IV

ADDITION PHENOMENA IN VISION AND HEARING

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Studies on the threshold perception – first in the field of vision, later also in the field of hearing – have been a substantial part of the Institute's research programme from the beginning. Since only a few investigators had experience in both fields, an attempt to compare methods and results has never been made. The present author, one of these happy few 'amphibions', has tried here to synthesize his studies on addition in both fields and to relate Ricco's critical area in vision to the critical bandwidth in hearing in particular.

For more detailed information on both experimental procedures and results the reader is referred to the publications 13, 21, 53, 133, and 134 of the cumulative bibliography.

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

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

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

Ricco's law and the critical band

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

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

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

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

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

Threshold versus stimulus duration

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

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

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

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

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

Experiments on visual and auditive addition

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

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

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

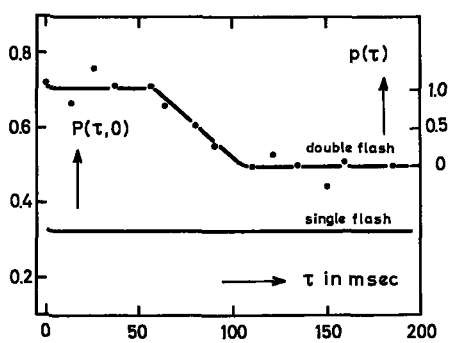


Fig. 1. An example of a measurement of the probability of seeing $P(\tau,o)$ as a function of the interval τ between two flashes. The right hand scale gives the chance of addition $p(\tau)$ according to the transformation formula (7° nasally, dark adapted eye, $\lambda = 510$ nm).

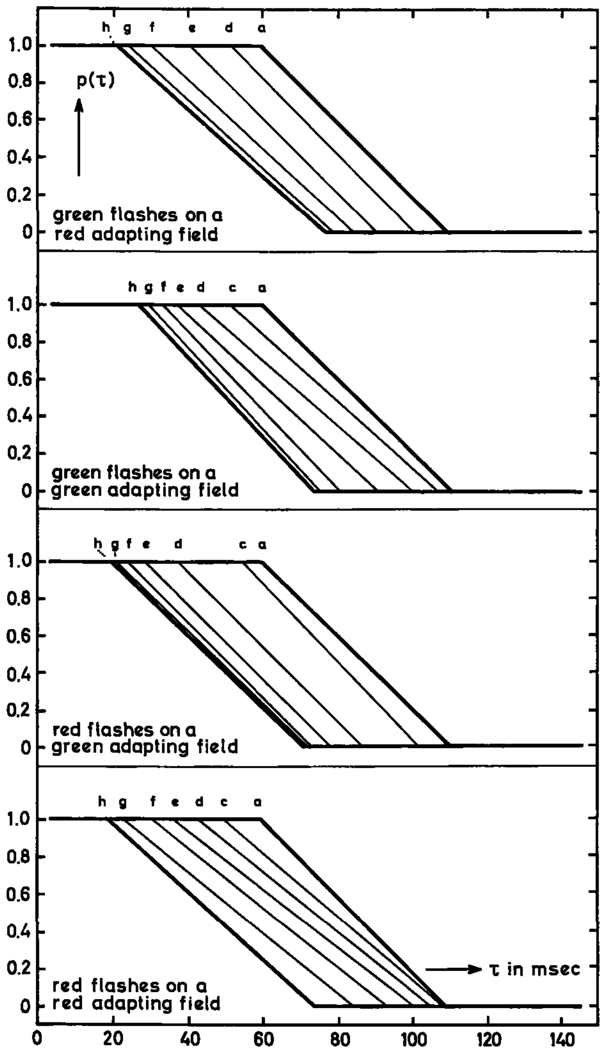


Fig. 2 left: The chance of visual temporal addition $p(\tau)$ for luminances ot the background and for various wavelength combinations of test flash and background at 7° nasally. Smoothed results from Van den Brink and Bouman (1954).

