are the averages of 16 threshold pairs. The curve running through these data is the integral of the impulse response calculated according to eq. (2.7). In fact, the measured impulse and step response were fitted simultaneously to find the proper values of the parameters of eq. (2.7). During these fittings, the impulse response was the exact derivative of the step response. This has to be in force when the visual system behaves linearly at threshold (Roufs and Blommaert, 1981; Blommaert and Roufs, 1987).



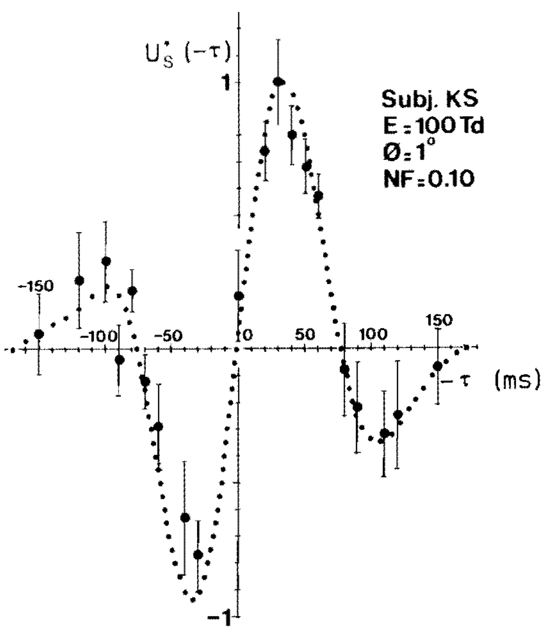


Figure 2.11: (a) Normalized impulse response for a circular one-deg field with dark surround. The retinal illuminance of the background was 100 Td. (b) Normalized step response for the same stimulus configuration. These responses were simultaneously fitted by the impulse and step response of a sixth order filter (see eq. (2.7)), the impulse response being the exact derivative of the step response. The dotted lines indicate the resulting functions. The corresponding values of the parameters can be found in Table 2.1, subject KS. Vertical bars: ± s.e.m.

Table 2.1: Values of the parameters that belong to the analytical expression given by eq. (2.7). The expression describes the impulse response of an n^{th} order linear filter with complex conjugated poles.

Subject	m	i	A_i	b_i (s^{-1})	ω_i (rad/s)	φ_i (rad)
HR	2	1	1.64	10.62	27.10	−2.05
		2	1.14	11.01	56.41	−11.72
KS	3	1	0.98	7.46	64.27	0.97
		2	2.01	7.97	46.47	−1.69
		3	0.88	5.42	29.85	1.92

The assumption of linearity has also been tested by comparing the predicted and measured thresholds of rectangular incremental flashes as a function of flash duration. In Figures 2.12 and 2.13 the open symbols represent the threshold characteristics of a one deg field with dark surround that was centrally fixated (open diamonds) or that was presented 40 min arc to the right of a fixation point (open circles). The data are based on 4 measurements and the standard deviation of the mean proved to be about 6% of the mean. The threshold curves have the same shape. At short durations, the data approximate an asymptote with slope −1 while at long durations the data are independent of flash duration. At the transition a dip can be seen that resembles the Broca-Sulzer effect. In earlier studies (Roufs, 1974a; Roufs and Bouma, 1980; Blommaert and Roufs, 1987), it was found that such a threshold curve is predicted quantitatively by assuming linear processing and peak detection. In the present study, this is confirmed by the good fit between the measured data (Figs 2.12, 2.13, open symbols) and the dashed lines, representing theoretical curves derived from the impulse responses of Figures 2.10 and 2.11a under the assumption of linearity and peak detection. It should be emphasized that no free parameters are involved. For subject KS, a small correction for "probability summation" (Roufs, 1974b; Blommaert, 1987) was incorporated to explain the difference between the predicted and measured thresholds at long durations. The resulting effect in the case of subject HR will be discussed further on. Extension of the background from a one-deg field to a 5.5 deg field causes a change in the shape of the threshold curve in that the dip disappears. The same results were obtained by Roufs (1974a) measuring at a 1200 Td background level. In addition, the extension of the background causes a lowering of the threshold for all durations (Figs 2.12, 2.13, filled symbols). This increase in sensitivity corresponds to results of earlier studies using rectangular flashes (Roufs, 1974a; Guth, 1973; Brussell et al., 1977) and sinusoidally modulated light (Roufs, 1972a; Harvey, 1970).

Thresholds of a flashed point source as a function of flash duration can be seen in Figure 2.4 (filled circles). These data are the averages of 4 measurements, the standard deviation of the mean being about 5% of the mean. At short durations, the data and model predictions derived from the impulse response of Figure 2.7

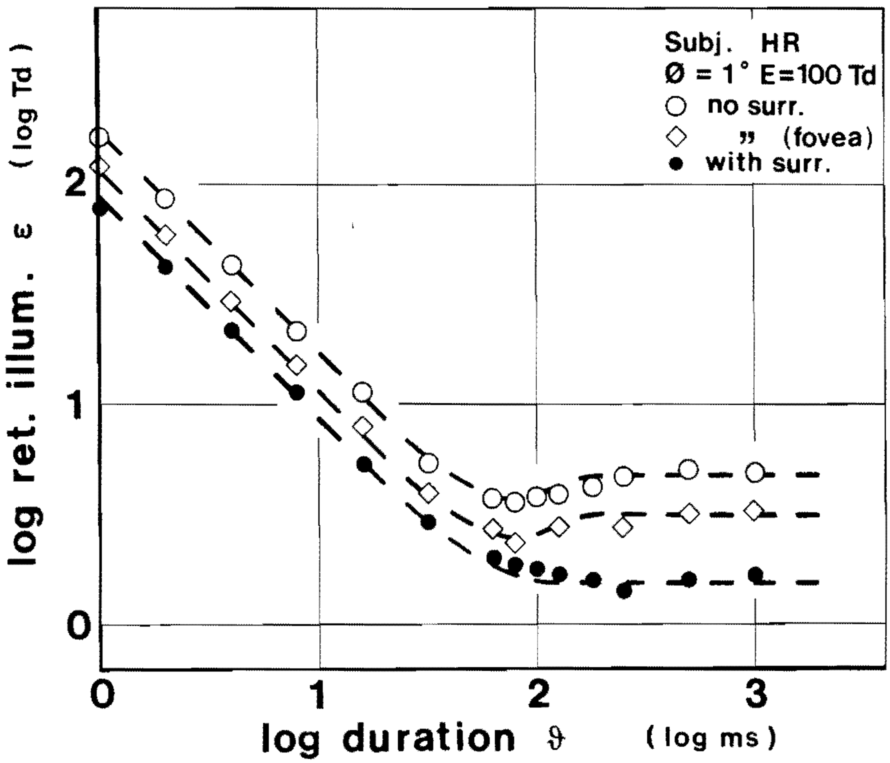


Figure 2.12: Incremental threshold curves as a function of flash duration. Open symbols: one-deg field with dark surround. Filled symbols: one-deg field with a surround having the same retinal illuminance as the background, viz. 100 Td. The centre of the one-deg field was presented either foveally (diamonds) or 40 min arc to the right of a fixation point (circles). The lower threshold curve was taken from Figure 2.2. The dashed lines fitted to the other curves indicate the calculated luminance increments required to obtain a constant peak response from the linear filter (see eq. (2.15)). Subject: HR.

fall on the same line, having a slope −1. For long flashes, the model predicts that the threshold becomes independent of duration because the peak value of the response to a flash with constant luminance does not continue to increase with duration (Roufs and Bouma, 1980; Blommaert and Roufs, 1987). The measurements, however, demonstrate a continuous decrease of the threshold with increasing duration. This discrepancy can be explained as follows. The step response remains at a constant level after an initial rise and, consequently, the flat crest of the response to a flashed point source becomes longer when the duration is increased. Since threshold d can in fact be considered a stochastic variable, the chance to detect this flash will also increase. In Figure 2.4, the continuous line represents the

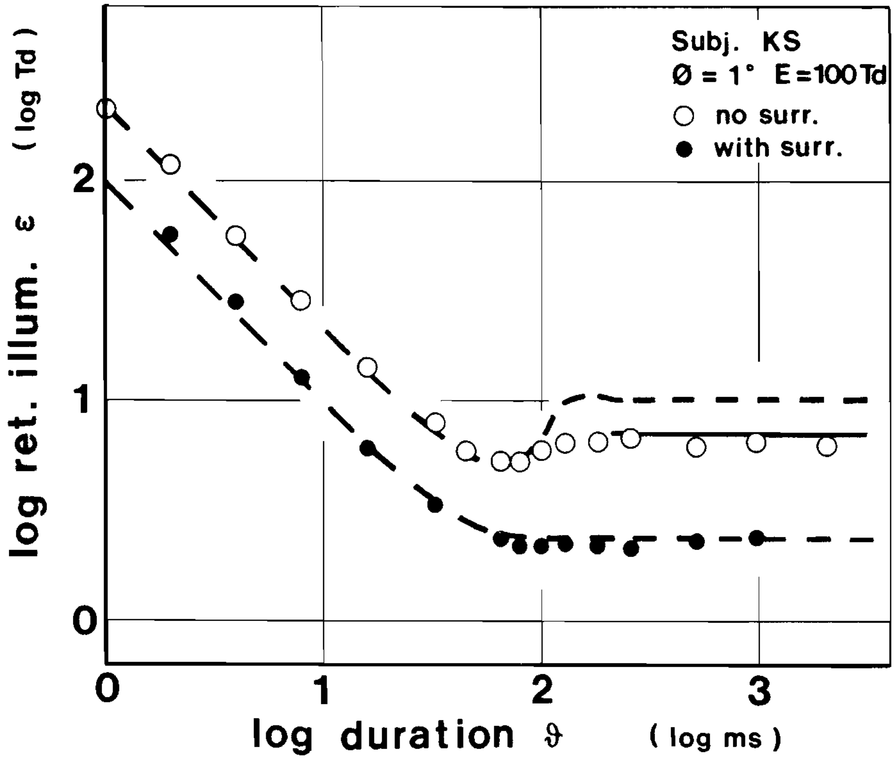


Figure 2.13: Same as Figure 2.12. The lower threshold curve was taken from Figure 2.3. The solid line shows the correction for probability summation. Subject: KS.

correction for this increased detectibility. This correction is based on noise data obtained from the slope of the psychometric function for the point source (Roufs, 1974b; Watson, 1986; Blommaert and Roufs, 1987).

2.3.4 Discussion

The impulse responses shown in Figures 2.9 and 2.10 correspond to those measured by Roufs and Blommaert (1981). The impulse response of subject KS (Fig. 2.11a) has a more pronounced oscillatory behaviour. In filter terms one would say that his visual system has a higher quality factor. For point sources projected on an extended background, the impulse response is monophasic whereas the impulse response for a one-deg field with dark surround is multiphasic. This difference indicates that these spatial configurations selectively stimulate two separate channels, viz. a sustained one that acts like a temporal low-pass filter and a transient one that acts like a temporal band-pass filter. The latter will mainly respond to relatively fast stimulus changes and will not let through any DC-component if it is a *pure* band-pass filter. The fact that for subject KS the step response approaches zero (Fig. 2.11b) is consistent with the last conclusion. Moreover, the correction for "probability summation" at long durations (Fig. 2.13) is small because there is only a significant response at the onset and offset of the stimulus. These responses have an opposite sign. However, internal threshold *d* is assumed to lie symmetrically around the zero level (Roufs, 1974a) and, consequently, positive and negative amplitude changes are equally effective for the detection of a long flash. For the sustained system, on the contrary, the step response will remain at some constant level, resulting in a monotonically decreasing threshold curve due to "probability summation" (Fig. 2.4).

There appears to be an intriguing difference between the two subjects. While the transient channel has a pure band-pass character for subject KS, this does not seem to be the case for subject HR. This can be appreciated when the impulse response of Figure 2.10 is integrated. The resulting function, being the step response of the transient channel for subject HR, does not return to the zero level when time goes to infinity. From the function, drawn through the experimentally obtained impulse response (Fig. 2.10), the step response is calculated to remain at approximately 60% of its peak value. The fact that the step response does not return to the zero level implies that the maximum of the response to the onset of a long flash is significantly larger than the maximum of the response to the offset. In other words, the response to a long flash will have only one pronounced maximum. From this, it is predicted that for subject HR there will be hardly any lowering of the detection threshold due to "probability summation" because the effect of noise is only relevant for the short transient at the beginning of the long duration block. This is corroborated by the data of Figure 2.12 since these data show that threshold curves, obtained under the same conditions that were used to measure the impulse response, are predicted from the impulse response without inclusion of "probability summation". This proved to be valid for the two retinal positions that were examined (Fig. 2.12, open symbols).

At threshold both subjects reported two different kinds of percepts depending on the spatial configuration used. "Agitation" that is inhomogeneously distributed over the stimulus area was seen in the case of one-deg fields with dark surround whereas a homogeneous brightness increase was reported in the case of point sources. This difference supports the suggestion that these spatial configurations selectively stimulate one of two systems operating in parallel. For the one-deg fields projected on the extended background a mixture of these percepts was observed, viz. an inhomogeneous brightness increase resembling "agitation" at durations shorter than 100 ms and a homogeneous brightness increase at durations longer than 128 ms. This mixture of percepts suggests that under these conditions both the transient and sustained system contribute to the detection of stimuli. One of the consequences of this mixture is that the threshold curve as a function of duration (Figs 2.12, 2.13, filled symbols) cannot be predicted from the impulse response of the transient system without prior knowledge of the interaction between the sustained and transient system.

The dashed lines that have been drawn through the last-mentioned threshold data represent merely a description of the data and have no theoretical meaning. Smith et al. (1984) obtained similar threshold curves when they flashed 1.2 deg white fields against a 4 deg white background. They fitted their data under the assumption of linear processing and peak detection, using the impulse response of a fifth order low-pass filter. Their suggestion that this will give virtually the same results as using a band-pass filter holds only for deterministic models, because introduction of noise would lead to continuously decreasing threshold curves in the case of a low-pass filter (Fig. 2.4) but not in the case of a band-pass filter.

2.4 Section III : A model to unify threshold and suprathreshold data

2.4.1 Dynamic brightness model

For one-deg fields, equal-brightness curves (Figs 2.2, 2.3, open symbols) strikingly resemble threshold curves, provided that during the threshold measurements the one-deg fields are surrounded by a dark field (Figs 2.12, 2.13, open symbols). This resemblance of curves of constant brightness and detectibility can be understood if the same linear system is underlying these curves. In addition, the brightness impression of a flash has to be determined by the extreme value given by the system's response peak. Note that the last assumption is analogous to peak detection at threshold. These two assumptions have led to a model that is meant to describe the brightness of time-dependent stimuli. According to the model that was first proposed to describe the brightness of incremental flashes of moderate energy (Roufs and Pellegrino van Stuyvenberg, 1979), the visual system consists of a quasi-linear filter that is followed by a quasi-memoryless compressive nonlinearity. In a refinement of the model (Roufs, 1980, 1981; de Ridder and Theelen, 1983, 1984) the

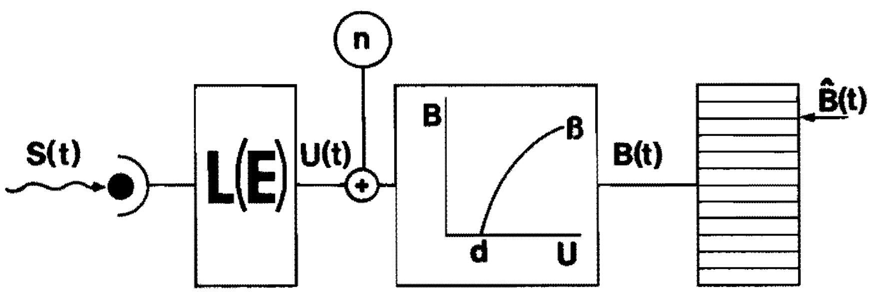


Figure 2.14: Dynamic brightness model. For details, see text.

nonlinearity has been combined with a threshold mechanism in order to include predictions of brightness perception in the vicinity of the detection threshold. This model is presented in Figure 2.14 and contains the following elements:

Linear filter L(E) The dynamic behaviour of the linear filter depends not only on background luminance E but also on the spatial configuration. This is shown by the different impulse responses for a point source (Fig. 2.9) and a one-deg field with dark surround (Figs 2.10, 2.11a) as well as by the different threshold characteristics for one-deg fields with and without surround (Figs 2.12, 2.13). The influence of the spatial configuration on the dynamic properties of the linear filter suggests a more extensive model, viz. one with two filters operating in parallel. Watson (1986) called this the strong version of the sustained-transient dichotomy. A milder version of this theory would only assert a relationship between the spatial configuration and the temporal properties of the linear filter (Watson, 1986).

Detection threshold The combination of linear filter L(E) and noisy threshold d resembles the detection model proposed by Roufs (1972b, 1974a). The main difference is that in the present model only the positive threshold is used.

Compression The model contains a quasi-memoryless compressive nonlinearity since it is commonly acknowledged that the visual system processes non-linearly at suprathreshold levels. The compression is efficiently described by a power function with an exponent less than one. This has the additional advantage that in this way Stevens' power law relating brightness to luminance (e.g. Marks, 1974; Stevens, 1975) is introduced into the model. Results of brightness-scaling experiments have sugggested that the exponent of this Stevens' relation depends on the area as well as the duration of a stimulus (Mansfield, 1973). This dependence can be tested by applying the brightness model to the brightness-matching data of Section I (see below).

Sample-and-hold mechanism The output of the nonlinearity has to be kept in some kind of memory in order to be able to relate the strength of the brightness impression to some aspect of the model's response, e.g. the peak in the case of fast-changing stimuli. This memory can be thought of as a sample-and-hold mechanism. In Figure 2.14 it has been visually represented using a stack.

The attractive property of this model is that, given the spatial configuration including background luminance E, response $B(t)$ to any arbitrary temporal pattern $S(t)$ can be calculated according to

$$B(t) = c\{U(t) - d\}^{\beta}\phi\{U(t) - d\} \tag{2.8}$$

$$\phi\{U(t) - d\} = \begin{cases} 0, & U(t) - d \leq 0 \\ 1, & U(t) - d > 0 \end{cases}$$

with

$$U(t) = \int_0^{\infty} S(t')U_{\delta}(t - t')\mathrm{d}t' \tag{2.9}$$

in which $U_{\delta}(t)$ represents the unit impulse response of the linear filter. In combination with some criterion, e.g. the peak value of $B(t)$ in the case of fast-changing stimuli, the model is able to predict quantitatively the strength of the brightness impression for any stimulus $S(t)$. These predictions can be tested in brightness-scaling and brightness-matching experiments. Examples of the former are described in Chapter 5 whereas examples of the latter are presented in the following section in which the correspondence between the brightness-matching data of Section I and model predictions derived from the measured impulse responses is examined.

2.4.2 Brightness matching and model predictions

According to the dynamic brightness model, brightness peak $\hat{B}$ of a rectangular incremental flash of duration ϑ and retinal illuminance ε is given by the following expression

$$\hat{B} = \{(\varepsilon - \varepsilon_0)\hat{U}_p(t;\vartheta)\}^{\beta}\phi(\varepsilon - \varepsilon_0) \tag{2.10}$$

$$\phi(\varepsilon - \varepsilon_0) = \begin{cases} 0, & \varepsilon \leq \varepsilon_0 \\ 1, & \varepsilon > \varepsilon_0 \end{cases}$$

in which $\hat{U}_p(t;\vartheta)$ represents the maximum of the unit block response of the linear filter and ε_0 is the 50% detection threshold for a flash of duration ϑ. If a flash is shorter than a given critical duration, then

$$\varepsilon\hat{U}_p(t;\vartheta) = \varepsilon\vartheta\hat{U}_{\delta}(t) \tag{2.11}$$

where $U_{\delta}(t)$ is the unit impulse response (Roufs, 1972b). In other words, at short durations the brightness is directly related to the energy of a flash (Bloch's law). At long durations $\hat{U}_p(t;\vartheta)$ becomes independent of ϑ.

An important assumption of the dynamic brightness model is that a test flash T and a reference flash R are matched in brightness if their brightness peaks are matched, or

$$\hat{B}_T = \hat{B}_R \tag{2.12}$$

For point sources the response of the linear filter to a rectangular flash is monophasic. It is obvious that in this case brightness peak $\hat{B}$ is related to the extremum of this (positive) phase. For large fields, however, the block response of the linear filter contains positive as well as negative phases and, accordingly, a positive and a negative extremum. Beforehand it is not clear whether brightness peak $\hat{B}$ is related to the positive or negative extremum or to both. Figure 2.15 shows both extrema as a function of flash duration. These curves were derived from the impulse responses of Figures 2.10 and 2.11a. For subject KS, both curves have an overshoot that resembles the Broca-Sulzer effect. For subject HR, on the contrary, only the curve of the positive extremum shows this effect. From this it was decided to take the positive extremum as the one that determines brightness peak $\hat{B}$. Note, however, that a symmetrical rectification of the block response will hardly change the curves predicted from the positive extremum only. The main difference will occur for subject KS around ϑ equal to 150 ms where the negative peak becomes larger than the positive one, removing the dip that the curve of the positive extremum demonstrates around this duration. However, it should be pointed out that, in the case of symmetrical rectification, the information of brightness in case of increments and decrements would be lost.

To measure an equal-brightness curve, $\hat{B}_R$ is kept constant. In that case, one obtains from eqs (2.10) and (2.12)

$$\log(\varepsilon_T - \varepsilon_{0T}) = -\log \hat{U}_p(t;\vartheta_T) + (\beta_R/\beta_T)\log\{(\varepsilon_R - \varepsilon_{0R})\hat{U}_p(t;\vartheta_R)\} \qquad (2.13)$$

where ε_{0R} is constant since ϑ_R is constant. When duration ϑ_T is small, then

$$\log(\varepsilon_T - \varepsilon_{0T}) = -\log\{\vartheta_T \hat{U}_\delta(t)\} + C_1 = -\log\vartheta_T + C_2 \qquad (2.14)$$

where C_1 and C_2 are constants. Retinal illuminance ε_{0T} changes as a function of ϑ_T within Bloch's region but remains constant for long flashes in the case of one-deg fields (Figs 2.12, 2.13, filled circles) or continues to decrease in the case of point sources (Fig. 2.4, filled circles). The model predicts that retinal illuminance ε required to obtain a constant peak response from the linear filter is given by

$$\log\varepsilon = -\log\hat{U}_p(t;\vartheta) + \text{constant} \qquad (2.15)$$

This function is represented by the broken lines that have been fitted to the measured equal-brightness curves of Figures 2.2, 2.3 and 2.4, with the exception of the lowest curves of Figures 2.2 and 2.3 where the influence of the threshold and, in particular, the influence of surround and noise on the threshold cannot be neglected. The model predictions have been derived from the measured impulse responses of Figures 2.9, 2.10 and 2.11a. The good fit between these predictions and the data implies that β_T in eq. (2.13) has to be constant when duration ϑ_T varies except in the unlikely case that both change with ϑ in exactly the same manner. However, this would only be obvious for durations outside Bloch's region, since within this region energy determines the response. Consequently, for large fields as well as point sources the exponent of the power function which

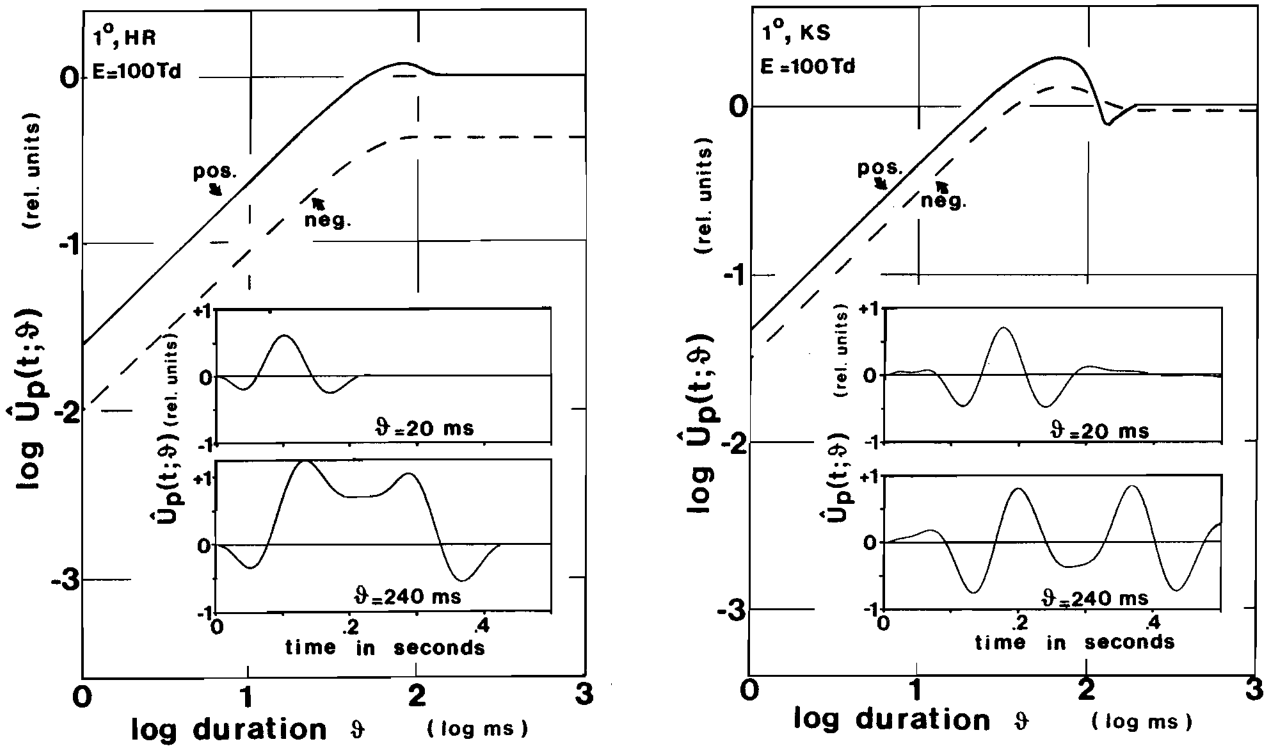


Figure 2.15: Calculated positive and negative extrema of the response of an n^{th} order linear filter with complex conjugated poles to a rectangular flash of varying duration ϑ. The positive and negative extrema are indicated by the solid and dashed lines respectively. Left panel: curves for subject HR derived from the impulse response of Figure 2.10. Right panel: curves for subject KS derived from the impulse response of Figure 2.11a. In both panels block responses are inserted that were calculated for $\vartheta = 20$ ms and $\vartheta = 240$ ms.

describes the relationship between brightness and luminance is most likely to be independent of flash duration. This result is contrary to findings based on the method of magnitude estimation (e.g. Mansfield, 1973; Stevens, 1975) since these findings suggest that the exponent is larger for short flashes than for long ones.