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

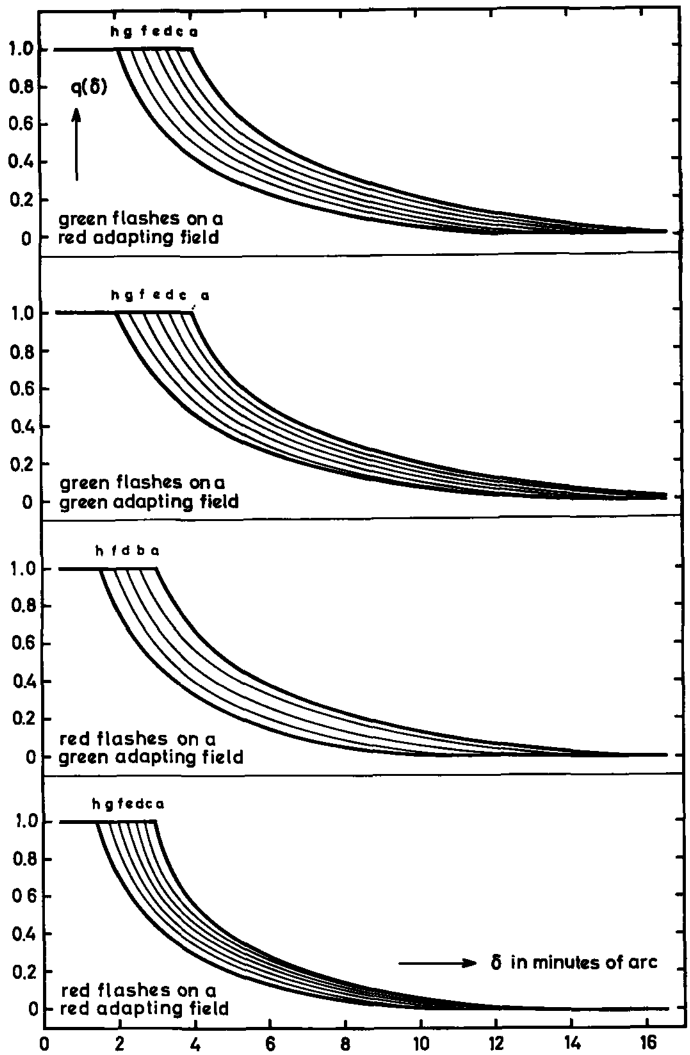


Fig. 2 right: Spatial addition under the same circumstances.

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

The most important results are:

1. For the dark-adapted eye, there is maximum addition of subliminal effects up to 60 msec, and no addition for intervals exceeding 110 msec. The addition functions are equal for rod and cone vision and are independent of the place on the retina, including the fovea.

2. Spatial addition appears to depend upon the place of the retina as well as upon the kind of receptors stimulated. For rod vision ($\lambda = 510$ nm) we found maximum addition up to about 4′ and no addition for distances exceeding about 20′ in the dark-adapted eye. For cones ($\lambda = 620$ nm) these angles are about 3′ and 15′, respectively, at 7° nasally. The values decrease with decreasing eccentricity.

3. Measurements with one red flash and one green flash result in similar functions, intermediate between those measured with either two green flashes or two red flashes. This demonstrates complete interaction between the rod and the cone systems as far as addition is concerned.

4. Measurements with a continuously present background, either red or green, show that $p(\tau)$ as well as $q(\delta)$ shift to lower values of τ and δ, respectively, with increasing luminance of the background. It might be interesting to repeat this experiment for different states of adaptation without simultaneous presentation of a background, in order to decide whether this effect is a contrast or an adaptation phenomenon.

5. In the fovea spatial addition occurs over a much smaller area than in the periphery. No significant differences are found either between the results with red and green flashes or between the results with or without a background. This may mean that the shape of this curve is rather due to diffraction, to aberrations in the optical system of the eye or to stray light, than to neural interaction (see also Ogle, 1962). In our opinion, this can not be the case with the results obtained in the periphery of the retina.