Another implication of the good fit is that the initial part of the visual system should be linear, even for large amplitude changes (more than 3 log units above threshold). This is corroborated by the parallelism of the matching curves of Figure 2.8. Since there is no influence of "probability summation" on the results of the brightness matchings, it seems more convenient to determine the parameters of the model at suprathreshold than at threshold level. The difference between an equal-brightness curve and a threshold curve is especially clear in the case of point sources (Fig. 2.4). But it is also interesting to observe the individual differences in the case of the one-deg fields. While for subject KS the dip is smaller at threshold than at suprathreshold levels due to the presence of "probability summation" at threshold level, no significant difference has been found for subject HR (Fig. 2.2). This suggests again that the transient system of subject HR does not act like a pure band-pass filter, in contrast with that of subject KS.

The results of the other brightness matching experiments of Section I (Figs 2.5, 2.6, 2.7, 2.8) can also be explained by the model. In these experiments the retinal illuminance of the reference flash was determined as a function of either the duration or the retinal illuminance of the test flash, keeping the remaining variables constant. According to the model, the results can be described as follows

$$\log(\varepsilon_R - \varepsilon_{0R}) = \frac{\beta_T}{\beta_R}\{\log(\varepsilon_T - \varepsilon_{0T}) + \log \hat{U}_p(t;\vartheta_T)\} + \text{constant} \tag{2.16}$$

At high luminance levels, where the influence of the threshold is negligible, the data will lie on straight lines with slope β_T/β_R whenever the duration of the test flash is constant (Fig. 2.8) or shorter than the critical duration (Figs 2.5, 2.6, 2.7). Given that exponent β is independent of ϑ, this implies that for the data of Figures 2.5 and 2.6, where both reference and test stimulus were point sources, the slope should be +1 at short durations. Near threshold, however, this slope is determined not only by the ratio of the brightness exponents of test and reference flash but also by ε_{0T} and ε_{0R}. According to Bloch's law, ε_{0T} will decrease as the flash duration is increased. Consequently, at short durations the brightness increase of the test flash in eq. (2.16) will depend on the increase of the flash duration as well as the increase of the "effective luminance" $(\varepsilon_T - \varepsilon_{0T})$. As ϑ_R is constant, the threshold luminance of the reference flash will also be constant. Both the duration-independence of the brightness exponent and the influence of the threshold have been taken into account during the fittings of the results of Figures 2.5 and 2.6. The predicted curves (dashes) are in reasonable agreement with the data found experimentally.

At high luminance levels, the data of Figures 2.7 and 2.8 lie on straight lines. Following eq. (2.16), the slope of these lines represents the ratio of the exponents for a one-deg field and a point source. It was found to be 1.18. Based on the results of magnitude estimations measured against a dark background (Mansfield, 1973), the slope was predicted to be approximately 0.5. This value was indeed found by Roufs and Pellegrino van Stuyvenberg (1979). Unfortunately, they measured only at one luminance level, comparable with the lowest level in Figure 2.7, and did not take into account the influence of the threshold correction. Therefore the match between their slope and the prediction on the basis of the Mansfield data has to be regarded as a misleading coincidence. The good fit of the model predictions to the present results (Figs 2.5, 2.6, 2.7) shows that the slope near threshold is reflecting not only the ratio of the exponents for the test and reference flash but also the fact that the brightness impression of both the test and reference flash is determined by the effective luminance.

All above-mentioned conclusions are valid if the brightness matchings meet the requirement of transitivity. This implies that if brightness B_A equals brightness B_B and brightness B_B, in its turn, equals brightness B_C, then brightness B_A should also equal brightness B_C. The transitivity of the brightness matchings was not explicitly examined. However, on many occasions the brightness of various kinds of test stimuli was matched with that of a flashed point source, lasting either 8 or 256 ms. For example, the lower curves in Figures 2.5 and 2.6 were determined with the same test stimulus, viz. a flashed point source having a retinal illuminance of 1100 Td. The only difference between these curves is the duration of the reference flash. From this kind of data a relation can be constructed between the retinal illuminance of the "8 ms flash" (ε_8) and the "256 ms flash" (ε_{256}). This relation has to be independent of the characteristics of the test flash if transitivity holds. Moreover, the constructed data should lie on a straight line with a slope +1 since the brightness exponent is independent of flash duration. In Figure 2.16 the constructed data are shown. They have been corrected for their thresholds. The data for different test stimuli overlap and lie approximately on a straight line, suggesting that transitivity holds. The drawn line in Figure 2.16 is a model prediction derived from the impulse response described by eq. (2.6), under the assumption that the brightness exponent is independent of flash duration. The fact that this model prediction fits reasonably well is another confirmation of this independence.

2.5 Conclusions

Since the discovery of the Broca-Sulzer effect at the beginning of this century, a large amount of research has been devoted to this brightness phenomenon, yet there is still no general consensus about its origin. The interocular-brightness matching experiments, described in Section I of the present study, aimed at finding a correlation between the size of the stimulus area and the existence of the Broca-Sulzer effect. This effect proved to be present with large (one-deg) fields but not with point sources. From this, it was concluded that the Broca-Sulzer effect is generated by the transient channel of the visual system. This conclusion is

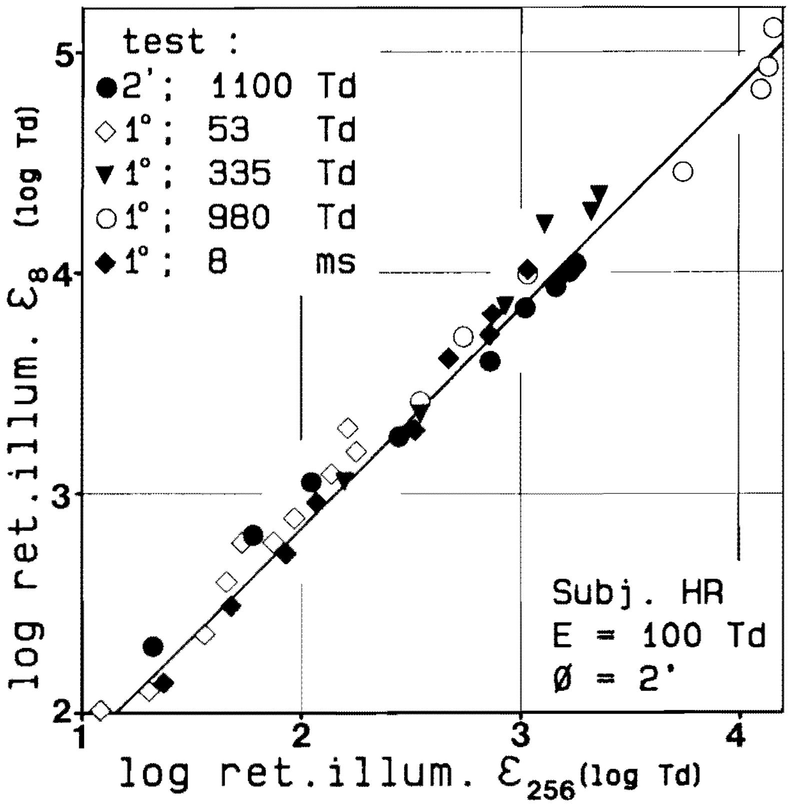


Figure 2.16: Constructed brightness-matching curve between flashed point sources, lasting 8 and 256 ms. The curve has been derived from measured brightness-matching curves between these stimuli and various test stimuli. The duration of the test flash was varied in all cases but one (test: one deg, 8 ms) where the luminance of the test flash was the independent variable. The data have been corrected for their thresholds. The straight line indicates a model prediction derived from the impulse response of Figure 2.9.

supported by the fact that the above-mentioned influence of stimulus area on the occurrence of the Broca-Sulzer effect is correctly predicted from impulse responses, measured at threshold (Section II). For point sources the impulse response was found to be monophasic and could be described by that of a fourth order low-pass filter, whereas for one-deg fields with dark surround it was found to be multiphasic and could be compared with that of an n^{th} order linear filter with complex conjugated poles. These results support the hypothesis that point sources stimulate the sustained system and large fields the transient one (Roufs and Blommaert, 1981).

In Section III a dynamic brightness model was presented that enabled the results of the threshold and suprathreshold measurements to be unified. The conclusions that can be drawn from the application of this model to the brightness matching data of Section I, are:

1. The initial part of the visual system is linear, even for large amplitude changes. At threshold, the assumption of linearity was confirmed by the finding that the impulse response is the derivative of the step response. Moreover, threshold curves as a function of flash duration could be predicted from the measured impulse responses. At suprathreshold levels, the linearity is confirmed by the validity of Bloch's law for short flashes and by the parallelism of matching curves with different short durations.

2. The exponent of the power function which is assumed to describe the relation between brightness and luminance is independent of flash duration.

3. The brightness of a fast-changing stimulus is related to the system's response peak.

4. The brightness impression is determined by the effective luminance, i.e. luminance above threshold.

An interesting problem arises when the Broca-Sulzer effect is related to the activity of the transient system. In general, this system acts like a band-pass filter and, accordingly, there is only a response at the onset and offset of a long flash. In between, however, the flash does not disappear to the subject's eyes. This suggests that the generation of brightness is taken over by another mechanism, probably the sustained system. If this is true, then both systems contribute to the brightness of a flash which brings up the problem of their interrelation. This has still to be investigated.

chapter 3

Influence of the state of adaptation on the Broca-Sulzer effect

Abstract

The influence of the state of adaptation of the eye on the Broca-Sulzer phenomenon has been investigated by measuring equal-brightness curves as a function of flash duration for circular one-deg fields projected against a photopic and a dark background. The results show that the Broca-Sulzer effect is present in both conditions. In the dark-field condition the Broca-Sulzer effect was found to shift to shorter durations with increasing flash luminance. For flashes presented against the photopic background, however, this shift is absent. Furthermore, the equal-brightness curves were found to be isomorphous. They coincide after translation along the luminance axis in the photopic background condition and after translation along the duration and luminance axes in the dark-field condition. Both the isomorphism of the equal-brightness curves and the absence of the shift in the photopic background condition suggest that the exponent of the power function, relating brightness to luminance, is independent of flash duration. It is argued that the explanation of the shift, observed in the dark-field condition, cannot be given in terms of different brightness exponents for short and long flashes. Alternatively, the shift of the Broca-Sulzer effect in the dark-field condition is attributed to disturbances of the adaptation level.

3.1 Introduction

Duration affects the brightness of a rectangular incremental flash in a complex way. At short durations, the brightness is determined by the energy of the flash (Raab, 1962; Aiba and Stevens, 1964; Osaka, 1978), implying that Bloch's law holds at suprathreshold levels. At long durations, however, the brightness is determined solely by the luminance of the flash. Consequently, the brightness of a flash of fixed luminance grows with duration in Bloch's region, but remains constant at long durations. For point sources, a smooth transition from Bloch's region to the constant level at long durations can be observed (de Ridder and Theelen, 1983; see also Chapter 2). For large fields, however, brightness increases monotonically with duration until a maximum is reached and then declines to the constant level (de Ridder and Theelen, 1984; see also Chapter 2). The resulting overshoot is known as the temporal brightness enhancement or Broca-Sulzer effect (Broca and Sulzer, 1902). Its dependence on the size of the stimulus field suggests that the Broca-Sulzer effect is generated by the transient channel of the visual system (e.g. Green, 1984; Watson, 1986).

More than a century ago, Exner (1868) showed that the flash duration required to produce maximum brightness decreases as luminance increases. Ever since, the existence of this shift has been confirmed so many times (e.g. Broca and Sulzer, 1902; Raab, 1962; Aiba and Stevens, 1964; Stevens and Hall, 1966) that it has become customary to regard the shift as a characteristic feature of the Broca-Sulzer effect. Bowen and Pokorny (1978), for example, used the occurrence of this shift to demonstrate the validity of their method to measure the Broca-Sulzer effect. Stevens (1966) proposed the following equation to relate duration ϑ_{BS}, which produces maximum brightness, to flash luminance ε

$$\vartheta_{BS} = C.\varepsilon^{\alpha} \tag{3.1}$$

with

$$\alpha = (\beta_l/\beta_s) - 1 \tag{3.2}$$

where β_l and β_s are the exponents of the power functions that are assumed to describe the brightness-luminance relation at long and short durations respectively and C is a dimensional constant. Eqs (3.1) and (3.2) also apply to the critical duration which is a measure for Bloch's region (Anglin and Mansfield, 1968). Results of magnitude estimations show that, for large fields, β_s is about 1/2 and β_l about 1/3 (Mansfield, 1973). Consequently, exponent α of eq. (3.2) should be about $-1/3$. This value has been confirmed experimentally (Mansfield, 1973; Osaka, 1982). In these experiments, subjects had to adjust the duration of a flash of constant luminance to determine the duration that produces maximum brightness. Finally, Aiba and Stevens (1964) found that, in the dark-adapted eye, exponent α remains constant for flash luminances ranging from a level close to the absolute threshold to a level more than 6 log units above the absolute threshold.

Eqs (3.1) and (3.2) imply that the brightness exponent changes as a function of flash duration in a more or less discrete way. This "abrupt rather than gradual" change (Mansfield, 1973), however, is not found in brightness-scaling experiments. Stevens and Hall (1966), for instance, observed a gradual instead of an abrupt change of the slope of the brightness-luminance relation at intermediate durations. Since they plotted their data in log-log coordinates, this slope should directly reflect the brightness exponent. The data of Raab (1962) demonstrate a similar trend. In order to make these results correspond to eqs (3.1) and (3.2) it is usually assumed that at intermediate durations the brightness-luminance relation in fact consists of two parts and that the gradual change "...happens because with decreasing duration the steeper segment of the two-segment function comes more and more to dominate in the least-squares solution" (Stevens and Hall, 1966).

All brightness-matching and brightness-scaling experiments that demonstrate the shift of the Broca-Sulzer effect have been performed against a dark background. In an earlier study (de Ridder and Theelen, 1984; see also Chapter 2) it was found that the shift is absent when the flashes are presented against an extended, photopic background. Using a spatial configuration like ours, Katz (1964) and White et al. (1976) obtained similar results under mesopic and scotopic conditions. It was concluded that the occurrence of the shift depends on "...procedural differences concerning the presence or absence of a background" (de Ridder and Theelen, 1984).

The purpose of the present study is to verify this conclusion. Therefore, equal-brightness curves as a function of flash duration have been measured for circular one-deg fields, projected against a photopic and a dark background. It was predicted that the shift of the Broca-Sulzer effect would only occur in the last-mentioned condition.

3.2 Method

Apparatus and procedure

The experimental situation was similar to that used in our earlier studies (de Ridder and Theelen, 1983, 1984) and has been extensively described in Chapters 2 and 3. Therefore, an enumeration of the essentials will suffice.

A six-channel, binocular Maxwellian-view optical system generated the stimulus configuration that was used to obtain equal-brightness curves in the presence of a photopic and a dark background. The curves were measured by matching the brightness peaks of two rectangular "white" flashes, viz. a test flash of variable luminance and duration and a constant reference flash. The two flashes had a synchronous onset and were produced by glow modulator tubes (Sylvania R1131C or EEV XL670), linearized and stabilized by light feedback. Both reference and test stimulus were circular one-deg fields. The method of constant stimuli was employed to determine the retinal illuminance at which the subject judged the test flash to be brighter than the reference flash in 50% of the trials. This procedure does not exactly give the retinal illuminance defining the point of subjective equality since the instruction forces the subject to surpass a just noticeable brightness difference which is reflected by a just noticeable difference in retinal illuminance. However, it seems fair to conclude that the Weber fraction is constant for the experimental conditions employed in the present study (e.g. Cornsweet and Pinsker, 1965; Whittle, 1986), leading to a constant and small shift of the data when they are expressed in log units.

In the photopic background condition, a circular 5.5 deg, 100 Td, "white" field was presented to each eye. A small, dim, red fixation light appeared in the centre of these fields. After fusion, both the backgrounds and the fixation lights were seen superimposed. The centre of the left-eye reference flash appeared 40 min arc to the left of the fixation light. Similarly, the centre of the right-eye test flash appeared 40 min arc to the right of the fixation light. This whole stimulus configuration was seen through artificial pupils 2 mm in diameter, equipped with an entoptic guiding system (Roufs, 1963). In the dark-field condition, the same configuration was used with the exception of the backgrounds, which were switched off.

During a given session, only one complete equal-brightness curve was measured. The retinal illuminance of the reference flash, which usually lasted 8 ms, was set at a constant level and the experimenter changed the duration of the test flash in random order. This duration varied from 2 to 975 ms. Each second session was a repetition of the previous one, the stimuli being presented in the reversed order. As is explained in the results section, this procedure was shortened for one subject by performing brightness matchings at only four flash durations (4, 8, 512, 975 ms).

Subjects

Two male subjects participated in the experiments. They were both well-trained. Subject HR, aged 30 years, as well as subject KS, aged 35 years, have normal vision.

3.3 Results

Equal-brightness curves, measured against the photopic and the dark background, are shown in Figures 3.1 and 3.2 respectively. They were determined for the same subject (HR). The data presented in these figures are the averages of six measurements. The standard error of the mean proved to be about 6 percent of the mean, irrespective of the experimental conditions. All equal-brightness curves have the same shape. At short durations, the data lie on straight lines with slope −1 and, thus, obey Bloch's law. At long durations, the curves are independent of the flash duration. At the transition, a "dip" of approximately 0.1 log Td can be seen, indicating that the Broca-Sulzer effect is present in both conditions. For flashes projected against the photopic background, the duration at which the Broca-Sulzer effect occurs remains the same for all luminance levels (Fig. 3.1). In the dark-field condition, however, the Broca-Sulzer effect occurs at shorter durations when the luminance of the reference flash is increased (Fig. 3.2). At threshold level, the "dip" has completely vanished (Fig. 3.1, filled circles), but it will reappear in the threshold curve as soon as the surround is removed (Fig. 3.1, filled triangles). This phenomenon has already been described elsewhere (Roufs, 1974a).

Figure 3.3 shows all brightness-matching data in a reduced form. Neglecting the Broca-Sulzer effect, the equal-brightness curves of Figures 3.1 and 3.2 can be described by two asymptotes, viz. an asymptote with slope −1 at short durations and a horizontal one at long durations. In order to construct Figure 3.3, the test flash durations of each equal-brightness curve were divided by its critical duration T_{CA} that is defined by the intersection of the two asymptotes. Similarly, the test flash luminances were divided by luminance ε_l that is associated with the horizontal asymptote. The resulting single curve demonstrates the already noted isomorphism of the equal-brightness curves. The same isomorphism was obtained by Roufs (1974a) who applied the above-mentioned normalization procedure to threshold-duration curves measured at different background levels.

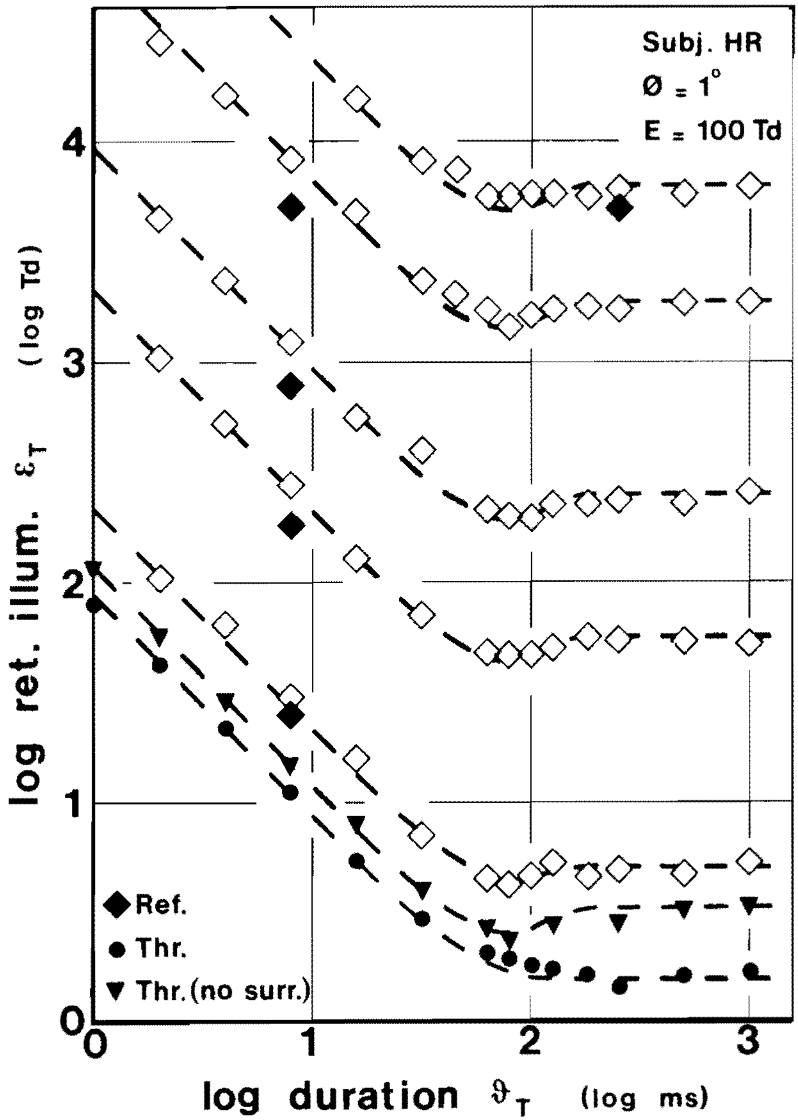


Figure 3.1: Equal-brightness and threshold curves for flashed one-deg fields with variable duration ϑ_T. The stimuli were presented against an extended 100 Td background, except for the upper threshold curve (filled triangles) where the background consisted of a foveally presented one-deg field with dark surround. The filled diamonds represent the reference flashes. The dashed lines fitted to the equal-brightness curves are curves predicted according to eq. (3.6). The function represented by the dashed line fitted to the lower threshold curve (filled circles) has been used to determine ε_{0T} in eq. (3.6). The dashed line fitted to the upper threshold curve (filled triangles) is a curve predicted according to eq. (3.6), using luminance ε_0 instead of the effective luminance $(\varepsilon - \varepsilon_0)$. Subject: HR.

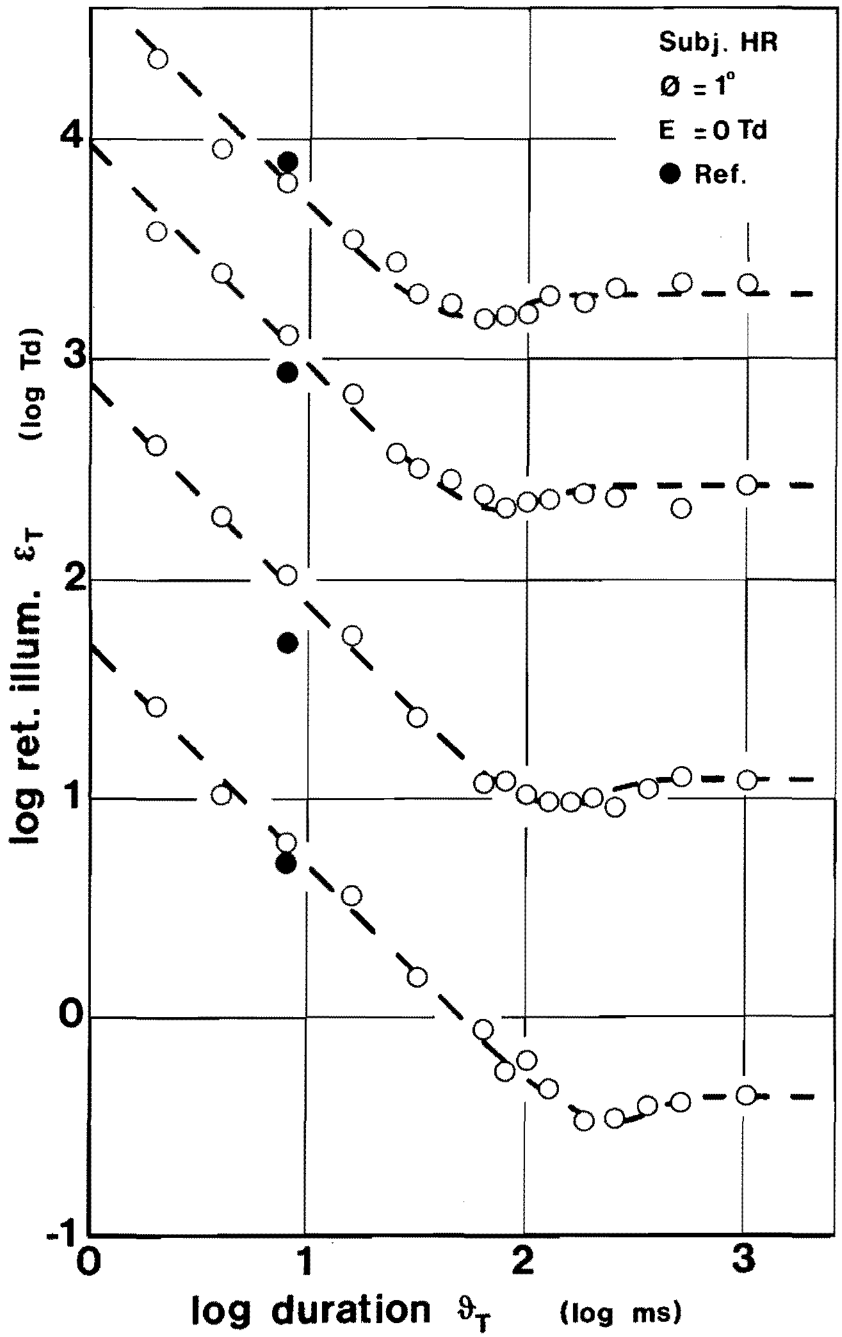


Figure 3.2: Equal-brightness curves for a flashed one-deg field with variable duration ϑ_T. Contrary to Figure 3.1, no background was present. The filled circles represent the reference flashes. The dashed lines are predicted curves derived from eq. (3.6). Subject: HR.

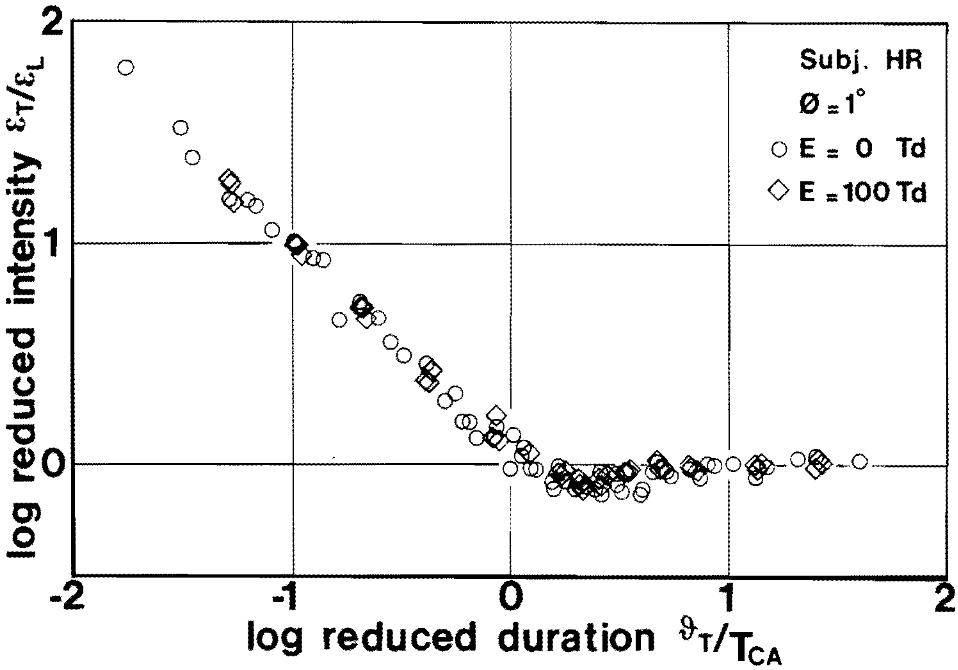


Figure 3.3: Brightness matching data of Figures 3.1 (diamonds) and 3.2 (circles) in reduced form. Test flash durations were divided by critical duration T_{CA} and test flash luminances by ε_l, being the mean luminances that have been determined for long flashes.

T_{CA} and ε_l can also be used to obtain a quantitative description of the shift of the Broca-Sulzer effect as was observed in the dark-field condition (Fig. 3.2). Because of the isomorphism of the equal-brightness curves (Fig. 3.3), T_{CA} and the Broca-Sulzer effect will exhibit the same shift. In Figure 3.4, $\log T_{CA}$ is plotted as a function of $\log \varepsilon_l$. For the dark-field condition, the data of Figure 3.4 have been fitted by a straight line with slope -0.18 ± 0.01 (95% confidence interval). The good fit indicates that eq. (3.1) also applies to these data, i.e. the critical duration changes as a power function of flash luminance. Approximately the same value for exponent α of eq. (3.1) was obtained by Aiba and Stevens (1964). In the photopic background condition, no shift was observed (Fig. 3.1) and, consequently, T_{CA} is independent of ε_l. The deviation near detection threshold (Fig. 3.4, filled diamond) is a consequence of the fact that the brightness impression of a flash is determined by its effective luminance, i.e. luminance above threshold (de Ridder and Theelen, 1983, 1984; see also Chapter 2).

The experiments have been repeated for a second subject (KS) in order to check the observed influence of the background on the shift of the critical duration T_{CA} and, thus, on the shift of the Broca-Sulzer effect. Instead of measuring a set of

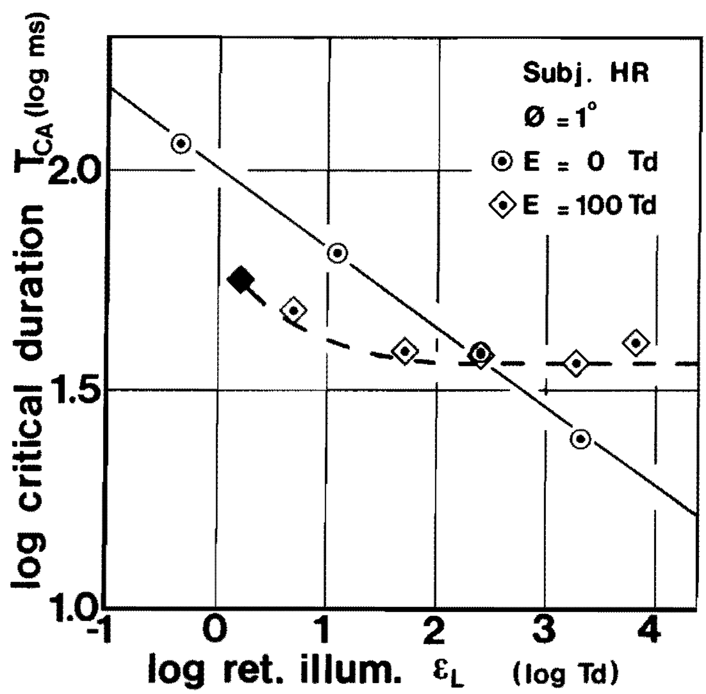


Figure 3.4: Critical duration T_{CA} as a function of flash luminance ε_l. The drawn line has been fitted to the critical durations determined for the dark-field condition (circles). The critical durations for the photopic background condition are represented by the diamonds, the filled one being the critical duration at threshold. The dashed line indicates a model prediction derived from eq. (3.6). Subject: HR.

complete equal-brightness curves, brightness matchings were performed at only four test flash durations: two short (4, 8 ms) and two long ones (512, 975 ms). The reference flash always lasted 8 ms. This reduction of experimental data is justified by the demonstrated isomorphism of the equal-brightness curves (Fig. 3.3). Critical durations were obtained by fitting a straight line with slope -1 to the test flash luminances measured at 4 and 8 ms and, similarly, a horizontal one to the luminances at 512 and 975 ms. As before, critical duration T_{CA} is defined by the intersection of these lines. Figure 3.5 shows that for the dark-field condition (open circles) the results are consistent with those presented in Figure 3.4. The critical duration shifts again as a power function of flash luminance, the exponent being -0.20 ± 0.04 (95% confidence interval). When a straight line is fitted to the critical durations obtained in the photopic background condition (Fig. 3.5, open diamonds), the slope of this line becomes -0.06 ± 0.03 (95% confidence interval). Consequently, these data do not exactly come up to the expectation that T_{CA} would lie on a horizontal line. However, it is clear that these data lie much

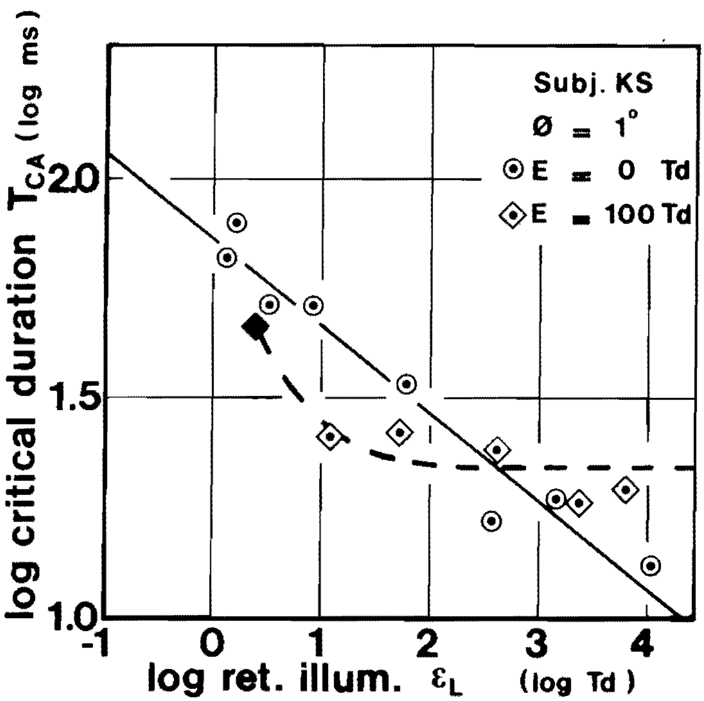


Figure 3.5: Same as Figure 3.4. Subject: KS.

closer to a horizontal line than to the one fitted to the critical durations obtained in the dark-field condition (slope −0.20). Furthermore, T_{CA} tends to be larger in the photopic background condition than in the dark-field condition when flashes of high luminances are employed. The same tendency can be seen in the data for subject HR (Fig. 3.4). It therefore seems reasonable to conclude that for both experimental conditions the data of Figure 3.5 correspond with those presented in Figure 3.4.

The absence or presence of the 100 Td background determines whether or not critical duration T_{CA} and, thus, the Broca-Sulzer effect shift as a function of flash luminance. The matching of the brightnesses of two flashes, on the contrary, is not influenced by these procedural differences. This can be seen in Figure 3.6, where the ratio of the luminances of the test and reference flash, required to match their brightness peaks when both flashes last 8 ms, is given as a function of the retinal illuminance of the reference flash. Circles represent data determined for the dark-field condition while diamonds give the ratios calculated for flashes projected against the photopic background. The data of these conditions overlap. Figure 3.6 also shows that this kind of brightness matching is not sensitive to the luminance of flashes. This proves to hold within a range of at least 3 log units. The ratio remains approximately 1 for subject KS. For subject HR, however, the ratio is greater, on average +0.14 log units. This systematic deviation from ratio 1 prob-

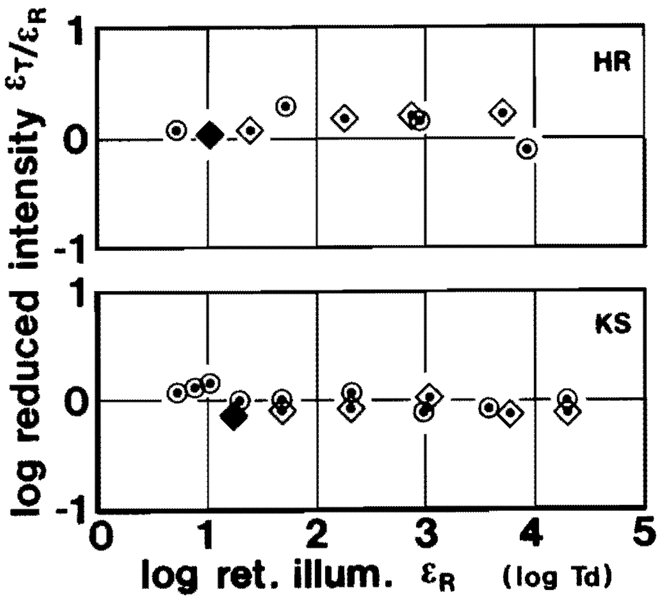


Figure 3.6: Ratio of the luminances of two rectangularly flashed one-deg fields, both lasting 8 ms, required to match their brightness peaks. The stimuli were flashed against a 100 Td background (diamonds) and a dark background (circles). The data for subject HR have been taken from Figures 3.1 and 3.2. The filled diamonds represent the ratio of the threshold luminances of the test and reference flash, measured against the 100 Td background in right and left eye respectively.

ably reflects differences between the eyes. This is supported by the fact that in an identical stimulus configuration approximately the same ratio (+0.16 log units) was found for point sources lasting 8 or 256 ms (de Ridder and Theelen, 1983; see also Chapter 2). Similar deviations have been reported by others (e.g. Whittle and Challands, 1969; Shevell, 1986; Georgeson, 1987). According to Shevell (1986), deviations of 0.3 log units frequently occur during interocular brightness matchings. The present results are well within this commonly observed range.

3.4 Discussion

The results of the present study show that the duration at which the Broca-Sulzer effect occurs shifts as a power function of flash luminance when the flashes are presented against a dark background. As was found by Aiba and Stevens (1964), the exponent of this function is approximately $-1/6$, which is significantly less than the usually quoted value of $-1/3$ (e.g. Marks, 1974). This last-mentioned value has been derived from the results of brightness-scaling experiments (Mansfield, 1973). In the present study, however, a brightness-matching technique has been employed. The same holds for the study of Aiba and Stevens (1964). Accordingly, the observed discrepancy may well be attributed to the different procedures employed in the two types of studies. This mutual inconsistency of brightness-scaling and brightness-matching techniques is usually neglected, although it was already noticed some twenty years ago (Stevens and Hall, 1966; Anglin and Mansfield, 1968).

The Broca-Sulzer effect does not shift with flash luminance when the flashes are projected against a photopic background. According to eq. (3.2), the absence of this shift implies that the exponent of the power function, relating brightness to luminance, has to be independent of flash duration. This conclusion is in agreement with the results of our earlier studies (de Ridder and Theelen, 1983, 1984; see also Chapter 2). These studies showed that the brightness of a fast-changing stimulus can be described by a dynamic brightness model that consists of a linear filter, followed by a combination of a threshold mechanism and a quasi-memoryless compressive nonlinearity. According to this model, brightness peak $\hat{B}$ of a rectangular flash of duration ϑ and retinal illuminance ε is given by the following expression

$$\hat{B} = \{(\varepsilon - \varepsilon_0)\hat{U}_p(t;\vartheta)\}^{\beta}\phi(\varepsilon - \varepsilon_0) \tag{3.3}$$

$$\phi(\varepsilon - \varepsilon_0) = \begin{cases} 0, & \varepsilon \leq \varepsilon_0 \\ 1, & \varepsilon > \varepsilon_0 \end{cases}$$

in which $\hat{U}_p(t;\vartheta)$ represents the maximum of the unit block response of the linear filter and ε_0 is the 50% detection threshold for a flash of duration ϑ. At threshold the impulse response of the linear filter, from which the unit block response is derived, can be measured with the drift-correcting perturbation technique introduced by Roufs and Blommaert (1981). Examples of impulse responses obtained in this way are shown in Figure 3.7. It is assumed in this model that a test flash T and a reference flash R are matched in brightness if their brightness peaks are matched, or

$$\hat{B}_T = \hat{B}_R \tag{3.4}$$

To measure an equal-brightness curve, $\hat{B}_R$ is kept constant. In that case, one obtains from eqs (3.3) and (3.4)

$$\log(\varepsilon_T - \varepsilon_{0T}) = -\log\hat{U}_p(t;\vartheta_T) + (\beta_R/\beta_T)\log\{(\varepsilon_R - \varepsilon_{0R})\hat{U}_p(t;\vartheta_R)\} \tag{3.5}$$

This function has been proved to fit measured equal-brightness curves if exponent β of eq. (3.3) is independent of flash duration (de Ridder and Theelen, 1983, 1984; see also Chapter 2). Consequently, eq. (3.5) becomes

$$\log(\varepsilon_T - \varepsilon_{0T}) = -\log\hat{U}_p(t;\vartheta_T) + \text{constant} \tag{3.6}$$

This function is represented by the dashed lines that fit the measured equal-brightness curves in Figure 3.1. The impulse response, from which these theoretical curves have been derived, can be found in Chapter 2. The good fit indicates that, at least in the photopic background condition, the exponent of the power function relating brightness to luminance is independent of flash duration.

At the same time, this good fit emphasizes the fact that impulse responses, obtained at *threshold* level with the use of the perturbation technique of Roufs and Blommaert (1981), are able to describe the dynamic behaviour of the visual system at *suprathreshold* levels. This is supported by the finding that individual differences in the value of the critical duration T_{CA} can be predicted from individual differences in the shape of the impulse response. At high flash luminances, where the influence of the threshold is negligible, T_{CA} was found to be larger for subject HR (Fig. 3.4, open diamonds) than for subject KS (Fig. 3.5, open diamonds). This difference between the two subjects is consistent with predictions from their impulse responses measured at the same 100 Td background level (see Chapter 2). It can be calculated from these responses that T_{CA} will be 36 ms for subject HR and 22 ms for subject KS. In Figures 3.4 and 3.5, these values are represented by the horizontal parts of the dashed lines. These lines indicate theoretical relationships between T_{CA} and ε_l which were derived from the impulse responses with the help of eq. (3.6). It can be seen that they approximate the measured critical durations reasonably well. This suggests that these predictions from the impulse responses do not only confirm the existence of a difference between the two subjects but may even provide a quantitative description of this difference.

Because of the isomorphism of the equal-brightness curves (Fig. 3.3), eq. (3.6) also applies to the curves obtained in the dark-field condition, provided that the predicted curves are shifted to shorter durations with increasing luminance of the reference flash (Fig. 3.2). Within the dynamic brightness model, such a shift along the duration axis can be translated into a scale factor of the time constant of the linear filter. This implies that the shape of the impulse response of the linear filter should remain constant but for a change of time scale (Roufs and Blommaert, 1981). In the visual system, this kind of scaling does indeed occur as can be seen in Figure 3.7. This figure shows two impulse responses that have been measured for one subject at two different background levels, viz. 100 Td (diamonds) and 1200 Td (circles). The stimulus configuration consisted of a circular one-deg field with dark surround. The time scale of the impulse response obtained at the 1200 Td level has been multiplied by a factor of 1.77. This value was determined independently by taking the ratio of the critical durations derived from the results of threshold measurements at the same two background levels. The resulting impulse responses are approximately the same, demonstrating a correlation between the critical duration and the time scale of the impulse response. Scaling along the time axis of otherwise identical normalized impulse responses has already been hypothesized (Roufs, 1972b, 1974a; Roufs and Blommaert, 1981; Blommaert

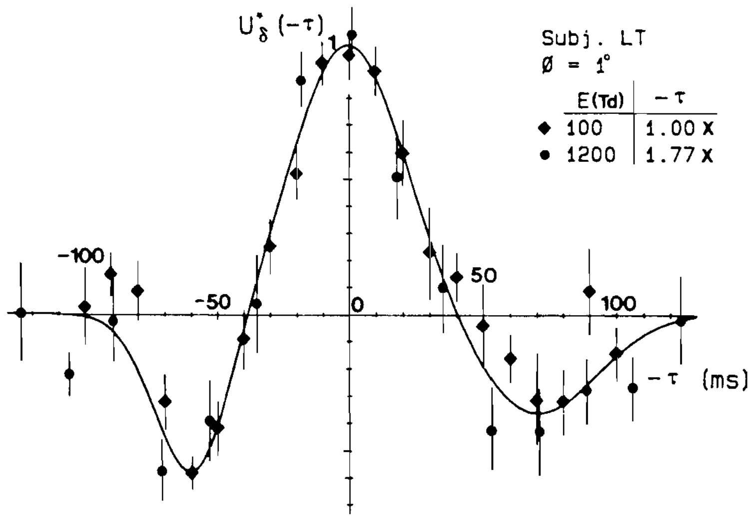


Figure 3.7: Normalized impulse responses for a foveally presented one-deg field with dark surround, obtained by means of the drift-correcting perturbation technique of Roufs and Blommaert (1981). Retinal illuminance E of the background was either 100 Td (diamonds) or 1200 Td (circles). The time scale of the impulse response determined in the last-mentioned condition has been multiplied by a factor of 1.77. Vertical bars indicate twice the standard error of the mean. Norm factors: 3.86 $Td^{-1}.s^{-1}$ for E = 100 Td; 0.59 $Td^{-1}.s^{-1}$ for E = 1200 Td. The solid line has been fitted by eye. It emphasizes the triphasic shape of the impulse response.

and Roufs, 1987). It may explain, among other things, the finding that for rectangularly flashed one-deg fields with dark surround the threshold characteristic, expressed in log-log coordinates, shifts along the duration axis as a function of background luminance without changing its shape (Roufs, 1972b, 1974a). The results of the present study suggest that the same principle underlies the shift of the equal-brightness curves in the dark-field condition, the independent variable being flash luminance instead of background luminance. A re-analysis of the data of Roufs (1972a, 1974b), supplemented with more recently gathered data, showed that the shift of the threshold characteristic as a function of background luminance can be described by a power function with exponent -0.17 ± 0.02 (95% confidence interval). This value is within experimental error of the exponents that have been determined for the shift of the Broca-Sulzer effect (Figs 3.4, 3.5). From this, it can be concluded that changes in background luminance have an effect on the shift of the threshold characteristic which is similar to that of changes in flash luminance on the shift of the Broca-Sulzer phenomenon.

One of the consequences of the good fit between measured and predicted curves in the dark-field condition (Fig. 3.2) is that, in this condition too, exponent β of eq. (3.3) is independent of flash duration. This implies that an explanation of the observed shift of the Broca-Sulzer effect in terms of different brightness exponents for short and long flashes as in eq. (3.2) may not be valid. It would also imply that it is not necessary anymore to look for a solution of the unsolved problem of the abrupt change in brightness exponent that is implicitly assumed when eq. (3.2) is used to describe the shift of the Broca-Sulzer effect (Anglin and Mansfield, 1968; Mansfield, 1973).

An alternative explanation for the observed shift of the Broca-Sulzer effect and its dependence on the background conditions is still lacking but a possible explanation may be the following. Time constants of the visual system depend on the state of adaptation of the eye (Fig. 3.7; see also Graham and Kemp, 1938; Keller, 1941; Herrick, 1956; Roufs, 1972a, 1974a; Roufs and Blommaert, 1981; Blommaert and Roufs, 1987; Watson, 1986). Suppose that in the photopic background condition the adaptation level is determined by the luminance of the background. In that case, the Broca-Sulzer effect will not shift as a function of flash luminance (Fig. 3.1). Figure 3.1 suggests that this may even hold for strong flashes. In the dark-field condition, however, a sequence of flashes may change the effective state of adaptation and, thus, affects the time constants of the visual system. If it is assumed that this change is in proportion to the luminance of the flashes raised to a power, then this will result in a shift of the Broca-Sulzer effect that is also in proportion to the luminance of the flashes raised to a power (Fig. 3.2).

During our experiments, one equal-brightness curve was measured in a given session. Accordingly, each curve of Figure 3.2 may have been measured under a different effective state of adaptation. Yet, the curves have the same shape. This suggests that the time constants of the mechanisms which control the effective adaptive state are so large that during the flashes it is not changed. Contrary to our approach, Aiba and Stevens (1964) examined only one test flash duration in a given session. Yet, they obtained approximately the same shift. Consequently, the size of the shift does not appear to depend on the way the data have been obtained. This may lead to the suggestion that the time constants of the mechanisms controlling the effective state of adaptation, should be small. From this it is evident that further research is needed to examine the relevance of the suggested explanation for the shift of the Broca-Sulzer effect.

3.4.1 Conclusions

The shift of the Broca-Sulzer effect as a function of flash luminance occurs only when there is no background. Consequently, this shift is not present in all experimental conditions, as is usually assumed. Both the absence of the shift in the photopic background condition and the isomorphism of the equal-brightness curves confirm our earlier conclusion (de Ridder and Theelen, 1983, 1984) that the exponent of the power function relating brightness to luminance is independent of flash duration. The explanation of the shift observed in the dark-field condition cannot be given in terms of different brightness exponents for short and long flashes. An alternative explanation is that in the dark-field condition the state of adaptation is changed by the flashes themselves.

chapter 4

Comparison of scaling methods applied to brightness of time-dependent stimuli

Abstract

Perceived brightness of rectangularly flashed point sources and one-deg fields has been measured as a function of flash duration and luminance using three direct scaling methods, viz. magnitude estimation, category scaling and bisection. The methods of magnitude estimation and bisection have been found to be mutually consistent, provided that no standard or modulus is used during the magnitude estimations. For stimuli presented against an extended photopic background, both methods show that the exponent of the power function, relating brightness to luminance, is larger for one-deg fields than for point sources. Under similar conditions, the method of category scaling produces a lower exponent than the two other methods do. It is argued that this is due to the restricted number of categories employed in the present study. All three methods indicate that under photopic conditions the brightness exponent is independent of flash duration. Furthermore, both magnitude estimation and category scaling show the occurrence of the Broca-Sulzer effect as well as the validity of Bloch's law at suprathreshold levels.

4.1 Introduction

Psychophysics is concerned with the relation between the physical properties of a stimulus and the sensations evoked by that stimulus. Stevens (1957, 1975) distinguished two kinds of sensations, one that deals with the question of *how much* (e.g. loudness, brightness), the other with the question of *what kind* or *where* (e.g. pitch, inclination). The first-mentioned sensations form the class of additive or prothetic continua, the last-mentioned sensations the class of substitutive or metathetic continua.

Perceived brightness of a self-luminous source varies monotonically with luminance, provided that special circumstances like temporal luminance modulation of the surround (De Valois et al., 1986) and relatively strong surrounds (Horeman, 1965) are omitted. Brightness, therefore, belongs to the class of prothetic continua. Stevens (1975) claimed that for brightness, like any other prothetic continuum, sensory magnitude Ψ is related to physical intensity Φ by a simple power function, or

$$\Psi = k.\Phi^{\beta} \tag{4.1}$$

where k is a dimensional constant and exponent β characterizes a sensory continuum. In doing so, Stevens (1961) proposed to discard Fechner's (1860) logarithmic law which states that the sensory magnitude is linearly related to the logarithm of the physical intensity.

In the last decennia the method of magnitude estimation (e.g. Marks, 1974; Stevens, 1975) has become the most widely used scaling technique to investigate the brightness-luminance relation. During a typical magnitude estimation experiment lights of different luminance are presented one at a time and subjects are instructed to assign numbers to them in proportion to the perceived brightness. Plotting the results of such an experiment in log-log coordinates, the relation between the assigned numbers representing brightness and the luminances will be a straight line, if eq. (4.1) holds and if subjects do handle numbers linearly (e.g. Stevens, 1975). In that case, the slope is a direct estimate of the brightness exponent. However, there are indications that the perceived magnitude of numbers grows as an increasingly decelerated function of their absolute magnitude (Banks and Hill, 1974; Curtis et al., 1968; Curtis, 1970; Rule and Curtis, 1973). This will lead to a lower "true" or genotypical brightness exponent than the phenotypical one obtained by magnitude estimation (Wagenaar, 1975).

Application of the method of magnitude estimation did not yield a single characteristic brightness exponent as the exponent was found to depend on the stimulus configuration. Mansfield (1973), for example, determined at least three different exponents for stimuli presented against a dark background, ranging from about 1 for a shortly flashed point source to about 1/3 for a large field turned on for at least one second. His results showed that the brightness exponent decreases in a more or less discrete way when duration is increased. This is opposed by Osaka (1977, 1981) who obtained a gradual decrease of the exponent from about 0.8 at 1 ms to 0.33 at 100 ms. De Ridder and Theelen (1984, 1985; see also Chapters 2 and 3), however, have deduced from results of brightness matching experiments that the brightness exponent has to be independent of flash duration. They attribute the differences in the brightness exponent, obtained in a dark-adapted condition, to disturbances of the state of adaptation brought on by the flashes themselves.

Accordingly, even for elementary stimuli like single light flashes, controversies still exist about the correct description of the brightness-luminance relation. These controversies are facilitated by the problematic validity of direct scaling methods. For example, exponents determined by magnitude estimation have been shown to depend on the experimental conditions and even on the instructions given to a subject (Poulton, 1968, 1979; Robinson, 1976; Pepermans and Corlett, 1983). Thus the estimated value of the power exponent correlates with the range of stimuli used in an experiment (Poulton, 1968; Teghtsoonian, 1971, 1973; Cannon, 1984). Another factor that may influence the exponent is whether or not a standard is used and, if so, what position it takes in the stimulus range and what number ("modulus") is assigned to it (Poulton, 1968; Marks, 1974). But even things like the kind of numbers the subject uses (e.g. fractions, one- or two-digit integers) may already affect the results of a scaling experiment (Poulton, 1979).

Another methodological problem concerns the mutual consistency of the various scaling techniques. Magnitude estimation belongs to the class of ratio scaling techniques. A second class of direct methods is formed by the interval scaling techniques (e.g. category scaling, bisection). Results obtained with these methods usually produce lower exponents than the method of magnitude estimation does. This led Stevens (1975) to call these exponents virtual, as they are "...not the actual exponent of the continuum in question" (p. 134). The nonlinear concave downward relation between the results of category scaling and magnitude estimation is often used to define a sensory continuum as a prothetic one (Marks, 1974; Stevens, 1975). This nonlinear relation, however, is likely to be caused by the restricted number of categories usually employed in category scaling (Gibson and Tomko, 1972; Foley et al., 1983).

Finally it has to be remarked that, in general, brightness exponents are obtained by averaging the results of a large number of subjects. This may obscure individual differences in brightness exponent (Marks and Stevens, 1965; Marks, 1974) or even in the shape of the brightness-luminance relation (Saunders, 1972; Bartleson and Breneman, 1973). Saunders (1972) pointed out that these differences do not necessarily imply differences in perception but may reflect differences in concepts of numerosity.

In the present study, the brightness of rectangularly flashed point sources and one-deg fields is estimated as a function of flash duration and luminance using three direct scaling methods, viz. magnitude estimation, category scaling and bisection. In the light of the methodological difficulties described above, it was felt necessary to examine the mutual consistency of these frequently employed methods. To facilitate comparison of the results, the experimental conditions remain the same throughout this study and at least one subject performs all measurements. In this way it is hoped to obtain a better insight in direct scaling methods. At the same time, this study is an attempt to clarify controversies concerning the influence of flash duration on the brightness-luminance relation and especially on the brightness exponent.

4.2 Magnitude estimation

4.2.1 Introduction

The brightness matching experiments of Aiba and Stevens (1964), performed against a dark background, have shown that at short durations the brightness of a flash is determined by its energy, implying that Bloch's law holds at suprathreshold levels. This has been confirmed by the results of the experiments described in Chapters 2 and 3, which were carried out against a dark as well as a photopic background. The reciprocity between luminance and duration, which suggests a linear initial operator, implies that in Bloch's region the growth of brightness with flash duration has to follow the same power function as the one that is assumed to describe the relation between brightness and luminance. Moreover, it implies that the brightness exponent must be independent of flash duration. This will be examined for a point source as well as a one-deg field.

In addition, the influence of stimulus area on the Broca-Sulzer effect is investigated. Contrary to short flashes, the brightness of a long flash is not related to its energy but to its luminance. Accordingly, the brightness of a flash of fixed luminance grows with duration in Bloch's region but remains constant at longer durations. For point sources, a smooth transition from Bloch's region to the constant level at longer durations can be observed (de Ridder and Theelen, 1983; see also Chapter 2). For one-deg fields, however, the transition occurs more abruptly, producing an overshoot (de Ridder and Theelen, 1984; see also Chapter 2). This overshoot is known as the temporal brightness enhancement or Broca-Sulzer effect (Broca and Sulzer, 1902). Its dependence on the size of the stimulus field has only been demonstrated by means of brightness matching. In this section it will be determined whether the method of magnitude estimation is also able to show this dependence.

4.2.2 Method

Apparatus

The left half of a six-channel, binocular Maxwellian-view optical system was used to present circular "white" test fields of varying luminance and duration against a photopic and a dark background. The optical system has already been described in Chapters 1 and 2. Three independent light channels were available, the light source of each being a glow modulator tube (Sylvania type R1131C or the equivalent type EEV XL670), linearized and stabilized by light feedback. In the photopic background condition, a circular 5.5 deg, 100 Td "white" field was presented to the left eye of the subject by one of these channels. A second channel projected a small dim red fixation light in the centre of this field. The last channel flashed the test field to the left of this fixation light in such a way that the distance between the centre of the test field and the fixation light always amounted to 40 min arc. The diameter of the test field was either 2 min arc (point source) or one degree. In the dark background condition the same configuration was used with the exception of the background which was switched off. The regulation of the time course and the intensity of the rectangular incremental flashes occurred electronically by means of a square-wave pulse generator and an attenuator respectively. In addition, the intensity range could be adjusted by inserting neutral density filters in the light beam. During the experiments the flash duration could vary between 1 and 975 ms. The subject saw the stimulus configuration through an eye piece which was fitted with an artificial pupil, 2 mm in diameter and equipped with an entoptic guiding system (Roufs, 1963). In order to optimize fixation, the head of the subject was immobilized using a chin-and-head rest.

General procedure

At the beginning of each session the subject was dark-adapted for about 10 minutes, followed by about 2 minutes adaptation to the 100 Td background, if present. The subject started a trial by pressing a button, thus releasing a single flash after a delay of 300 ms. In one session the brightness of either the one-deg field or the point source was estimated. They never appeared in the same session. The stimuli were presented to the subject in random order, except that a strong light never followed a weak light and vice versa. The subject was allowed to repeat a trial as many times as was desired before giving an answer. In all experiments the subjects received the explicit instruction to estimate the brightness peak.

Two variants of the method of magnitude estimation have been employed. In one, a standard was presented to the subject after every 10 trials. The brightness of this standard was given the value (modulus) "100". The subject was asked to assign numbers to the brightness of the other stimuli so as to preserve ratios. That is, if a flash appeared to be half as bright as the standard, its brightness should be estimated to be "50". This variant has only been applied to scale the brightness of point sources.

The other variant did not contain either a standard or a modulus. The subject was simply asked to assign numbers to the stimuli in proportion to their perceived brightness. At the beginning of each session, eight stimuli were presented consisting of the two stimuli having the lowest and the highest brightness of all stimuli used in that session and six other stimuli situated at regular intervals between the two extreme ones. The numbers assigned to these stimuli were excluded from the final calculations.

Subjects

One male subject (HR) participated in all experiments. He had normal, uncorrected vision. In addition, five other subjects, four male (JB, MP, AK, LT) and one female (JGR), participated in one or more experiments. Two of them (JB, LT) were members of the Institute. The age range of the subjects was 22 to 35 years. Three of them (JB, AK, LT) had normal vision after correction. An ocular lens, especially adapted to the vision of a particular subject, could be inserted in the eye piece of the optical system. In this way, normal acuity was ascertained for each subject. None of the subjects had previous experience with brightness estimation or scaling methods in general.

4.2.3 Results and discussion

Point source

In the first experiment, the brightness was estimated of briefly flashed point sources, seen against a dark background. The flashes lasted 4, 8, 16 and 32 ms.

Their retinal illuminance ranged from 2.65 to 4.35 log Td in regular steps of 0.17 log Td. In one session all 44 stimuli were presented to the subject. They always appeared in a random order which was reversed in each second session. The standard (16 ms, 3.64 log Td), labelled "100", was also included in the estimations. The final results, expressed as the geometric mean of 10 measurements, are presented in Figures 4.1, 4.2 and 4.3. On average, the standard deviation was 0.1 log units. The data of subject HR (Figs 4.1, 4.2) lie on parallel straight lines,

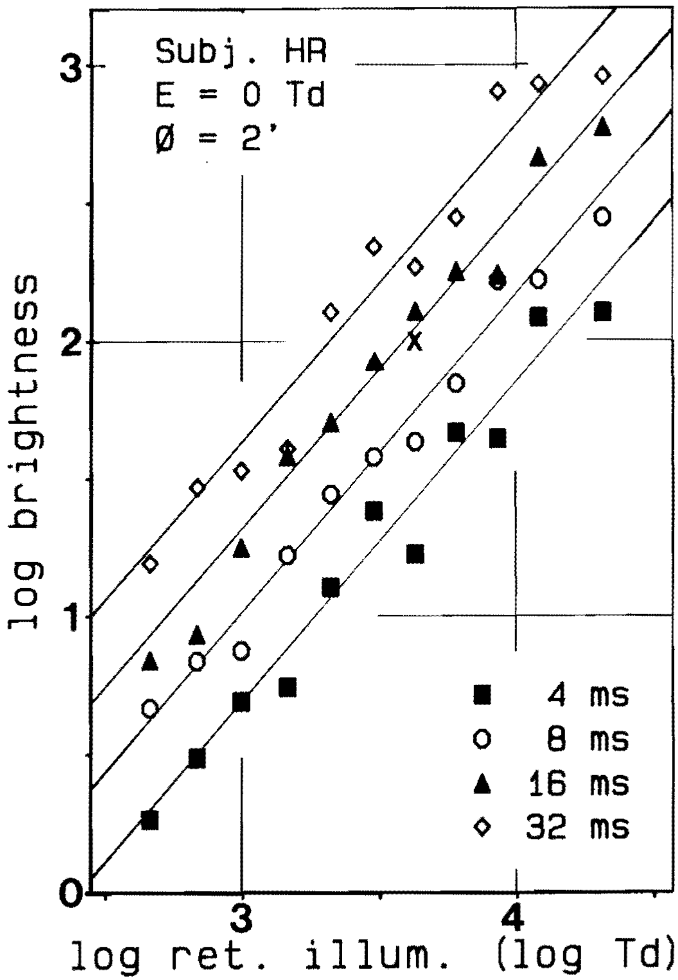


Figure 4.1: Brightness estimates for rectangularly flashed point sources, obtained by the method of magnitude estimation. The stimuli were presented against a dark background. The black cross denotes the standard labelled "100". The results of a multiple linear regression analysis are given by the solid lines having a slope of 1.16. Subject: HR.

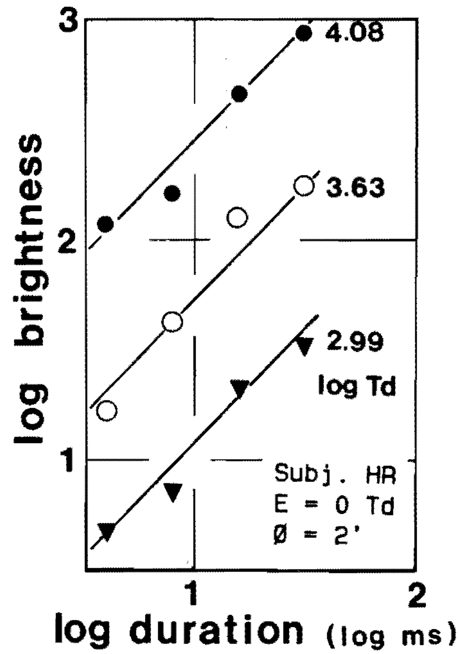


Figure 4.2: Brightness of a flashed point source as a function of flash duration. Data have been taken from Figure 4.1. The solid lines denote results of a multiple linear regression analysis.

suggesting that there is no interaction between luminance and duration. This has to be in force when brightness is determined by the energy of a flash. A multiple linear regression analysis confirmed the absence of an interaction between luminance and duration. Moreover, it showed that changes in duration have the same effect on perceived brightness as changes in luminance. The brightness exponent derived from this analysis proved to be 1.16.

The results of four other subjects are given by the four lower curves of Figure 4.3. The upper curve represents data of Figure 4.1 but now the brightness estimates are plotted as a function of energy. Figure 4.3 shows that the linear function obtained for subject HR is not representative for the results of all subjects. Note in particular the nonlinear function of subject JB. Based on the shape of brightness-luminance curves measured by means of magnitude estimation, Bartleson and Breneman (1973) were able to classify their subjects into four types: type I producing a concave downward curve, type II a concave upward curve, type III a cubic nonlinear curve and type IV a linear curve. The same classification can be applied to the subjects of the present study. This means that subjects HR and AK belong to the linear type IV, whereas subjects MP and LT can be classified as type I and subject JB as the (rare) type III. Despite these differences, all subjects estimated the brightness of the standard correctly. That is, they gave numbers close to "100".

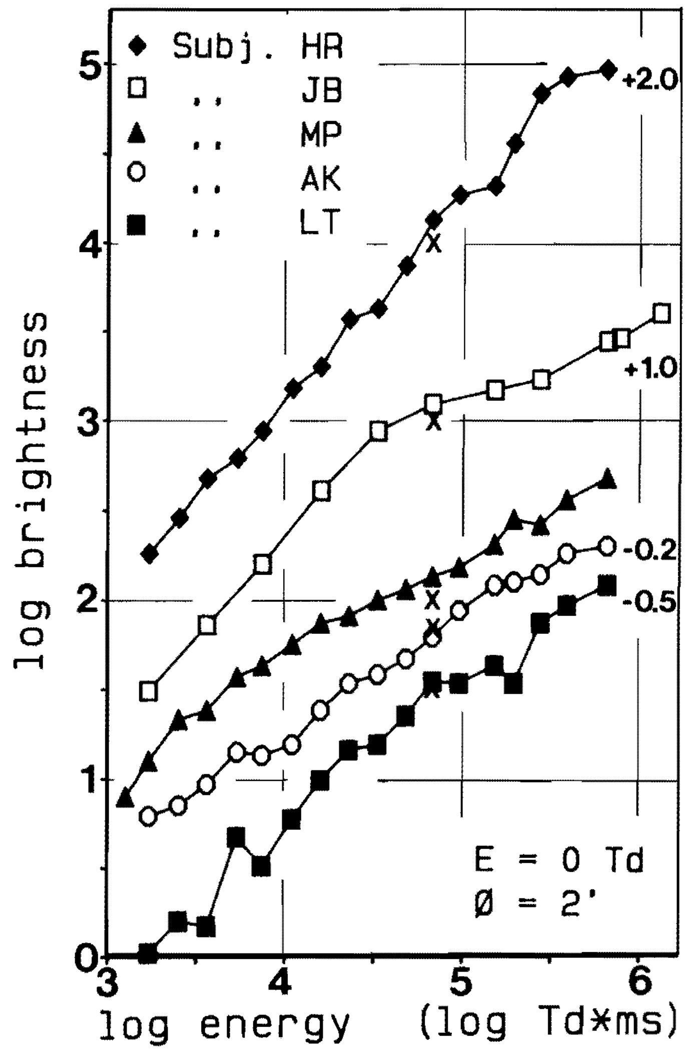


Figure 4.3: Brightness estimates for rectangularly flashed point sources as a function of flash energy, obtained by the method of magnitude estimation for five subjects. The stimuli, lasting 4, 8, 16 and 32 ms, were flashed against a dark background. The black crosses denote the standard labelled "100". The curves have been vertically shifted for clarity of representation. The numbers on the right side of the curves denote the magnitude of the replacements expressed in log units. The upper curve represents data from Figure 4.1.

Consequently, the data of the subjects could be averaged without shifting the individual curves. The resulting curve is shown in Figure 4.4. A straight line was fitted to these averaged data using the method of least squares. The best fit gave

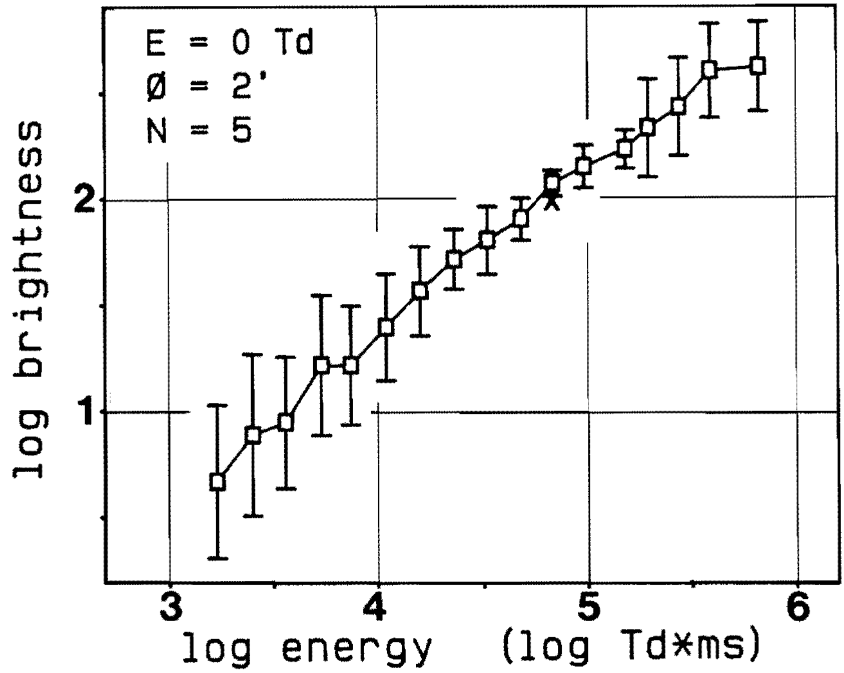


Figure 4.4: Brightness estimates for shortly flashed point sources, presented against a dark background. The data are the average of the five curves shown in Figure 4.3. The vertical bars denote twice the standard error.

a slope of 0.77. By applying linear regression to the individual data, the following slopes were obtained: 1.16 (HR), 0.69 (JB), 0.55 (MP), 0.64 (AK) and 0.81 (LT). In a comparable study, Mansfield (1973) averaged the data of 24 observers and determined a brightness exponent of 0.94. In the Discussion of that study the exponent was rounded off to 1. This value appeared in Table I of Stevens (1975) as the representative exponent for a "... point source briefly flashed" (p. 15). Finally, Figure 4.4 shows that variability increases when a stimulus deviates more and more from the standard. A similar trend is observed in the data of Bartleson and Breneman (1973). In both instances, this increased variability can be attributed to the systematic differences between subjects.

The effect of introducing an extended 100 Td background is shown in Figure 4.5. Approaching the detection threshold level (dashed line), the curve starts to deviate from a straight line and becomes steeper (Fig. 4.5, open squares). This implies that the simple power function described by eq. (4.1) no longer holds and a threshold parameter has to be incorporated. The threshold corrections that have been proposed in the literature fall into two categories, one involving a translation along the stimulus axis (Marks and Stevens, 1968; Marks, 1974; Stevens, 1975),

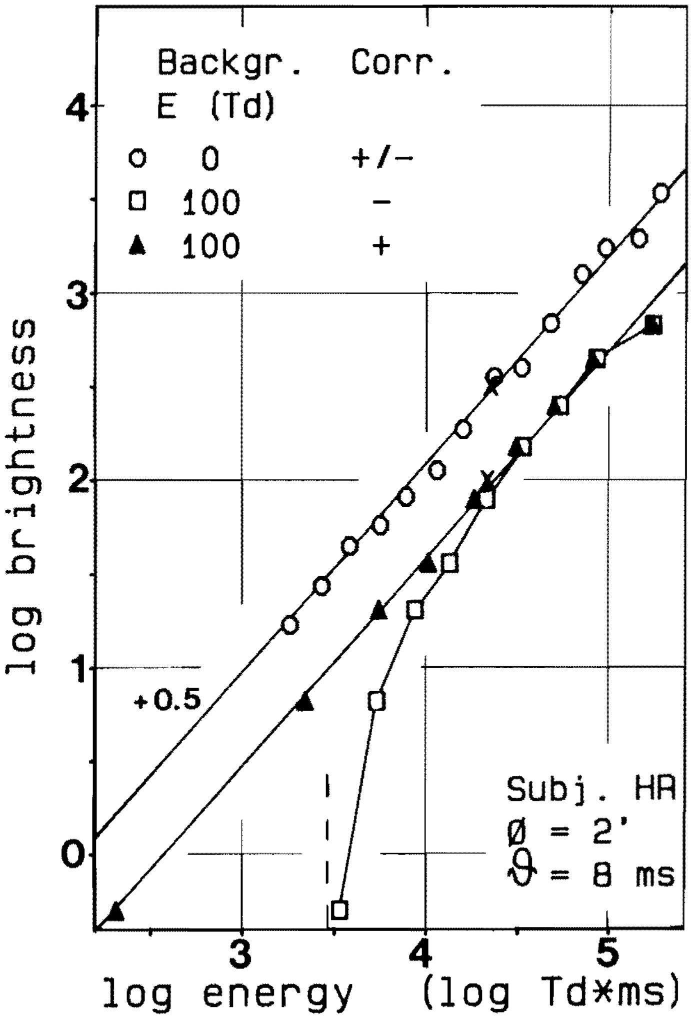


Figure 4.5: Influence of background level on the brightness-luminance relation for shortly (8 ms) flashed point sources. The method of magnitude estimation was employed. The black crosses denote the standard labelled "100". The data obtained against the 100 Td background are indicated by the open squares. After a correction for the detection threshold according to eq. (4.2), the data (filled triangles) fall on the same straight line that has been fitted to the brightness estimates obtained in the dark-field condition (open circles). The dashed line denotes the experimentally determined 50% detection threshold for the 100 Td background condition. Correction for detection threshold did not affect the results obtained in the dark-field condition. These data have been shifted 0.5 log units for clarity of representation. Subject: HR.

the other involving a translation along the response axis (Fagot, 1966, 1975; Fagot and Stewart, 1968; Krantz, 1972). However, only minor differences have been found between curves corrected in both ways (Marks and Stevens, 1968; Fagot and Stewart, 1968). In view of the model used in Chapter 2 and consistent with the corrections used to explain the results of brightness matching experiments (e.g. de Ridder and Theelen, 1983, 1984), it was decided to make use of the first-mentioned correction along the stimulus axis leading to the following general expresssion

$$B = k.(\varepsilon - \varepsilon_0)^{\beta} \tag{4.2}$$

where B is a number representing the brightness of a flash of retinal illuminance ε and ε_0 is its 50% detection threshold. A similar definition of the threshold parameter was suggested by Onley (1961) and Ekman and Gustafsson (1968). The black triangles in Figure 4.5 give the corrected data. They fall on the same straight line that was fitted to the data obtained in the dark-field condition (open circles). Accordingly, the brightness exponent for the point source did not change with background.

For two subjects (HR, LT) the measurements with variable duration were repeated against the photopic background. In this experiment, the duration of the stimulus varied from 1 to 32 ms and for each duration only four retinal illuminances were employed, ranging from 3.02 to 4.58 log Td in steps of about 0.5 log units. The principal change with respect to the previous experiment, however, is that no standard appeared during the measurements. Six sessions were run. Figure 4.6 shows the data for subject HR. In comparison to Figure 4.5, the resulting curve has clearly a shallower slope. The best fit of eq. (4.2) obtained by means of the method of least-squares gave an exponent of 0.43 (Fig. 4.6, solid line). Since the main difference between Figures 4.5 and 4.6 is the presence or absence of the standard, this suggests that the increase in the brightness exponent may be due to the standard. Another interesting result of this experiment is that there were hardly any differences between the two subjects, contrary to the large differences shown in Figure 4.3. For instance, the brightness exponent for subject LT was determined to be 0.49, which is close to the exponent obtained for subject HR. This suggests that the inclusion of the standard and modulus may have biased the previous data. Consequently, in the following experiments only the standard-free method was employed.

Brightness-matching experiments (de Ridder and Theelen, 1983; see also Chapter 2) have shown that the brightness of a flashed point source increases with duration in Bloch's region and approaches a constant level at long durations without producing the Broca-Sulzer effect. Figure 4.7 indicates that this can also be demonstrated by means of magnitude estimation. The experimental conditions were the same as in Figure 4.6, but now durations outside Bloch's region were also included. The data of Figure 4.7 are based on the results of three subjects (HR, LT, JGR), the results of LT and JGR being shifted +0.14 and +0.85 log units, respectively, so that their overall mean coincided with that of HR. After this correction,

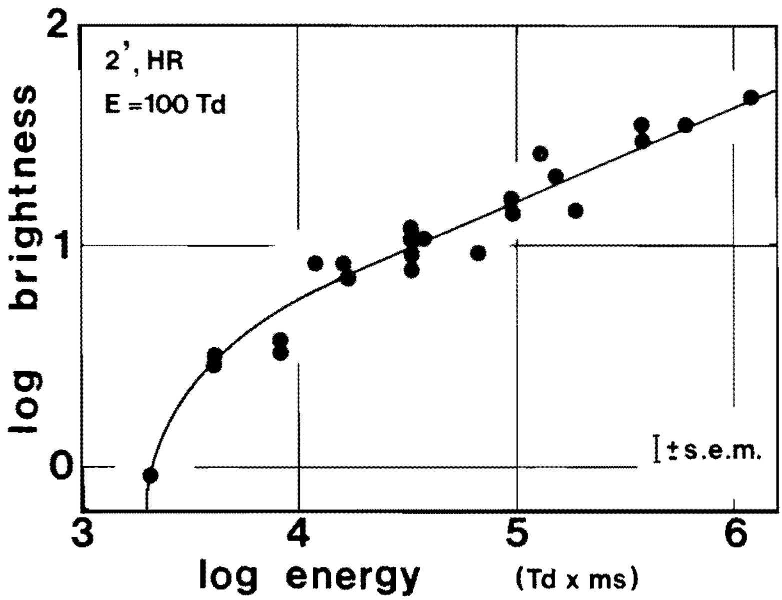


Figure 4.6: Brightness estimates for rectangularly flashed point sources as a function of flash energy, obtained by a standard-free method of magnitude estimation. The duration varied between 1 and 32 ms. An extended 100 Td background was employed. The solid line represents a least-squares fit of eq. (4.2). Subject: HR.

only minor differences could be observed between the results of the subjects. At long durations, the four curves run parallel. At short durations, however, the curves tend to converge with increasing duration. A similar effect was observed by Osaka (1977, 1981), estimating the brightness of a foveally presented circular field, 44 min arc in diameter, flashed against a dark background. From this, Osaka (1977, 1981) concluded that the brightness exponent increases when duration decreases. This conclusion runs counter to the fact that for the same durations Bloch's law has been found to hold, implying that the brightness exponent must be independent of flash duration. A possible solution for this controversy may be the following. Osaka (1977, 1981) fitted his data by a power function according to eq. (4.1), thus neglecting the potential influence of the threshold. This is allowed when the flashes are far above threshold. Near threshold, however, eq. (4.2) must be used. In Bloch's region the threshold of a flash is determined by its energy. Accordingly, ε_0 in eq. (4.2) decreases with increasing flash duration. This implies that, using the same luminance range for all durations, the effective range between the highest and lowest luminance level will increase with decreasing flash duration, leading to higher exponents when the influence of ε_0 is not taken into account (Teghtsoonian, 1971).

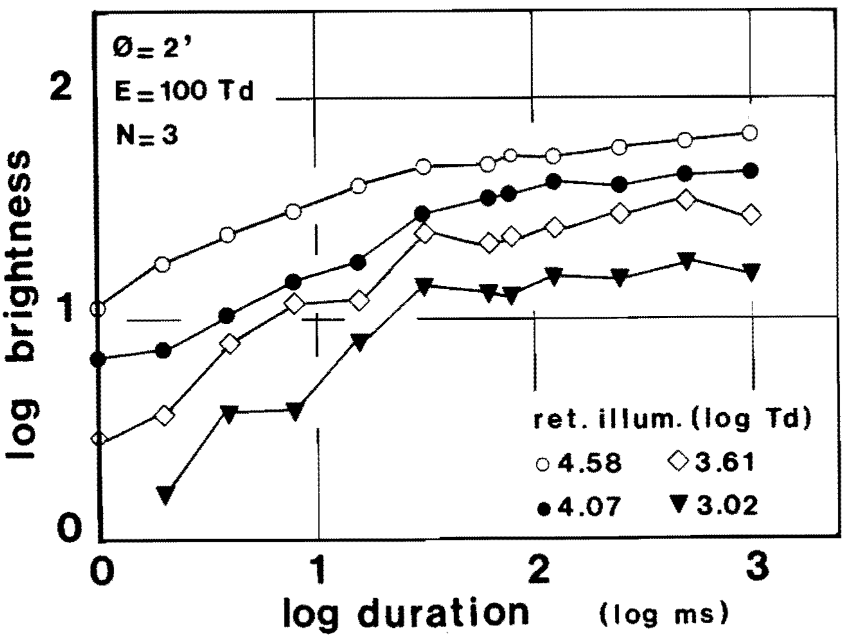


Figure 4.7: Brightness-duration relations at four retinal illuminance levels for point sources, projected against an extended 100 Td background. The data, averaged over three subjects, were obtained by the method of magnitude estimation.

Table 4.1: Brightness exponent $\beta \pm$ SD as a function of flash duration for rectangularly flashed point sources, presented against an extended 100 Td background. Subject: HR.

duration (ms)	β	SD	duration (ms)	β	SD
1	0.47	0.07	64	0.41	0.03
2	0.44	0.05	80	0.41	0.02
4	0.43	0.05	128	0.40	0.04
8	0.52	0.04	256	0.43	0.05
16	0.43	0.07	512	0.39	0.02
32	0.38	0.03	975	0.51	0.04

The data of Figure 4.7 were fitted by eq. (4.2) using the method of least squares. For subject HR, the resulting brightness exponents as a function of flash duration are summarized in Table 4.1. Two conclusions can be drawn from this Table. Firstly, there seems to be no systematic change of the brightness exponent as was found by Osaka (1977, 1981). This confirms the necessity to correct for the varying influence of the detection threshold. If no correction had been used, then a gradual decrease would have occurred in Bloch's region. For instance, the exponent would have been 0.78 and 0.50 instead of 0.44 and 0.43 at 2 and 4 ms respectively. Secondly, the brightness exponent remains approximately the same for short and long flashes. Its value is, on average, 0.44 ± 0.04. The suggestion that the brightness exponent is independent of flash duration disagrees with the two exponents mentioned by Mansfield (1973), viz. 1 at short durations and 0.5 at long durations. However, the latter exponents were obtained under dark-adapted conditions whereas the present results were determined against a photopic background.

One-deg field against an extended 100 Td background

From the measurements with point sources it can be learned that in Bloch's region the brightness of a flash is determined by its energy. This has also been examined for one-deg fields flashed against the 100 Td background. To this end, flashes lasting 1, 2 ,4, 8, 16 and 32 ms were used. For each duration, six retinal illuminances were chosen in such a way that for all durations the same six energy levels were generated. The energy ranged from 2.34 log(Td.ms) to 3.84 log(Td.ms) in steps of 0.3 log units. Four sessions were run, each session containing all 36 stimuli (six energy levels times six durations). Three subjects (HR, LT, JGR) participated in this experiment. The results shown in Figure 4.8 were obtained by averaging the results of the three subjects after a correction of their data so that their overall means coincided. This correction consisted of a multiplication of all data of a subject by the same constant. Accordingly, the ordinate does not indicate the absolute numbers given by the subjects. If the brightness is determined by the energy of the flashes, then six horizontal functions are to be expected in Figure 4.8. In order to test this prediction, a two-way analysis of variance was conducted on the data of Figure 4.8. Energy proved to have a significant effect ($F(5,396) = 362.57$, $p < 0.001$) but duration did not affect the result ($F(5,396) = 0.92$, $p > 0.25$), neither was there a significant interaction between duration and energy ($F(25,396) = 1.38$, $0.05 < p < 0.10$). Analysis of the data for each subject separately gave similar results. Consequently, in this experiment the sole determinant of brightness appears to be the energy of a flash. The average of each energy level was calculated for the three subjects in order to determine their brightness exponents. The three resulting brightness-energy relations have been plotted in Figure 4.9. Contrary to Figure 4.8, the ordinate now indicates the numbers used by the subjects. The functions drawn through the data are least-squares fits of eq. (4.2). In this manner, the following exponents were obtained: 0.64 (HR), 0.56 (JGR) and 0.71 (LT). These values are somewhat higher than the exponent of about 0.5 obtained against a dark background (Raab, 1962; Stevens and Hall, 1966; Mansfield, 1973).

The purpose of the magnitude estimations described in this paragraph is to demonstrate the presence of the Broca-Sulzer effect for one-deg fields. Brightness-matching experiments (see Chapter 2) have indicated that this effect should occur around 80 ms when the one-deg fields are flashed against an extended 100 Td background. In this experiment four retinal illuminances were employed ranging

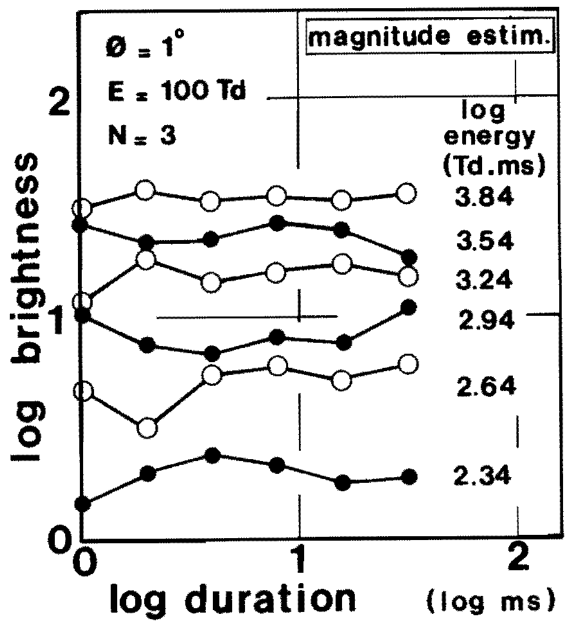


Figure 4.8: Brightness estimates for rectangularly flashed one-deg fields, obtained by the method of magnitude estimation. The stimuli were presented against an extended 100 Td background. The data of the three subjects, participating in this experiment, were corrected so that their overall means coincided. Accordingly, the ordinate is expressed in relative values.

from 2.34 to 3.84 log Td in steps of 0.5 log Td and twelve durations ranging from 1 to 975 ms. Again, there were three subjects (HR, LT, JGR). This time, eight sessions were run, split up into two experiments of four sessions, each with a time interval of two months between the experiments. Only small differences could be observed between the results of the two experiments. For instance, the brightness exponents determined in the first and second experiment were about the same. This is indicated by their ratio: 0.99 (HR), 1.03 (LT) and 0.91 (JGR). Accordingly, all data were combined. The final results are shown in Figure 4.10. At short durations brightness grows with duration and at long durations the brightness becomes independent of duration. At the transition the Broca-Sulzer effect is hard to distinguish. Only the two upper curves suggest a shallow maximum around 60 - 80 ms. The same difficulty to demonstrate the Broca-Sulzer effect can be seen in the results of other magnitude estimation experiments (Raab, 1962; Stevens and Hall, 1966). It must be remembered, however, that the Broca-Sulzer effect is a relatively small effect. According to Aiba and Stevens (1964) the size of the effect varies between 0.2 and 0.3 log units. For one of the present subjects (HR) an even smaller Broca-Sulzer effect was determined, viz. 0.1 log Td (see Chapter 2).

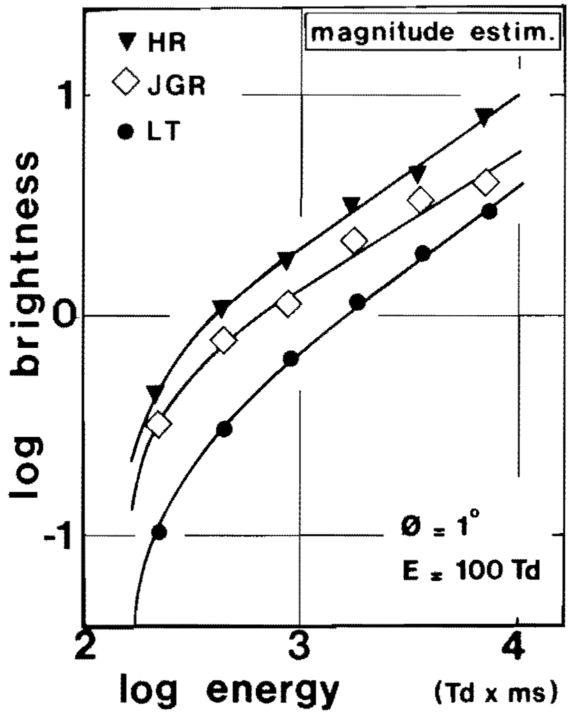


Figure 4.9: Brightness estimates for rectangularly flashed one-deg fields as a function of flash energy. The data are the same as in Figure 4.8, except that there was no correction for individual differences in the overall mean. Solid lines represent least-squares fits of eq. (4.2).

Assume that the brightness exponent is about 0.5. In that case, the overshoot representing the Broca-Sulzer effect will be 0.05 log units on brightness estimation. Indeed a small effect to be measured by means of magnitude estimation! On the other hand, a more abrupt transition from the Bloch's region to the constant level at long durations can be observed for the one-deg field (Fig. 4.10) than for the point sources (Fig. 4.7). This difference agrees with the conclusion drawn from brightness matching experiments that the Broca-Sulzer effect is a phenomenon related to large fields.

4.3 Category scaling

4.3.1 Introduction

In the experiment to be described in this section the perceived brightness of rectangularly flashed one-deg fields is estimated by means of category scaling. In this manner, it becomes possible to test the mutual consistency of this scaling method and the method of magnitude estimation as was described in the previous

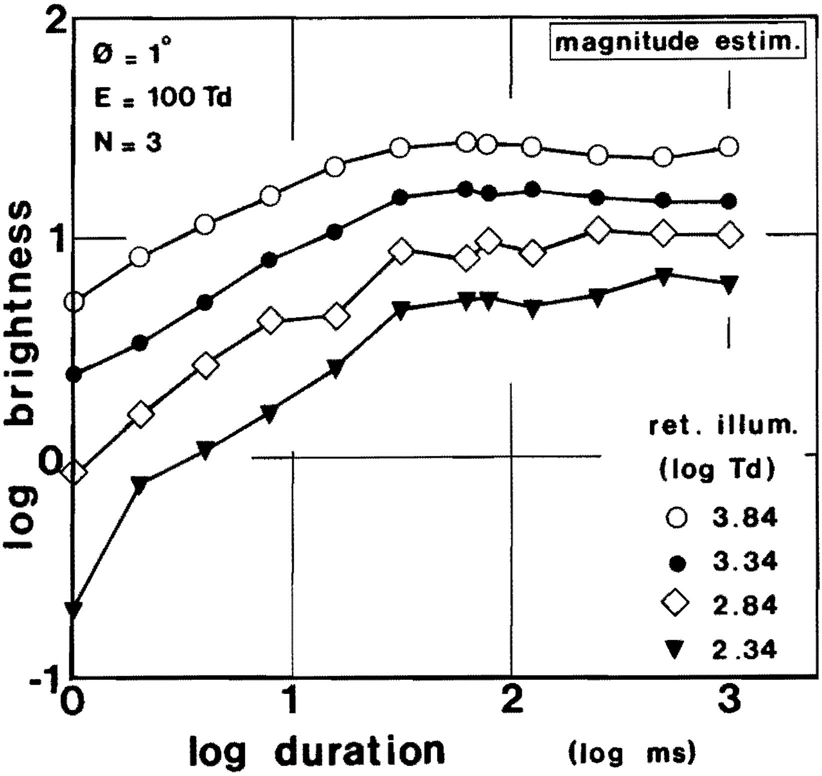


Figure 4.10: Brightness-duration relations at four retinal illuminance levels for one-deg fields, projected against an extended 100 Td background. The data, averaged over three subjects, were obtained by the method of magnitude estimation.

section. Up to the present, the comparison of magnitude estimation and category scaling has been confined to static light stimuli (Stevens and Galanter, 1957; Marks, 1968, 1974; Curtis, 1970). Dynamic stimuli, however, have the advantage over static ones that well-established brightness phenomena like Bloch's law and the Broca-Sulzer effect can be incorporated as criteria. These phenomena have already been demonstrated by magnitude estimation (e.g. Raab, 1962; Stevens and Hall, 1966; Mansfield, 1973; Osaka, 1978) but for category scaling the situation is less clear. To the best of our knowledge, Raab et al. (1961), Lewis (1965) and Blanc-Garin (1972) have been the only ones who employed category scaling to measure the brightness of rectangular incremental flashes. The study of Blanc-Garin (1972) was restricted to short durations and showed small deviations from Bloch's law. Raab et al. (1961) and Lewis (1965) also included flashes longer then the critical duration. Raab et al. (1961) measured a constant luminance curve for a flashed one-deg field and found a gradual brightness increase from 10 to 500 ms. For a foveally presented 0.5 deg field, flashed against a dark background, Lewis (1965) constructed constant-response functions from category judgments, plotting energy as a function of duration. These functions were consistent with Bloch's law but the Broca-Sulzer effect was not obtained. From this, Stevens (1966) concluded that category scaling is not suited to measure the brightness of time-dependent stimuli. However, Stevens and Hall (1966) pointed out that even for magnitude estimation the construction of equal-brightness curves is not sensitive enough to "...preserve the Broca-Sulzer hump" (p. 323). Since constant-luminance curves as shown in Figure 9 suggest the existence of the Broca-Sulzer effect for magnitude estimations, this kind of approach seems more apt to reveal this effect. In this section, this will be examined for category scaling.

4.3.2 Method

The experimental conditions were identical to the ones used in the last-mentioned magnitude estimation experiment, the results of which can be found in Figure 4.9. Again, one-deg fields were flashed against the 100 Td background. The same four retinal illuminances and twelve durations were employed. Moreover, the same three subjects participated in this experiment. They were instructed to rate the brightness of the stimuli on a 10-point numerical scale, assigning "one" to the weakest brightness and "ten" to the strongest brightness. If a stimulus could not be perceived, a "zero" had to be given. Six sessions were run. Each session consisted of three parts. In the first part, eight stimuli were shown, ranging in brightness from the weakest to the strongest one. This was done to familiarize the subject with the stimulus range. The second part contained all stimuli in a random order. In the third part the stimuli were shown again, but now in reversed order. For the final calculations the eight trials of the first part of the sessions were discarded. For each stimulus the arithmetic mean of the twelve replications was calculated.

4.3.3 Results and discussion

Figure 4.11 shows the four equal-luminance curves obtained by category scaling. The results of the three subjects were pooled and averaged as was also done in the magnitude estimation experiment (Fig. 4.10). Only minor differences were observed between the subjects. The standard deviation was hardly influenced by the duration and luminance of the stimulus. On average, the standard deviation was 0.79 for subject HR, 0.68 for subject LT and 1.04 for subject JGR. From a comparison of Figures 4.10 and 4.11 it can be learned that category scaling and magnitude estimation produce similar results. Both methods confirm the growth of the perceived brightness in Bloch's region for each retinal illuminance level. From 256 ms the curves tend to run parallel. All four curves suggest a local maximum around 60 - 80 ms. This is especially clear at the two upper retinal

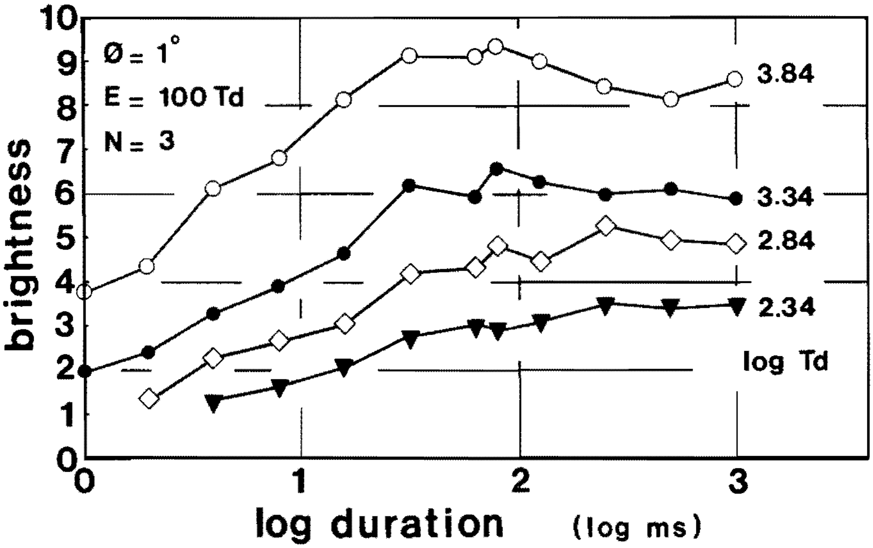


Figure 4.11: Same as Figure 4.10, except that brightness estimates were obtained by the method of category scaling. A 10-point numerical scale was employed.

illuminance levels. At the two lower levels, however, the maximum is somewhat overshadowed by the increase between 100 and 250 ms towards the constant level at long durations. The reason for this increase is not clear. A closer look at the results of the magnitude estimations (Fig. 4.10) reveals the same tendency, suggesting that the maximum is also present in the lower curves of Figure 4.10. This maximum is, of course, the well-known Broca-Sulzer effect. From the data of Figure 4.11 the following conclusions can be drawn. Firstly, the Broca-Sulzer effect can be measured by means of category scaling. This is contrary to the results of Raab et al. (1961) and Lewis (1965) and enervates one of Stevens' (1966) arguments why category scaling is not suited to scale brightness. Secondly, the duration at which the Broca-Sulzer effect occurs does not shift as a function of flash luminance. This is consistent with the results of the magnitude estimations (Fig. 4.10) and agrees also with the absence of a shift demonstrated by interocular brightness matching under similar conditions (de Ridder and Theelen, 1984, 1985; see also Chapter 2).

For the durations up to 32 ms, the brightness estimates of Figure 4.11 have been replotted in Figure 4.12 where they are given as a function of the logarithm of the flash energy. Represented in this way, the brightness estimates should form a single curve if Bloch's law holds. Despite the spread at the higher levels, a tendency can be observed to approach a single concave upward curve. This is confirmed by the dotted line, representing a least-squares fit of a simple power

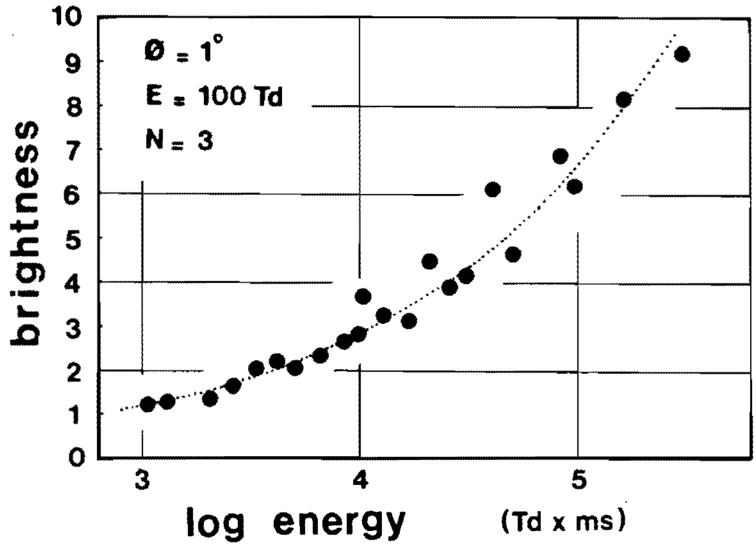


Figure 4.12: Brightness estimates as a function of flash energy for shortly flashed one-deg fields. The data were taken from Figure 4.11. The duration varied between 1 and 32 ms. The dotted line represents the best fit of a simple power function with an exponent of 0.37, obtained by the method of least-squares.

function with an exponent of 0.37 (r^2=0.96). This curved line is in contrast with the straight line obtained by Blanc-Garin (1972) using a 9-point scale and a dark background.

The dotted line in Figure 4.12 was meant to demonstrate the curvature of the function formed by the data. At the same time, however, it suggests that the relation between category ratings and flash luminances can be described by a simple power function. This agrees with the recent findings of Foley et al. (1983) obtained by scaling line length, number and sound pressure. It implies that eq. (4.2) can be applied to the results of Figure 4.11. This implication has been examined for subject HR because his threshold curve as a function of flash duration is known for the same stimulus configuration. The resulting brightness exponents as a function of flash duration are shown in the second column of Table 4.2. The third column contains brightness exponents obtained by applying eq. (4.2) to the magnitude estimations of the same stimulus set. Table 4.2 suggests that for both methods the brightness exponent does not vary systematically with duration. This is consistent with the above-mentioned absence of the time shift of the Broca-Sulzer effect. On average, the exponents obtained by category scaling and magnitude estimation are 0.31 and 0.57 respectively. The lower exponent for the category scaling is consistent with the notion of a virtual exponent as described by Marks (1968) and

Table 4.2: Brightness exponent β of eq. (4.2) as a function of flash duration for rectangularly flashed one-deg fields, presented against an extended 100 Td background. The exponents were obtained by the methods of magnitude estimation (β_{me}) and category scaling (β_{cs}). Subject: HR.

duration (ms)	β_{cs}	β_{me}	β_{cs}/β_{me}
1	0.32	0.86	0.37
2	0.35	0.55	0.64
4	0.38	0.63	0.60
8	0.29	0.56	0.52
16	0.38	0.58	0.66
32	0.32	0.53	0.60
64	0.32	0.61	0.52
80	0.31	0.58	0.53
128	0.30	0.62	0.48
256	0.23	0.47	0.49
512	0.27	0.41	0.66
975	0.27	0.48	0.54
Mean	0.31	0.57	0.55
SD	0.05	0.11	0.09

Stevens (1975). However, our data indicate that category scaling, like magnitude estimation, is able to demonstrate Bloch's law and the Broca-Sulzer effect. Moreover, results obtained by both methods confirm the suggestion that the brightness exponent is independent of flash duration when stimuli are presented against a photopic background (de Ridder and Theelen, 1984, 1985; see also Chapters 2 and 3). Accordingly, based on these criteria no decision can be made about the correct description of the brightness-luminance relation.

4.4 Bisection

4.4.1 Introduction

In addition to magnitude estimation and category scaling, a third direct scaling method, viz. bisection, has been employed to estimate the brightness exponent for rectangular incremental flashes. On each trial of the bisection experiments to be described in this section, a sequence of three flashes differing only in luminance is presented to the subject. The luminances of the first and third flash are fixed and the subject has to indicate at which luminance of the second flash the brightness of this flash appears halfway between the brightnesses of the two other flashes. At that luminance, the relation between brightness B_m of the second flash and brightnesses B_l and B_h of the two other flashes, having a lower and a higher luminance respectively, can be derived from

$$B_h - B_m = B_m - B_l \tag{4.3}$$

and is given by the following expression

$$B_m = \frac{1}{2}(B_l + B_h) \tag{4.4}$$

By combining eqs (4.2) and (4.4), it follows that

$$(\varepsilon_m - \varepsilon_0)^\beta = \frac{1}{2}\{(\varepsilon_l - \varepsilon_0)^\beta + (\varepsilon_h - \varepsilon_0)^\beta\} \tag{4.5}$$

where $0 < \varepsilon_l < \varepsilon_m < \varepsilon_h$. Since ε_l and ε_h are fixed and ε_m and ε_0 can be obtained experimentally, exponent β can be solved numerically from this equation (Fagot, 1963; Stewart et al., 1967). In this section, this method will be applied to determine the brightness exponent for rectangularly flashed point sources and one-deg fields at various flash durations.

4.4.2 Method

The spatial configuration did not change with respect to the previous experiments and, hence, the reader can be referred to Section 4.2.2 for a full description. One subject (HR) participated in the bisection experiments. On each trial, he released a sequence of three flashes by pressing a button. These flashes were always presented at the same retinal position. The first flash appeared after 300 ms. The time interval between the offset of the first flash and the onset of the second flash as well as between the offset of the second flash and the onset of the third flash was kept constant at 500 ms. For the point sources the three flashes lasted either 8 ms or 256 ms. For the one-deg fields, on the contrary, the duration of these flashes varied from 2 to 975 ms. The one-deg fields were flashed against the 100 Td background, whereas for the point sources bisection experiments were conducted against the dark as well as the 100 Td background. It is known that results obtained by the method of bisection are affected by the sequence in which the stimuli are presented (Stevens, 1957, 1961; Marks, 1974). Stevens (1957) termed this effect "hysteresis". To avoid this effect, two series of experiments were carried out at each duration. In one series, the luminances of the three flashes appeared in an ascending order, in the other series the luminances were presented in a descending order. The results of both series were always pooled in an attempt to obtain an unbiased estimation of ε_m of eq. (4.5).

For the point sources, ε_m was measured by means of a double staircase method (Cornsweet, 1962). The luminance of the second flash varied in steps of 0.05 log units. A reversal in direction of luminance change occurred after two successive incremental luminance steps at which the subject stated that brightness B_m is closer to brightness B_h than to brightness B_l. Similarly, a reversal occurred after two successive decremental luminance steps at which the subject stated that brightness B_m is closer to brightness B_l than to brightness B_h. In this manner, 20 reversals were determined in one experiment. Since a descending as well as an ascending order of luminances of the flashes has been employed, 40 luminances at which reversals occurred have eventually been used to calculate the average luminance of the second flash.

For the one-deg fields, the method of constant stimuli was employed to determine the luminance of the second flash at which the subject judged brightness B_m of this flash to be closer to brightness B_h than to brightness B_l in 50% of the trials. This procedure introduces a small deviation from the luminance at which brightness B_m appears halfway between the brightnesses of the other two flashes because the instruction forces the subject to surpass a just noticeable brightness difference. However, it seems fair to assume that the Weber fraction is constant for the experimental conditions employed in this study (e.g. Cornsweet and Pinsker, 1965; Whittle, 1986), leading to a constant, negligible small shift of ε_m when it is expressed in log units. Four sessions in which the luminances appeared in an ascending order and four sessions in which the luminances appeared in a descending order were run. During a session, all durations were presented in a random order which was reversed in each second session.

4.4.3 Results and discussion

Point source

Contrary to magnitude estimation and category scaling, bisection generates observations on the physical continuum. For the point sources, these observations are the luminances that belong to the reversals obtained by the double staircase method. The averaging, however, has to be done on the psychological continuum, i.e. brightness. According to Fagot (1963), this averaging problem is optimally solved by making use of the following equation

$$\varepsilon_m = \bar{\varepsilon} + (\beta - 1)\left(\frac{s(\bar{\varepsilon})^2}{2\bar{\varepsilon}}\right) \tag{4.6}$$

where, in this case, $\bar{\varepsilon}$ and $s(\bar{\varepsilon})$ are the arithmetic mean and standard deviation, respectively, of the luminances at which the reversals occurred. Subsequently, the best-fitting combination of $(\varepsilon_m - \varepsilon_0)$ and β can be deduced from eqs (4.5) and (4.6) by means of an iterative procedure. The first four columns of Table 4.3 give the stimulus configurations that were used to estimate the brightness exponent for the point sources. Note that ratio $(\varepsilon_h - \varepsilon_0)/(\varepsilon_l - \varepsilon_0)$ was kept constant at about 12. This was done because Stewart et al. (1967) have shown that this ratio can have a significant effect on the brightness exponent. Columns 7 and 8 give the results as they were obtained by applying the above-mentioned procedure. For comparison, the last column shows the exponents as they were calculated from the arithmetic

Table 4.3: Determination of the brightness exponent for rectangularly flashed point sources of duration ϑ presented against an extended background of retinal illuminance E, by means of the method of bisection. The last two columns give brightness exponents β and β^* as they were calculated by using eq. (4.6) and arithmetic means $\bar{\varepsilon}$ of column 5, respectively. Background level E and flash increments ε are expressed in Td. Duration ϑ is expressed in ms. Subject: HR.

1	2	3	4	5	6	7	8	9
E	ϑ	$\varepsilon_l - \varepsilon_0$	$\varepsilon_h - \varepsilon_0$	$\bar{\varepsilon}$	$s(\bar{\varepsilon})/\bar{\varepsilon}$	$\varepsilon_m - \varepsilon_0$	β	β^*
	8	1131	12885	4885	0.37	4645	0.27	0.34
		7387	84156	32865	0.21	32416	0.37	0.39
0	256	100	1135	447	0.22	440	0.37	0.40
		1131	12885	5802	0.23	5741	0.60	0.62
	8	927	12681	5163	0.45	4867	0.44	0.51
		7041	83819	34978	0.29	34171	0.47	0.51
100	256	83	1118	424	0.28	413	0.38	0.41
		1097	12851	5002	0.22	4928	0.37	0.39

means of column 5. Fagot (1963) considered the arithmetic mean the worst estimator of ε_m. However, the differences are small, the difference being 0.07 at most. The results of Table 4.3 show that, especially in the photopic background condition, the brightness exponent remains reasonably stable over a luminance range of about 2 log units. Whereas the data suggest that in the photopic background condition the brightness exponent is larger for short than for long flashes, the reverse seems to be the case in the dark background condition. This is contrary to the finding of Mansfield (1973), obtained by magnitude estimation, that the exponent for short flashes is about twice the exponent for long flashes. If it is assumed that the brightness exponent is independent of flash duration (de Ridder and Theelen, 1983; see also Chapter 2), then the exponent is about the same for the dark and photopic background conditions, viz. 0.40 ± 0.14 and 0.42 ± 0.05. The last-mentioned value agrees with the exponent determined by magnitude estimations under identical conditions, viz. 0.44 ± 0.04 (see Table 4.1). This similarity between exponents derived from magnitude estimation and bisection experiments has also been observed by du Buf (1984, 1987), measuring the brightness exponent for a point source, flashed against an extended 100 Td background for 10 ms. The values he obtained were 0.36 and 0.35 ± 0.05 for magnitude estimation and bisection respectively.

One-deg field

The hypothesis that the brightness exponent is independent of flash duration has been examined systematically for the one-deg fields. At each of the 15 durations employed, ε_l and ε_h were kept constant at 490 and 4190 Td respectively. These values are well above detection threshold so that the influence of the threshold was negligible. The final results of the measurements are shown in Figure 4.13. The upper panel gives retinal illuminance ε_m as a function of flash duration, obtained

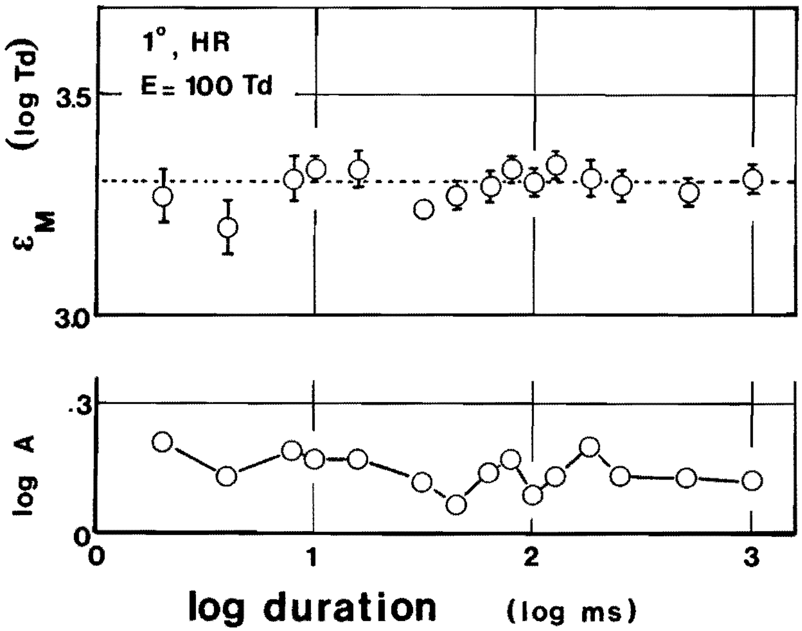


Figure 4.13: Upper panel denotes bisection point ε_m of eq. (4.5) as a function of flash duration for one-deg fields projected against an extended 100 Td background. Retinal illuminances ε_l and ε_h were kept constant at 490 and 4190 Td, respectively. The lower panel demonstrates the hysteresis effect as log A represents the difference between log ε_m determined in sessions in which the flashes appeared in ascending order of retinal illuminance and log ε_m determined in sessions in which the flashes appeared in descending order of retinal illuminance. Subject: HR.

after averaging the data of four sessions of ascending order of luminance presentation and four sessions of descending order of luminance presentation. In the lower panel, log A represents the difference between log ε_m determined from the sessions in which the ascending order was used and log ε_m determined from the sessions in which the descending order was used. On average, log A is 0.14 which is in agreement with the difference of 0.2 log units obtained by Stevens (1961, 1975). From the data of the upper panel of Figure 4.13 it can be concluded that ε_m does not vary systematically with duration. Moreover, ε_m appears to remain constant, the average being 1980 Td (Fig. 4.13, dashed line). Employing eqs (4.5) and (4.6), the brightness exponent belonging to this average was determined to be 0.58. Directly calculated from the arithmetic mean, the exponent becomes 0.60. These values correspond to the exponent derived from magnitude estimation, viz. 0.57 ± 0.11 (see Table 4.2). This correspondence is consistent with the results of Bodmann et al. (1980) who showed that brightness scales obtained by bisection are linearly related to those obtained by magnitude estimation. For a shortly flashed 0.5-deg field presented against an extended 100 Td background, du Buf (1984, 1987) deduced the same brightness exponent from bisection and magnitude estimation experiments, viz. 0.52. This value is near the exponent determined in the present study.

4.5 General discussion

If it is assumed that perceived brightness is related to luminance by a power function (e.g. Stevens, 1975), then the determination of the exponent of this function becomes one of the main purposes of brightness scaling. In the present study three direct scaling methods have been employed, viz. magnitude estimation, category scaling and bisection. For one condition, namely the one in which a one-deg field has been flashed against an extended 100 Td background, results obtained by these three methods can be compared directly. In addition, these measurements were performed by the same subject so that individual differences can be excluded. The results show that bisection and magnitude estimation yield the same exponent of about 0.6, whereas category scaling produces a lower exponent, viz. 0.3. Furthermore, for point sources presented against the same 100 Td background bisection and magnitude estimation give again the same exponent but in this case the value of the exponent is about 0.4. Bisection belongs to the class of interval-scaling methods and magnitude estimation to the class of ratio-scaling methods. Consequently, our data do not support the assumption of Stevens (1975) that results obtained by interval-scaling and ratio-scaling methods are always nonlinearly related when these methods are used to examine a prothetic continuum. To quote Bodmann et al. (1980):"... Thus it has been shown that there is a linear connection between a brightness scale obtained by bisection and one using magnitude estimation. Both are metric scales and the critical subdivision insisted on by Stevens does not appear to be necessary" (p. 100). Besides, the experimental method by which bisection point ε_m is determined (method of constant stimuli, double staircase method) appears to have no influence on the mutual consistency of magnitude estimation and bisection.

Despite the fact that our data are in agreement with the results of Bodmann et al. (1980) and du Buf (1984, 1987), the mutual consistency of bisection and magnitude estimation remains a remarkable finding as bisection is subject to both an averaging problem (Fagot, 1963) and hysteresis, i.e. bisection point ε_m of eq. (4.5) depends on the order in which the stimuli appear (Fig. 4.13, lower panel). A solution for the latter may be to present the stimuli simultaneously at different retinal positions. However, even then precautions have to be taken since Fagot and Stewart (1970) have shown that a response bias can still be observed under these conditions. On the other hand, averaging the results of sessions in which stimuli are given in an ascending and a descending order may already be sufficient to eliminate hysteresis, as is suggested by the results of the present study.

Category scaling deviates from the other two methods in that it produces a lower brightness exponent. This does not have to imply that the method of category scaling cannot be used for brightness scaling. Like magnitude estimation, it indicates that Bloch's law holds at suprathreshold levels (Fig. 4.12). Moreover, it shows that the Broca-Sulzer effect is present with large fields and that this effect does not shift as a function of flash luminance when the stimuli are presented against an extended photopic background (Fig. 4.11). Consistent with the last-mentioned finding, the brightness exponent remains approximately constant with flash duration (Table 4.2). This is confirmed by the results obtained by the two other methods.

In Figure 4.14, the category ratings of Figure 4.11 have been plotted as a function of the magnitude estimations of Figure 4.10. The resulting data fall on a single

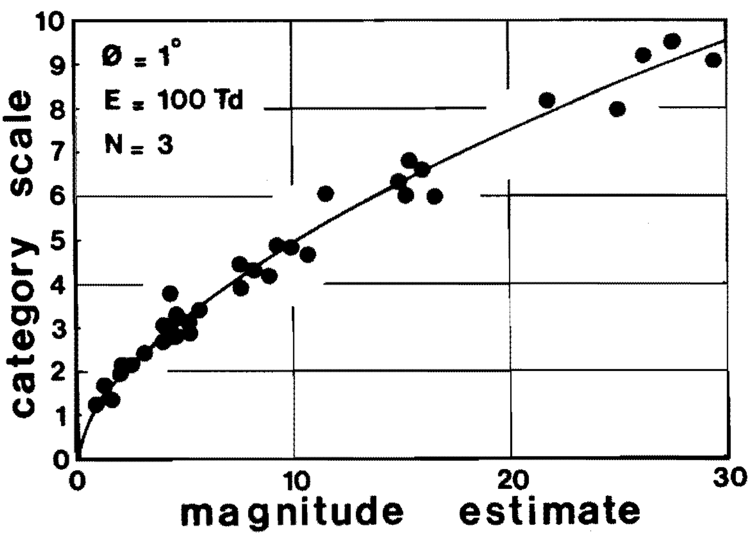


Figure 4.14: Category ratings of Figure 4.11 as a function of the magnitude estimations of Figure 4.10. The solid line represents the best fit of a simple power function with an exponent of 0.61, obtained by the method of least-squares.

curve which can be described by a simple power function with an exponent of 0.61 (r^2=0.98). This implies that both methods will yield the same results (Bloch's law, Broca-Sulzer effect) but that the brightness exponent obtained by category scaling is about 0.6 times the exponent obtained by magnitude estimation. Two possible explanations for this discrepancy have been examined, one in relation to the assumption of equal distances between the categories and the other in relation to the restricted number of categories employed in the present study.

The method of category scaling is based on the assumption that the distances between the categories are subjectively equal. However, this assumption may have been violated in the present study. In order to check for this possibility, the data of Figure 4.11 were analysed by the method of successive interval scaling (Edwards, 1957). It was found that at the lower three categories the subjective distance is larger than predicted from a linear transformation of the 10-point scale on the psychological scale but equal or slightly smaller at the other categories (Fig. 4.15). Accordingly, the distances between the categories are not subjectively

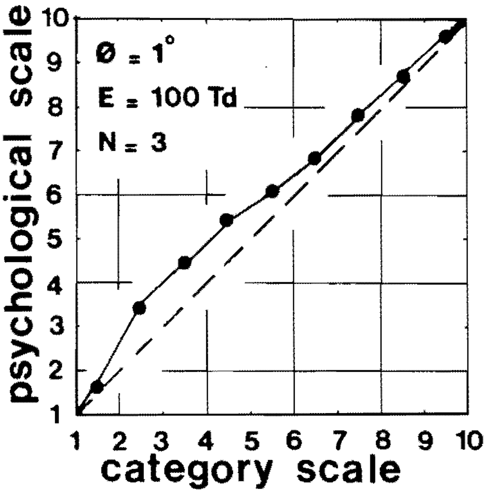


Figure 4.15: Analysis of the results of Figure 4.11 by means of the method of successive interval scaling (Edwards, 1957). Dashed line denotes the linear transformation of the category scale on the psychological scale.

equal. This, however, cannot explain the lower exponent obtained by category scaling because, taking into account these deviations, an even smaller exponent is obtained and the brightness-luminance relation approaches a logarithmic function. Consequently, in this way the observed discrepancy will only be enhanced.

The other possible explanation stems from the work of Teghtsoonian (1971, 1973) who hypothesized that exponent β of eq. (4.1) depends on the stimulus as well as the response range employed in an experiment. This dependence is described by the following equation

$$\beta = \frac{\log R_\Psi}{\log R_\Phi} \tag{4.7}$$

where R_Φ is the ratio of strongest to weakest stimulus and R_Ψ is the ratio of the corresponding judgments. In our case, stimulus range R_Φ is the same for the magnitude estimation and category scaling experiment. Then, it follows from eq. (4.7) that

$$\frac{\beta_{cs}}{\beta_{me}} = \frac{\log R_{\Psi,cs}}{\log R_{\Psi,me}} \tag{4.8}$$

where "*me*" and "*cs*" stand for magnitude estimation and category scaling, respectively. Response range $R_{\Psi,cs}$ is limited to 10, whereas this restriction does not hold for response range $R_{\Psi,me}$. Applying eq. (4.8) to the data of Figure 4.14, ratio β_{cs}/β_{me} becomes 0.59. This value corresponds with the exponent of the power function that was fitted to the data of Figure 4.14. Table 4.2 shows that for subject HR the ratio of the brightness exponents is 0.55 ± 0.09 when exponents are derived from the magnitude estimations and category ratings by means of eq. (4.2). Calculated from eq. (4.8), this ratio becomes 0.58. This correspondence suggests that the lower brightness exponent obtained by the method of category scaling may result from the limited number of categories employed in the present study. This suggestion corresponds with the work of Marks (1968), Gibson and Tomko (1972) and Foley et al. (1983) who found that the value of exponent β decreases when the number of categories is restricted.

For large static fields, light adaptation has been shown to raise the brightness exponent from about 0.33 to about 0.5 (Onley, 1961; Stevens and Stevens, 1963; Warren, 1981). Accordingly, the exponent of 0.6 determined for the one-deg field flashed against the 100 Td background is not unexpected. The results for the point source presented against the dark background, on the contrary, are less clear. While the method of bisection produces an exponent of about 0.4 (Table 4.3), the method of magnitude estimation suggests a value around 1 for shortly flashed point sources (Fig. 4.1). During the last-mentioned experiments, a standard labelled "100" has been employed. It is possible that the use of this standard has raised the value of the exponent. However, this does not completely explain the observed difference in exponents because Mansfield (1973), using a standard-free method of magnitude estimation, also obtained an exponent of about 1. This result does not correspond with ours since the present study has shown that bisection and the standard-free method of magnitude estimation are mutually consistent. Further research is needed to clarify this discrepancy.

4.5.1 Conclusions

The methods of magnitude estimation and bisection are mutually consistent provided that no standard or modulus is used during the magnitude estimations. When stimuli are presented against an extended photopic background, both methods are able to demonstrate the dependence of the brightness exponent on the stimulus area, the exponent being larger for one-deg fields than for point sources. Under similar conditions, the method of category scaling produced a lower brightness exponent than the two other methods did. This difference may be attributed to the restricted number of categories employed in the present study. The validity of Bloch's law at suprathreshold levels and the occurrence of the Broca-Sulzer effect as well as its dependence on the stimulus area can be demonstrated by magnitude estimation and category scaling.

chapter 5

On the mutual consistency of brightness scaling and matching for time-dependent stimuli

Abstract

Results of scaling and matching experiments concerning the perceived brightness of rectangularly flashed point sources and one-deg fields have been compared in order to examine the mutual consistency of these methods. Equal-brightness curves as a function of flash duration as well as a brightness matching curve between a briefly flashed point source and a briefly flashed one-deg field were constructed from scaling experiments. No significant differences were found between these curves and similar curves obtained by interocular brightness matching. Predictions of a dynamic brightness model were verified by results of both methods. They show not only that the Broca-Sulzer effect depends on the stimulus area but also that it does not shift as a function of flash luminance when the one-deg field is flashed against an extended 100 Td background. These results indicate that brightness scaling and matching are mutually consistent. Furthermore, it is shown that the same differences between brightness exponents for one-deg fields and point sources are obtained whether they are determined in separate sessions or within the same session.

5.1 Introduction

Methods to measure perceived brightness of light sources can be divided into two categories: scaling and matching. Little attention has been paid to the mutual consistency of these methods, yet this problem is important for the development of any kind of general theory on brightness perception.

Stevens (1966) assumed that brightness scaling (especially magnitude estimation) and brightness matching yield mutually consistent results. His assumption was based mainly on the fact that, for rectangular incremental flashes of varying luminance and duration, both methods are able to demonstrate Bloch's law at suprathreshold levels and also the occurrence of the Broca-Sulzer effect near the critical duration as well as its shift to shorter durations with increasing flash luminance (Raab, 1962; Aiba and Stevens, 1964; Katz, 1964). The prediction derived from this shift, viz. the exponent of the power function relating brightness to luminance is larger for short than for long flashes (Stevens, 1966; Anglin and Mansfield, 1968), has been confirmed by results obtained by the method of magnitude estimation (Stevens and Hall, 1966; Mansfield, 1973).

The above-mentioned resemblance, however, is only a qualitative one. For example, the shift of the Broca-Sulzer effect, measured by means of brightness matching, is significantly smaller than the shift obtained by means of magnitude estimation (Stevens and Hall, 1966; Anglin and Mansfield, 1968; de Ridder and

Theelen, 1985; see also Chapter 3). Furthermore, de Ridder and Theelen (1985) have argued that the explanation of this shift in terms of different brightness exponents for short and long flashes (Stevens, 1966; Anglin and Mansfield, 1968; Mansfield, 1973; Osaka, 1982) cannot be valid. Alternatively, they suggest that the brightness exponent is independent of flash duration and that the shift of the Broca-Sulzer effect, observed in dark-background conditions, may be due to changes in the effective state of adaptation leading to changes in the time constant of the visual system. Finally, brightness-matching curves constructed from magnitude estimations sometimes deviate from directly measured brightness-matching curves (Greenstein and Hood, 1981). Accordingly, mutual consistency of brightness scaling and matching is still a matter of controversy.

Two conditions have to be fulfilled in order to be able to examine this mutual consistency properly. In the first place, brightness-scaling and brightness-matching experiments must be carried out under identical conditions. This means not only that the same stimulus configuration is employed but also that the same subjects participate in both types of experiments. Secondly, there must be a theoretical model that enables results of brightness-scaling and brightness-matching experiments to be unified.

In Chapter 2, results of a series of interocular brightness-matching experiments have been described in which circular one-deg fields and point sources were flashed against an extended 100 Td background. The flashes had a rectangular time course and they were varied in luminance as well as in duration. One of the two subjects who participated in these experiments also performed a series of brightness-scaling experiments in which the same stimuli appeared as were employed during the brightness matchings. The results of these experiments can be found in Chapter 4. In addition, a model to describe the brightness of time-dependent stimuli was presented in Chapter 2. This dynamic brightness model, based on general principles of systems analysis, yields quantitative predictions of the brightness of relatively fast-changing stimuli like rectangular light flashes. Some of these predictions have already been tested and verified by means of brightness matching (de Ridder and Theelen, 1983, 1984, 1985; see also Chapters 2 and 3). In the present study, these predictions will be compared with the results of the brightness-scaling experiments of Chapter 4. In this manner, it is hoped to establish mutual consistency of brightness scaling and matching.

One of the conclusions, drawn from the fitting of the dynamic brightness model to the results of the brightness matchings, is that the brightness exponent is larger for one-deg fields than for point sources when stimuli are presented against an extended photopic background. For one subject, the ratio of these exponents was found to be about 1.2 (de Ridder and Theelen, 1984). This value corresponds to the brightness exponents that were determined for the same subject by means of the method of magnitude estimation, viz. 0.57 and 0.44 for the one-deg field and point source, respectively (see Chapter 4). The last-mentioned exponents were obtained in separate experiments. Consequently, it is possible that slight changes could have occurred in the subject's scale across experiments and that these scale changes could have affected the brightness exponents. To check for this possibility, the magnitude-estimation experiments have been repeated, but in this case the one-deg field and the point sources always appeared in the same session. This experiment is described in Section 5.2.

In Section 5.3, predictions of the dynamic brightness model are compared with the results of the brightness-scaling experiments of Chapter 4. This makes it possible to examine mutual consistency of brightness scaling and matching more quantitatively than has been done up to the present, the more so as the two conditions for a proper check of mutual consistency, viz. same experimental conditions during scaling and matching as well as the presence of a theoretical model, are fulfilled.

5.2 Brightness exponent for point sources and one-deg fields

5.2.1 Introduction

The relationship between brightness and luminance is often described by a power function (e.g. Stevens, 1975). For light flashes against a dark background, the exponent of this function has been found to depend on the area of the light source, the exponent being larger for small areas than for large ones (Mansfield, 1973; Stevens, 1975). For flashes against an extended photopic background, however, results of brightness-scaling and brightness-matching experiments seem to suggest the reverse (du Buf, 1984, 1987; de Ridder and Theelen, 1984; see also Chapters 2 and 4). The purpose of the present section is to verify this suggestion. Therefore, brightness exponents are determined for a point source and a circular one-deg field, projected against an extended 100 Td background. The point source and one-deg field always appear within the same session so that possible differences between sessions are excluded.

5.2.2 Method

Apparatus

The left half of a six-channel, binocular Maxwellian-view optical system was used to present the stimulus configuration to the left eye of the subject. An extensive description of the optical system can be found in Chapters 1 and 2. Three independent light channels were available, the light source of each being a glow modulator tube (Sylvania type R1131C or equivalent type EEV XL670), linearized and stabilized by light feedback. One of these channels produced a circular 5.5 deg, 100 Td "white" steady background. A small black dot, painted on a glass plate that was inserted in the light beam of this channel, served as fixation point. It was positioned in the centre of the 5.5-deg field. A second light channel projected a circular one-deg field to the left of the fixation point in such a way that its centre appeared 40 min arc to the left of the fixation point. The same holds for the third light channel except that the diameter of this field was 2 min arc (point source). During a trial, either the one-deg field or the point source appeared as a rectangular incremental, achromatic light flash. Duration and luminance were electronically varied by means of square-wave pulse generators and attenuators, respectively. The flashes lasted 2, 4, 8, 16 and 32 ms. A pilot study showed that the subject was not able to identify the durations of the flashes. This underlines the fact that the flashes were all within the integration time of the visual system and, consequently, that the brightness of the flashes must be related to their energy (e.g. Roufs, 1972b; Watson, 1986). Retinal illuminances were chosen in such a way that for the one-deg field the flash energy varied from 2.06 to 4.46 log(Td.ms) in steps of 0.3 log units whereas for the point source flash energy varied from 3.33 to 5.73 log(Td.ms), also in steps of 0.3 log units. The subject saw the whole stimulus configuration through an eye piece which was fitted with an artificial pupil, 2 mm in diameter and equipped with an entoptic guiding system (Roufs, 1963). In order to optimize fixation, the head of the subject was immobilized using a chin-and-head rest.

Procedure

At the beginning of each session the subject was dark-adapted for about 10 minutes before he adapted to the 100 Td background level for about 2 minutes. In the experiment following after that, the subject initiated a trial by pressing a button, thus releasing a single flash after a delay of 300 ms. Subsequently, the subject had to assign a number to the flash in proportion to its perceived brightness (method of magnitude estimation). No standard was employed and the subject received the explicit instruction to estimate the brightness peak. During a session, the whole set of stimuli was presented, i.e. all flash energies for the one-deg field as well as for the point source. These two sets of stimuli were randomly interspersed among each other. In addition to the magnitude estimations, the threshold energies for the one-deg field and the point source were measured at the beginning as well as at the end of a session. The method of constant stimuli was employed to determine their 50% detection thresholds.

Subject

The experiment was performed by one male subject (the author, 32 years old) who has normal uncorrected vision. He had already participated in brightness-scaling and brightness-matching experiments which were carried out under identical conditions.

5.2.3 Results and discussion

The experiment consisted of four sessions. During a session, all stimuli appeared in random order. The second and fourth session were repetitions of the first and third one, except that the stimuli appeared in the reversed order. Figure 5.1 shows the final results of this experiment. The data points are the geometric

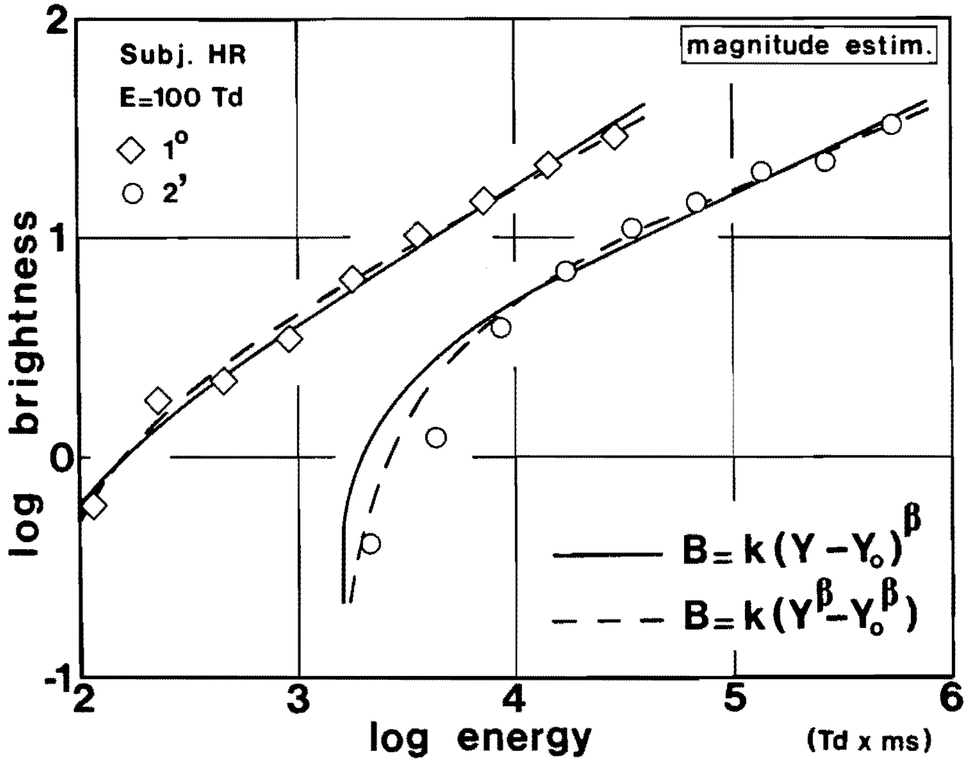


Figure 5.1: Brightness estimates for rectangularly flashed point sources (open circles) and one-deg fields (open diamonds) as a function of flash energy, obtained by a standard-free method of magnitude estimation. The duration varied from 2 to 32 ms. The stimuli were presented against an extended 100 Td background. Solid and dashed lines represent least-squares fits of Φ- and Ψ-translated power functions, respectively.

means of the four sessions, the average standard deviation of the mean being 0.08 log units for the point source and 0.05 log units for the one-deg field. For the point source (open circles) as well as the one-deg field (open diamonds), brightness increases monotonically with energy. At the higher levels, the data approximate straight lines, indicating that the results can be described by power functions (e.g. Stevens, 1975). In order to take into account the observed increase in steepness of the brightness-energy relations at the lower levels, two frequently employed modifications of a simple power function have been examined. One involves a threshold correction on the stimulus axis (sometimes termed the Φ-translation; Fagot, 1966, 1975; Fagot and Stewart, 1968; Marks and Stevens, 1968), the other involves a correction on the response axis (Ψ-translation; Fagot, 1966, 1975; Fagot and Stewart, 1968; Marks and Stevens, 1968). In Figure 5.1, the solid and dashed lines indicate the Φ- and Ψ-translation, respectively. Both translations are also given by the expressions, inserted into Figure 5.1. In these expressions, Y represents flash energy and B represents brightness. The curves denote the best least-squares fits to the data, using the experimentally determined threshold energies as correction factor (Y_0). The threshold energies were 1.7 and 3.2 log(Td.ms) for the one-deg field and point source, respectively. The best fit of the Φ- and Ψ- translated power functions yielded the following brightness exponents for the one-deg field: 0.62 and 0.50. For the point source, these values became 0.46 and 0.32. The last-mentioned exponents were obtained by a least-squares fit to all data, except the two lowest ones from the curve for the point source. Figure 5.1 shows that both translations fail to fit these data points.

The main purpose of the present experiment was to verify the suggestion that the brightness exponent is larger for one-deg fields than for point sources when stimuli are presented against an extended photopic background. And, although the fitting of the Φ- and Ψ-translations of a simple power function yielded different exponents, this dependence of the brightness exponent on the stimulus area is confirmed in both instances. Consequently, the difference in brightness exponents for one-deg fields and point sources as was observed in the previous chapter cannot be attributed to the fact that these exponents were determined in separate experiments. This conclusion corresponds to the results of Greenstein and Hood (1981) who compared the brightness of foveal flashes to the brightness of flashes presented 4 deg temporal to the fovea. They obtained similar results whether the two brightness-luminance relations were determined in separate sessions or within the same session.

Furthermore, the data of Figure 5.1 have the additional advantage that the brightness of the one-deg field and the point source have been estimated on a common scale. Accordingly, it is permitted to construct a brightness-matching curve from these data which can be compared with a directly measured brightness-matching curve. This provides a useful check of the mutual consistency of scaling and matching as will be shown in the following section.

5.3 Brightness scaling and model predictions

In this section results of brightness-scaling experiments are shown that have been obtained with the same stimulus configuration as was used in the brightness-matching experiments. That is, point sources and one-deg fields were rectangularly flashed against an extended 100 Td background. This configuration was presented to the left eye of the subject, the centre of the stimuli always appearing

40 min arc to the left of a centrally positioned fixation point (for further details, see Chapter 4). Subject HR participated in the experiments.

The results shown in Figures 5.2 and 5.3 for the one-deg field and point source respectively were obtained by a standard-free method of magnitude estimation (e.g. Stevens, 1975). Both figures indicate that, at short durations, brightness grows with flash duration. Furthermore, at these durations the data tend to converge when duration increases. At long durations, on the contrary, the data become more or less independent of flash duration. In the equal-luminance curves of Figure 5.2 an overshoot can be observed around 80 ms that is not present in the results of Figure 5.3. This confirms once more the dependence of the Broca-Sulzer effect on the stimulus area (de Ridder and Theelen, 1983, 1984). In both figures the dashed lines represent predictions of the dynamic brightness model according to

$$\log \hat{B} = \beta \log\{(\varepsilon - \varepsilon_0)\hat{U}_p(t;\vartheta)\} + K \tag{1}$$

which is derived from eq. (2.10) by taking the logarithm. Exponent β and constant K are free parameters and ε_0 decreases as a function of ϑ within Bloch's region (see eq. (2.11)). These model predictions, derived from the impulse responses of Figures 2.10 and 2.9, were simultaneously fitted to all data by means of the method of least-squares under the assumptions that (1) exponent β is independent of flash duration and (2) the dynamic behaviour of the linear filter, represented by unit block response $U_p(t;\vartheta)$, does not alter with flash luminance. These two restrictions were deduced from the correspondence between model predictions and results of brightness-matching experiments such as the equal-brightness curves of Figures 5.5 and 5.6 (see also Chapter 2). The best fit was obtained with β=0.55 (r^2=0.98) for the one-deg field (Fig. 5.2, lower panel) and with β=0.46 (r^2=0.97) for the point source (Fig. 5.3, lower panel). The former deviates from the exponent for the dark-adapted observer at long durations (β=0.33)(Stevens, 1966, 1975; Aiba and Stevens, 1964; Mansfield, 1973), whereas the same holds for the latter at short durations (β=1 for the dark-adapted observer)(Mansfield, 1973; Stevens, 1975). The fair correspondence between measured data and model predictions supports the suggestion that the brightness exponent is independent of flash duration when stimuli are presented against an extended photopic background (de Ridder and Theelen, 1983, 1984). Finally, the theoretical curves of Figure 5.2 emphasize the fact that the Broca-Sulzer effect remains around 80 ms at all four retinal illuminance levels. This absence of a shift is another confirmation of the mutual consistency of scaling and matching.

Model predictions have also been fitted to data obtained by means of category scaling. These data can be seen in Figure 5.4. The set of stimuli was identical to the one used for the magnitude estimation experiment of Figure 5.2. The perceived brightness of the flashes was rated on a 10-point numerical scale. Subsequently, the logarithm of the arithmetic means was calculated in order to fit eq. (5.1) to these results. The best least-squares fit produced an exponent of 0.30 (r^2=0.96).

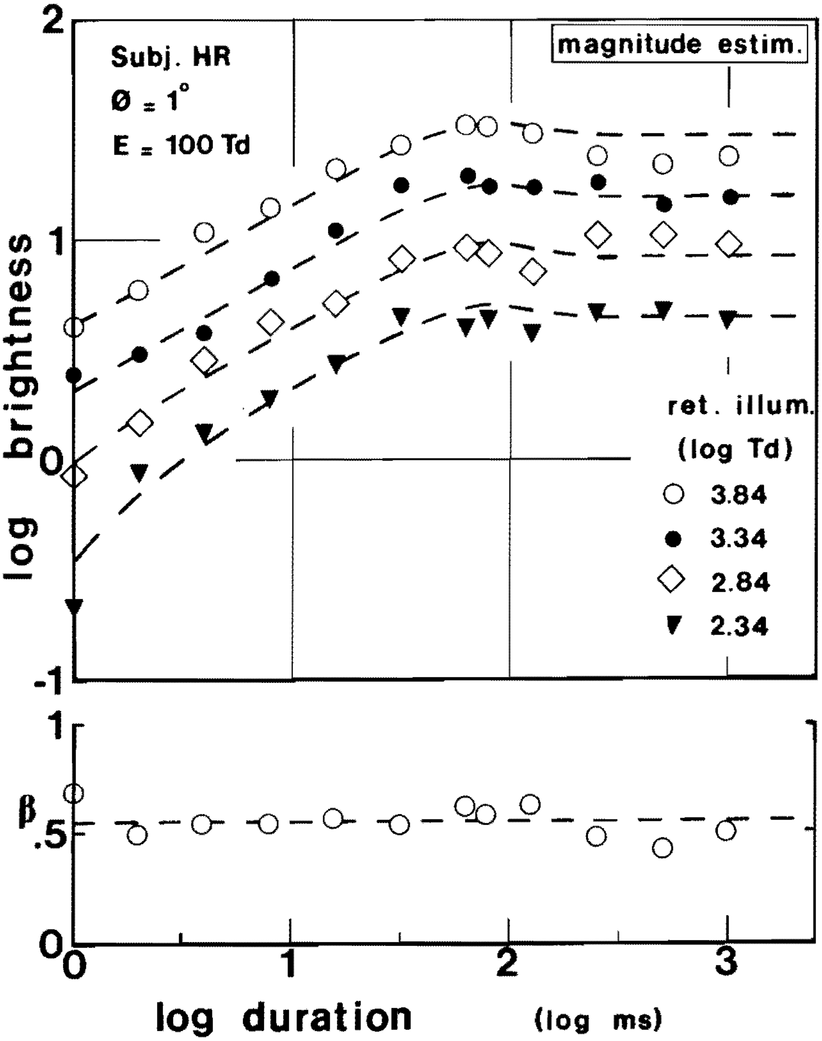


Figure 5.2: Brightness estimates for a rectangularly flashed one-deg field as a function of duration and retinal illuminance, obtained by the method of magnitude estimation. Background level E was 100 Td. Data are based on eight measurements, the average standard error of the mean being 0.06 log units. The dashed lines denote model predictions according to eq. (5.1) under the assumption that brightness exponent β is independent of flash duration (lower panel, dashed line).

The reasonable correspondence between the theoretical curves and the measured data is contrary to the idea that category scaling is not suited to examine prothetic continua like brightness (Stevens, 1966, 1975). Again, the occurrence of the Broca-

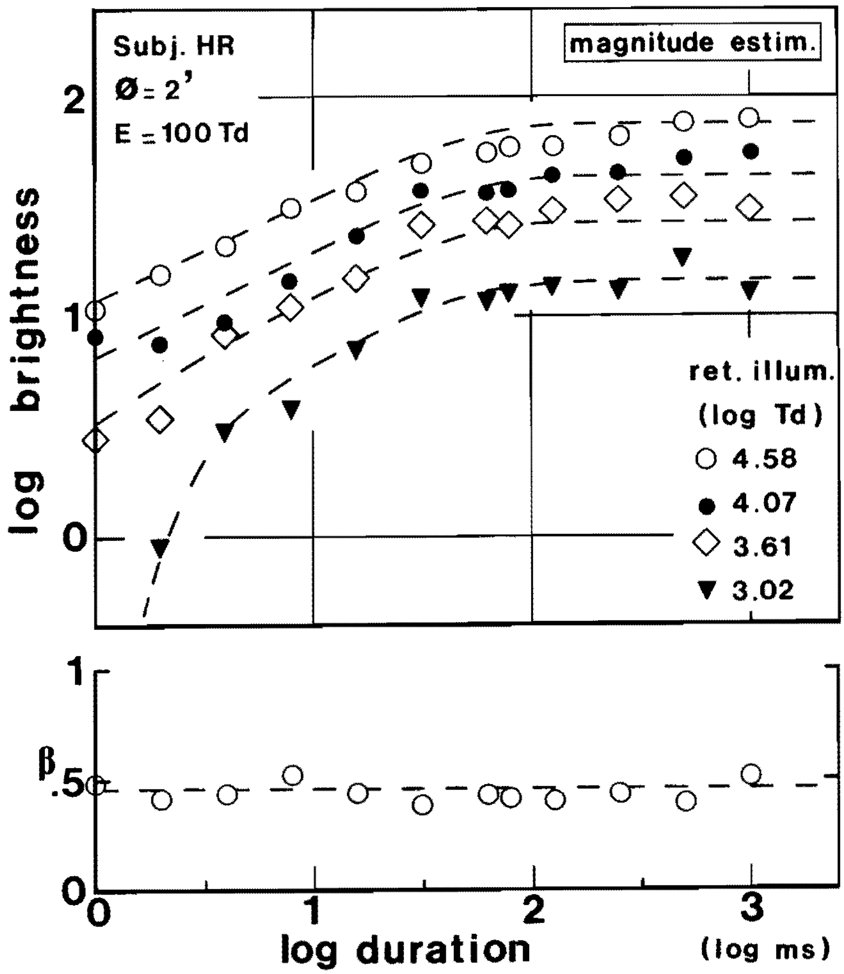


Figure 5.3: Same as Figure 5.2 except that the stimulus is a point source. Data are based on six measurements, the average standard error of the mean being 0.05 log units.

Sulzer effect around 80 ms can be observed. Furthermore, the brightness exponent is found to be independent of flash duration. An explanation for the fact that the brightness exponent obtained by category scaling is less than the one obtained by magnitude estimation (Fig. 5.2) is beyond the scope of the present study and the reader is referred to Chapter 4 where this difference is discussed.

Another possibility to test the mutual consistency of scaling and matching is to construct equal-brightness curves from results of brightness-scaling experiments and to compare these curves with actually measured equal-brightness curves. The data of Figures 5.2, 5.3 and 5.4 may be considered as a series of brightness-

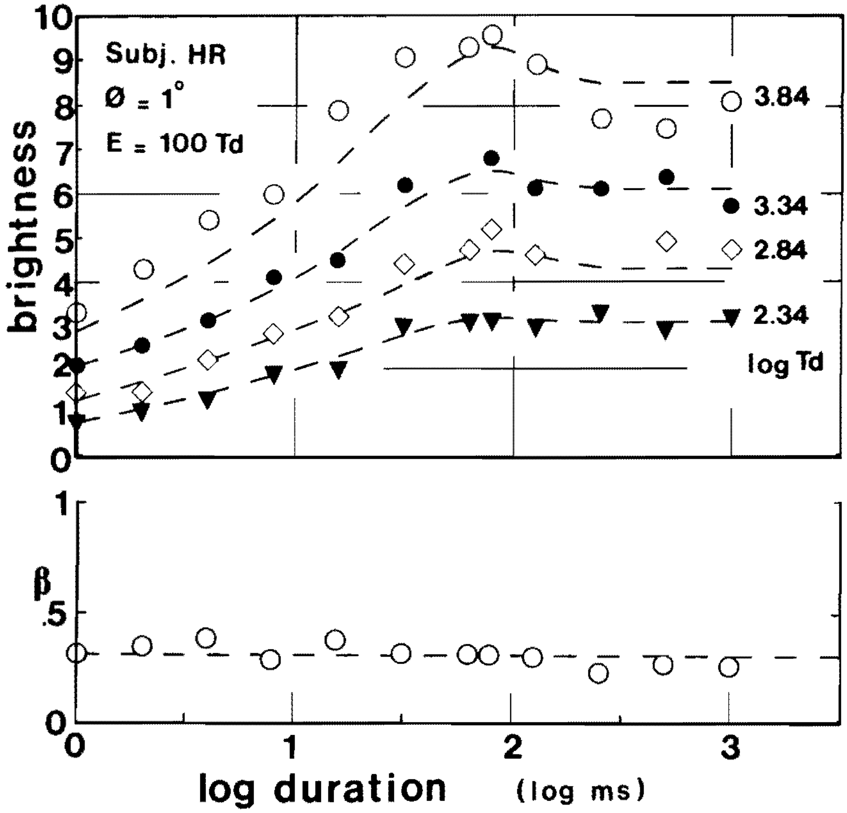


Figure 5.4: Same as Figure 5.2 except that in this case the brightness of the flashed one-deg field has been estimated by means of category scaling, using a 10-point numerical scale. Data are based on twelve measurements, the average standard error of the mean being 0.21.

luminance relations at various flash durations. Consequently, equal-brightness curves as a function of flash duration can be derived from these data by determining at each duration the luminance that is required to obtain the same brightness estimate. Equal-brightness curves that were obtained in this manner are shown in Figures 5.5 and 5.6. Filled circles and open diamonds denote data deduced from magnitude estimates and category ratings, respectively. For the construction of the equal-brightness curves, category rating "4" and magnitude estimate "5" have been employed for the one-deg field (Fig. 5.5). Similarly, magnitude estimate "15" has been used for the point source (Fig. 5.6). In both figures the open circles denote actually measured equal-brightness curves having approximately the same absolute position as the constructed ones. These measured curves have been shifted one log unit downwards. Figures 5.5 and 5.6 show that there exists a close correspondence between measured and constructed curves. This implies an addi-

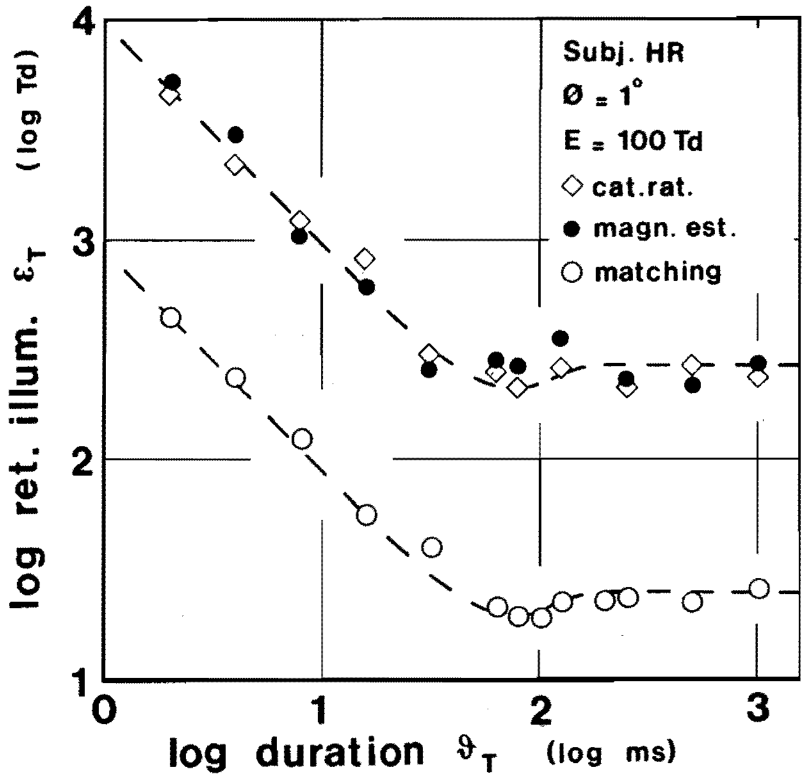


Figure 5.5: Equal-brightness curves for a flashed one-deg field with variable duration ϑ_T. The upper curve has been constructed from the magnitude estimates of Figure 5.2 (filled circles) and the category ratings of Figure 5.4 (open diamonds). The open circles denote an equal-brightness curve, obtained by interocular brightness matching between the test flash and a constant reference flash (8 ms flashed one-deg field). These data have been shifted one log unit downwards. The dashed lines are theoretical curves predicted according to eq. (2.13).

tional confirmation of the mutual consistency of scaling and matching. At least there must be a stable monotonic relation between the scaled brightness values and the perceived brightness. At short durations, all data lie on straight lines having a slope −1, thus obeying Bloch's law, whereas at long durations the curves are independent of flash duration. As was already noticed by Stevens and Hall (1966), the construction of equal-brightness curves hardly preserves the Broca-Sulzer effect in view of the smallness of this effect relative to the spread in the estimated values. On the other hand, the transition from Bloch's region to the constant level at long durations is correctly indicated by these data. Furthermore, Figures 5.5 and 5.6 show that the constructed curves correspond with the theoretical curves (dashed

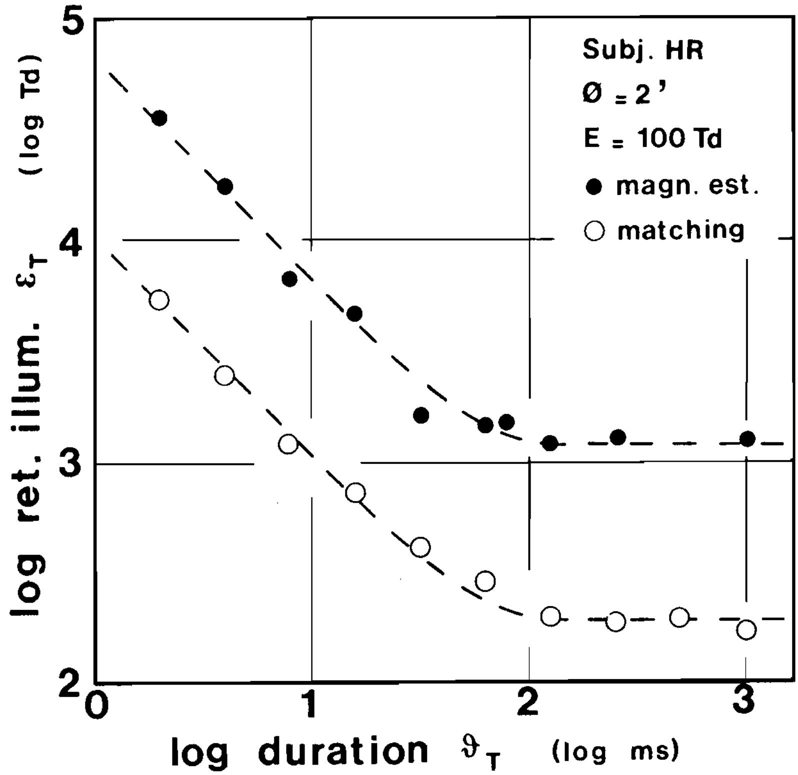


Figure 5.6: Same as Figure 5.5 except that the stimulus is a point source. The upper curve has been constructed from the magnitude estimates of Figure 5.3. The open circles denote an equal-brightness curve, obtained by interocular brightness matching between the test flash and a constant reference flash (256 ms flashed point source).

lines) derived from the impulse responses of Figures 2.10 and 2.9 respectively. The theoretical curves were determined on the assumption that the brightness exponent is independent of flash duration. The fact that the model predictions fit reasonably well affirms this independence.

In the experiment described in Section 5.2 the brightness of a shortly flashed one-deg field and a shortly flashed point source have been estimated on a common scale (Fig. 5.1). This means that, analogous to the above-mentioned equal-brightness curves, a brightness-matching curve can be constructed from these data. To this end, adjacent data points of Figure 5.1 were connected by straight-line segments and, subsequently, horizontal cuts were made through the two resulting curves at regular intervals. In this manner, each horizontal cut yielded a pair of flash energies, one for the one-deg field and one for the point source, that produce in principle the same brightness estimate. The brightness matching curve, obtained by this so-called magnitude matching procedure (Stevens and Marks, 1980; Ward, 1982), can be seen in Figure 5.7 (filled circles) where the energy of

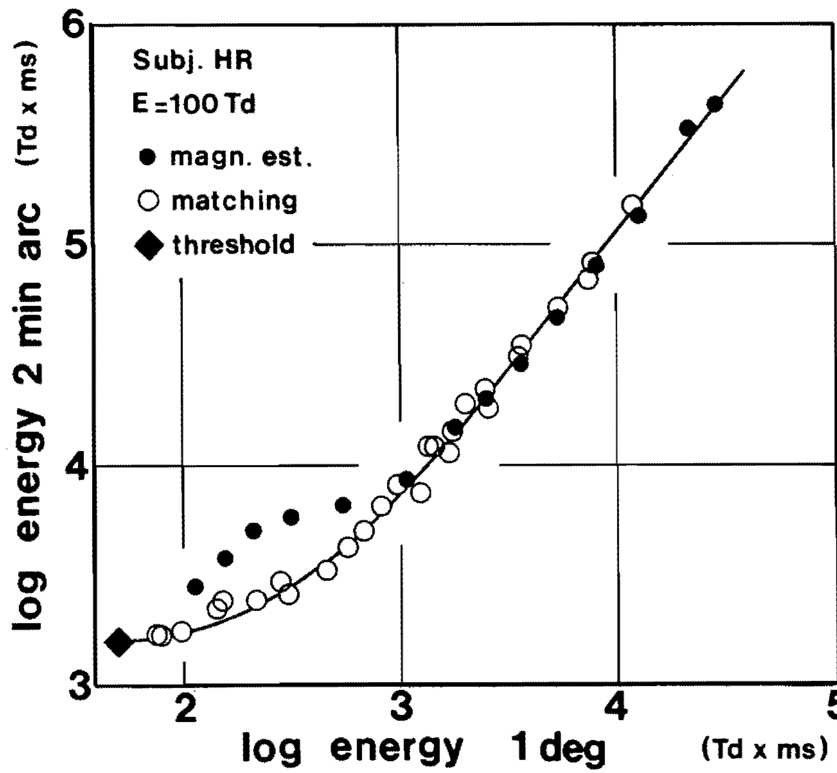


Figure 5.7: Brightness matching between a shortly flashed point source and a shortly flashed one-deg field. Filled circles denote data constructed from the magnitude estimates of Figure 5.1 by means of the method of magnitude matching. Open circles are actually measured brightness-matching data (de Ridder and Theelen, 1984). The solid line represents a least-squares fit of a Φ-translated power function to the constructed data.

the point source is plotted as a function of the energy of the one-deg field. At the higher levels, the data lie on a straight line but, approaching the detection threshold (filled diamond), a positive hump is observed. This hump can be attributed to the low magnitude estimates at the two lowest energy levels for the point source (Fig. 5.1). These low values were not expected since a similar scaling experiment, in which the brightness-energy relation was determined for the point source alone, did not yield significant deviations from a Φ-translated power function (see Fig. 4.6). Ignoring the hump, a power function was fitted to the remaining data points which had been corrected for their thresholds by means of Φ-translations on both axes. The best least-squares fit (Fig. 5.7, solid line) yielded an exponent of 1.25 (r^2=0.995), i.e. brightness increases faster with energy for the one-deg field than for the point source. This corresponds with directly measured brightness-matching data (Fig. 5.7, open circles). These data have been taken from an earlier study (de Ridder and Theelen, 1984; see also Chapter 2) in which the brightness of a shortly (8 ms) flashed point source was matched to that of shortly (4, 8, 32 ms) flashed one-deg fields. Figure 5.7 shows that they approximate the power function fitted to the results of the magnitude matching procedure. The fact that data points from both types of experiments have the same *absolute* values suggests not only that brightness scaling and matching are mutually consistent but also that our brightness-matching experiments did not suffer from a regression bias (Stevens and Greenbaum, 1966; Stevens, 1975) since the method of magnitude matching eliminates this effect (Stevens and Marks, 1980). Results of matching experiments showing a regression effect (Aiba and Stevens, 1964; Stevens and Greenbaum, 1966; Marks, 1966; Teghtsoonian, 1973; Stevens, 1975) have been obtained by means of the method of adjustment. In our studies, the method of constant stimuli has always been employed (de Ridder and Theelen, 1983, 1984, 1985; see also Chapters 2 and 3). Accordingly, the occurrence of a regression bias in a matching experiment appears to depend on the technique used to determine the point of subjective equality.

5.4 Conclusions

From the present study it can be concluded that brightness scaling and matching yield mutually consistent results. It is shown that the brightness of relatively fast-changing stimuli like rectangular flashes is efficiently described by a model whose main part consists of a linear filter and a compressive nonlinearity. In combination with model predictions, phenomena like Bloch's law and the Broca-Sulzer effect can be employed to examine the mutual consistency of various scaling and matching techniques as is demonstrated in the present study. Finally, our results show that the usually recommended values of the brightness exponent obtained under dark-adapted conditions (Mansfield, 1973; Stevens, 1975) cannot always be used in other conditions. Further research is needed to examine the influence of the background on the brightness exponent.

Concluding remarks

The various kinds of brightness-scaling and brightness-matching experiments described in this thesis gave mutually consistent results. This points to a stable monotonic relation between brightness and luminance. The dynamic brightness model, introduced in Chapter 2, proved to be able to describe the influence of flash duration on this brightness-luminance relation, suggesting that the dynamic brightness model can predict the perceived brightness of relatively fast-changing stimuli. This has to be tested for other, more complex temporal signals like twin flashes and flash trains (de Ridder et al., 1986).

A one-deg field with dark surround was employed to determine the temporal impulse response of the transient channel, using "agitation" as detection criterion. The Broca-Sulzer effect, on the contrary, was measured against an extended background by means of brightness matching and/or scaling. The finding that the Broca-Sulzer effect is predicted from the impulse response suggests that the same mechanism (transient channel) is involved. Additional evidence may be obtained by measuring impulse responses at suprathreshold levels. At the same time, this may provide a better insight into the possible interactions between the temporal channels that are assumed to operate in the visual system. In this way, other findings are hoped to be explained, for instance the observed influence of the surround on threshold-duration curves.

The results of Chapter 3 show that under certain conditions the time constants of the visual system are smaller for one-deg fields flashed against a dark background than for those flashed against a photopic background. This unexpected result needs further research which may lead to a better understanding of the mechanisms controlling the adaptive state of the visual system.

This thesis concentrated on the temporal aspects of suprathreshold vision, keeping the spatial parameters as fixed as possible. Spatial configurations were used that are assumed to isolate the sustained and transient channels (Roufs and Blommaert, 1981). However, in order to arrive at a spatiotemporal model of suprathreshold vision, it is obvious that the spatial parameters cannot be neglected and that both spatial and temporal aspects of vision have to be taken into account in future research.

Summary

This thesis is concerned with the dynamic properties of human brightness perception. Brightness-scaling and brightness-matching experiments are described that have been carried out by a number of subjects under the same, well-defined experimental conditions. One of the subjects participated in all experiments. The main purpose of the experiments was to test predictions of a dynamic brightness model. These predictions referred to the brightness of rectangularly flashed one-deg fields and point sources of varying luminance and duration. In all experiments but one, the stimuli were presented against an extended 100 Td background by means of a six-channel, binocular Maxwellian-view optical system.

The necessity of giving explicit instructions to subjects about their brightness judgments is pointed out in Chapter 1. Subsequently, it is shown that for dichoptically presented point sources brightness matching of flashes of unequal duration is hardly affected by variations in Stimulus Onset Asynchrony (SOA) if a subject is requested to match the brightness peaks of the flashes. It is concluded that during brightness-matching experiments a simultaneous onset of test and reference flash is to be preferred for the investigation on dynamic brightness phenomena like the Broca-Sulzer effect. The Broca-Sulzer efffect refers to the observation that a flash of constant luminance but variable duration may appear brightest at some intermediate duration.

The investigation on the influence of stimulus area on the Broca-Sulzer effect is presented in Section I of Chapter 2. This effect was found to be present with large (one-deg) fields but not with point sources. This led to the conclusion that the Broca-Sulzer effect is generated by the transient channel of the visual system, the more so as the above-mentioned influence of stimulus area on the occurrence of the Broca-Sulzer effect is correctly predicted from differences in temporal impulse responses measured at threshold by means of a drift-correcting perturbation technique (Section II of Chapter 2). A description of the dynamic brightness model that enables these threshold and suprathreshold data to be unified and whose main part consists of a linear filter followed by a quasi-memoryless compressive nonlinearity is given in Section III of Chapter 2.

The results of the brightness-matching experiments presented in Chapter 2 indicate that the duration at which the Broca-Sulzer effect occurs does not show the usually reported shift as a function of flash luminance when stimuli are flashed against an extended photopic background. This has been re-examined and confirmed in an additional series of brightness-matching experiments. The results of these experiments can be found in Chapter 3. They show that the shift in duration of the Broca-Sulzer effect occurs only when there is a dark background.

In Chapters 2 and 3, a fair correspondence between model predictions and results of brightness-matching experiments has been observed. This led to the conclusion that the first part of the visual system is linear even for large amplitude changes and, hence, Bloch's law must hold at suprathreshold levels. Furthermore, it is concluded from this correspondence that the exponent of the power function, relating brightness to luminance, is independent of flash duration. Consequently, the current explanation of the shift in duration of the Broca-Sulzer effect in terms of different brightness exponents for short and long flashes must be rejected. Alternatively, the shift of the Broca-Sulzer effect observed in the dark-background condition is attributed to disturbances of the effective state of adaptation by the flashes themselves (Chapter 3). Finally, the correspondence between model predictions and experimental data suggest that the brightness exponent is larger for one-deg fields than for point sources when stimuli are presented against an extended photopic background.

The above-mentioned conclusions have been used to examine the mutual consistency of various scaling methods (Chapter 4) as well as the mutual consistency of brightness scaling and matching (Chapter 5). Chapter 4 shows that the methods of magnitude estimation and bisection yield the same brightness exponents, confirming the dependence of the brightness exponent on stimulus area as well as the independence of the exponent on flash duration. Furthermore, it is found that a third direct scaling method, viz. category scaling, produces a lower exponent than the two other methods do under similar conditions. This may be attributed to the fact that a restricted number of categories was employed. Like magnitude estimation, the method of category scaling is found to demonstrate the validity of Bloch's law at suprathreshold levels and the occurrence of the Broca-Sulzer effect.

Finally, mutual consistency of brightness scaling and matching has been investigated (Chapter 5). To this end, a direct comparison of results obtained by both methods has been made as well as a comparison between these results and predictions of the dynamic brightness model. Both kinds of comparison confirm the mutual consistency. The finding that the dynamic brightness model is able to demonstrate the mutual consistency of scaling and matching underlines once more the ability of this model to describe the brightness of time-dependent stimuli.

Samenvatting

Dit proefschrift heeft betrekking op de dynamische eigenschappen van de menselijke helderheidswaarneming. Helderheidsschalings- en gelijkstellingsexperimenten worden beschreven welke uitgevoerd zijn door een aantal proefpersonen onder dezelfde, strikt gedefinieerde experimentele condities. Een van de proefpersonen nam deel aan alle experimenten. Het voornaamste doel van de experimenten was het toetsen van voorspellingen van een dynamisch helderheidsmodel. Deze voorspellingen hadden betrekkking op de helderheid van rechthoekig geflitste eengraad velden en puntbronnen waarvan zowel de luminantie als de duur werden gevarieerd. Op een experiment na, werden de stimuli steeds aangeboden tegen een uitgebreide fotopische achtergrond waarvan de retinale verlichtingssterkte 100 Td bedroeg. Dit gebeurde met behulp van een zeskanaals-, binoculair optisch systeem waarmee de stimuli in "Maxwellian view" werden aangeboden.

In Hoofdstuk 1 wordt gewezen op de noodzaak proefpersonen expliciete instructies te geven over hun helderheidsbeoordelingen. Vervolgens wordt aangetoond dat voor dichoptisch aangeboden puntbronnen het gelijkstellen van de helderheid van flitsen van ongelijke duur nauwelijks wordt beinvloed door veranderingen in de "Stimulus Onset Asynchrony" wanneer een proefpersoon wordt verzocht om de maxima van de helderheden van de flitsen gelijk te stellen. Verder wordt geconcludeerd dat voor het onderzoek naar dynamische helderheidsfenomenen zoals het Broca-Sulzer effect gedurende helderheidsgelijkstellingsexperimenten een gelijktijdig aangaan van test en referentieflits de voorkeur verdient. Het Broca-Sulzer effect staat voor de waarneming dat een flits van constante luminantie maar variabele duur soms het helderst lijkt bij een bepaalde tussenliggende duur.

Sectie I van Hoofdstuk 2 bevat een onderzoek naar de invloed van het stimulusoppervlak op het Broca-Sulzer effect. Dit effect bleek wel bij grote (een-graad) velden op te treden maar niet bij puntbronnen. Dit leidde tot de conclusie dat het Broca-Sulzer effect wordt gegenereerd door het transiënte systeem. Dit wordt ondersteund door het gegeven dat de hierboven vermelde invloed van het stimulusoppervlak op het optreden van het Broca-Sulzer effect correct voorspeld wordt vanuit verschillen in temporele impulsresponsies welke op drempelniveau worden gemeten met behulp van een drift-corrigerende stoortechniek (Sectie II van Hoofdstuk 2). In Sectie III van Hoofdstuk 2 wordt een beschrijving gegeven van het dynamische helderheidsmodel dat het mogelijk maakt deze data, verkregen op drempel- en bovendrempelige niveau's, met elkaar in overeenstemming te brengen. Het belangrijkste deel van het model bestaat uit een lineair filter dat wordt gevolgd door een schijnbaar geheugenloze comprimerende niet-lineariteit.

De resultaten van de helderheidsgelijkstellingen welke in Hoofdstuk 2 worden gepresenteerd, geven aan dat de duur waarbij het Broca-Sulzer effect optreedt niet de normaliter vermelde verschuiving als functie van de flitsluminantie vertoont wanneer stimuli tegen een uitgebreide fotopische achtergrond worden geflitst. Dit is opnieuw onderzocht in een extra serie helderheidsgelijkstellingen. De resultaten van deze metingen staan in Hoofdstuk 3. Deze laten zien dat het verschuiven in duur van het Broca-Sulzer effect slechts optreedt wanneer een donkere achtergrond wordt gebruikt.

In de Hoofdstukken 2 en 3 werd een redelijke overeenkomst gevonden tussen predicties van het model en resultaten van helderheidsgelijkstellingen. Dit leidde tot de conclusie dat zelfs voor grote uitsturingen het eerste deel van het visuele systeem lineair is. Dit betekent dat de wet van Bloch ook bovendrempelig dient op te gaan. Verder wordt uit de gevonden overeenkomst tussen data en predicties van het model geconcludeerd dat de exponent van de machtsfunctie welke de relatie tussen helderheid en luminantie beschrijft, onafhankelijk van de flitsduur is. Dit betekent dat de huidige verklaring voor het verschuiven in duur van het Broca-Sulzer effect in termen van verschillende helderheidsexponenten voor korte en lange flitsen verworpen moet worden. Een alternatieve verklaring is dat de verschuiving van het Broca-Sulzer effect, waargenomen in de conditie met donkere achtergrond, het gevolg is van verstoringen van de effectieve adaptatietoestand door de flitsen zelf (Hoofdstuk 3). Tenslotte suggereert de overeenkomst tussen predicties van het model en experimentele data dat de helderheidsexponent groter is voor eengraad velden dan voor puntbronnen wanneer stimuli worden gepresenteerd tegen een uitgebreide fotopische achtergrond.

Vervolgens zijn de hierboven vermelde conclusies gebruikt om zowel de onderlinge consistentie van verschillende schalingstechnieken (Hoofdstuk 4) als de onderlinge consistentie van schaling en gelijkstelling (Hoofdstuk 5) te onderzoeken. Hoofdstuk 4 laat zien dat magnitudo-schattingen en bisecties dezelfde helderheidsexponenten opleveren. Beide methoden bevestigen dat de helderheidsexponent afhangt van het stimulus-oppervlak maar niet van de flitsduur. Verder wordt gevonden dat een derde directe schalingsmethode, nl. categorie-schaling, onder gelijke omstandigheden een lagere exponent oplevert dan het toepassen van de twee andere methoden. Dit kan wellicht toegeschreven worden aan het beperkte aantal categoriëen dat werd gebruikt. Evenals de magnitudo-schatting bleek categorieschaling in staat zowel de geldigheid van de wet van Bloch op bovendrempelige niveau's als het optreden van het Broca-Sulzer effect aan te tonen.

Ten slotte is de onderlinge consistentie van helderheidsschaling en gelijkstelling onderzocht (Hoofdstuk 5). Daarvoor zijn resultaten, verkregen met beide methoden, niet alleen rechtstreeks met elkaar vergeleken maar ook met voorspellingen van het dynamische helderheidsmodel. Beide vergelijkingen bevestigen de onderlinge consistentie. Het gegeven dat het dynamisch helderheidsmodel in staat is de onderlinge consistentie van schaling en gelijkstelling aan te tonen, onderstreept nogmaals de mogelijkheid de helderheid van tijdafhankelijke stimuli te beschrijven met behulp van dit model.

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Nawoord

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Stellingen

I

Uit het feit dat in bepaalde gevallen de duur waarbij het Broca-Sulzer effect optreedt korter wordt naar mate de flitsluminantie toeneemt, concludeert Stevens (1966) ten onrechte dat de helderheidsexponent groter moet zijn voor kortdurende dan voor langdurende stimuli.

Stevens, S.S. (1966)
Duration, luminance, and the brightness exponent. Perception and Psychophysics, 1, 96-100.

II

Het schema van Mansfield (1973) is een onjuiste weergave van de invloed van duur en oppervlakte op de helderheidsexponent en dient derhalve niet meer te worden gebruikt.

Mansfield, R.J.W. (1973)
Brightness function: Effect of area and duration. Journal of the Optical Society of America, 63, 913-920.

III

Het ontbreken van het Broca-Sulzer effect bij het gelijktijdig aangaan van test- en referentieflits gedurende helderheidsgelijkstellingen van puntbronnen duidt niet op een experimenteel artefact maar betekent dat het Broca-Sulzer effect niet optreedt bij puntbronnen.

Naus, D.A. (1971)
A case for the short flash- a realistic equivalent fixed intensity calculation for flashing point sources. In: The perception of flashing lights. Adam Hilger Ltd, London.

IV

De conclusie van Osaka (1981) dat bij relatief kortdurende flitsen de helderheidsexponent afhangt van de flitsduur, is strijdig met de geldigheid van de wet van Bloch op bovendrempelige niveau's.

Osaka, N. (1981)
Brightness exponent as a function of flash duration and retinal eccentricity. Perception and Psychophysics, 30, 144-148.

V

Gezien de onderlinge consistentie van bisectie en magnitudo-schatting bij helderheidsschaling, vervalt het al dan niet optreden van een lineair verband tussen resultaten verkregen via interval- en ratio-schaling als criterium bij het classificeren van sensorische continua als metathetisch resp. prothetisch.
Marks, L.E. (1974)
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VI

Zo lang geen rekening wordt gehouden met het bestaan van minimaal twee temporele kanalen in het visuele systeem, blijft het afleiden van impulsresponsies uit de Lange-krommen tijdverspilling.
Stork, D.G., Falk, D.S. (1987)
Temporal impulse responses from flicker sensitivities. Journal of the Optical Society of America A, 4, 1130-1135.

VII

Om kinderen met taalproblemen zo vroeg mogelijk te signaleren, dient reeds vanaf de eerste levensmaanden de communicatieve ontwikkeling van een kind regelmatig tijdens het bezoek aan het consultatiebureau te worden gevolgd.

VIII

Voor een beter begrip van een psychologische theorie is het aan te bevelen om de biografie van de grondlegger te bestuderen.

IX

Wanneer menselijk gedrag wordt toegeschreven aan het onbewuste, gebeurt dat bewust.

H. de Ridder

Eindhoven, 13 oktober 1987