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

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

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

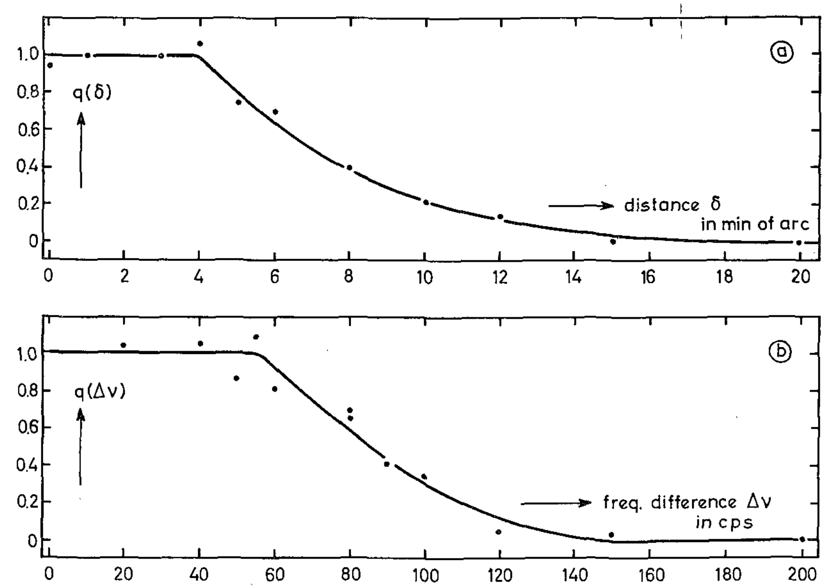


Fig. 3a. Visual spatial addition q (δ) as a function of the distance δ between two flashes (7° nasally, dark adapted eye, $\lambda = 510$ nm).
3b. Auditive addition q ($\Delta\nu$) as a function of the frequency difference $\Delta\nu$ between two tone pulses ($\nu = 800$ cps).

Other procedures for critical band determination

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

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

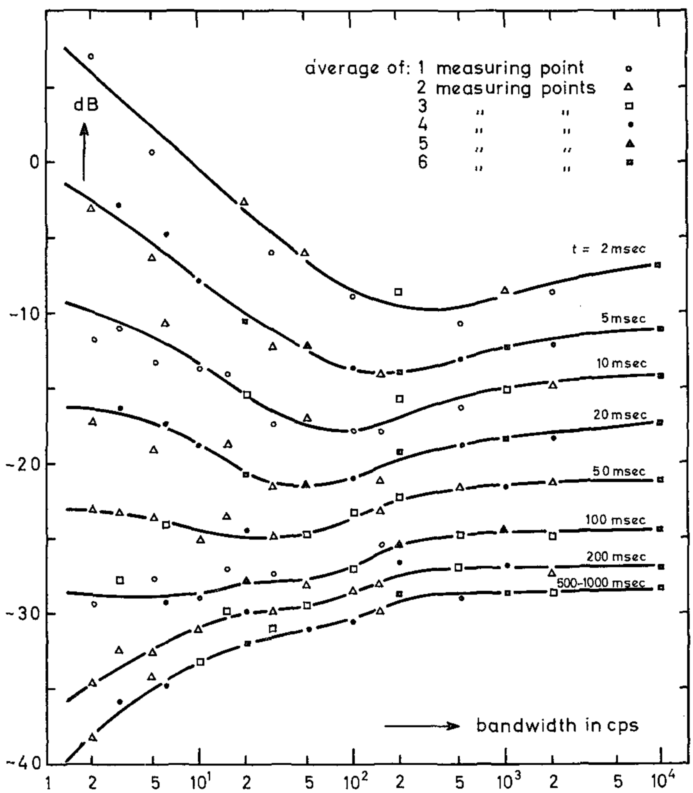


Fig. 4. Noise masked auditive threshold as a function of the bandwidth of the masking noise for various tone pulse durations (ν = 800 cps).

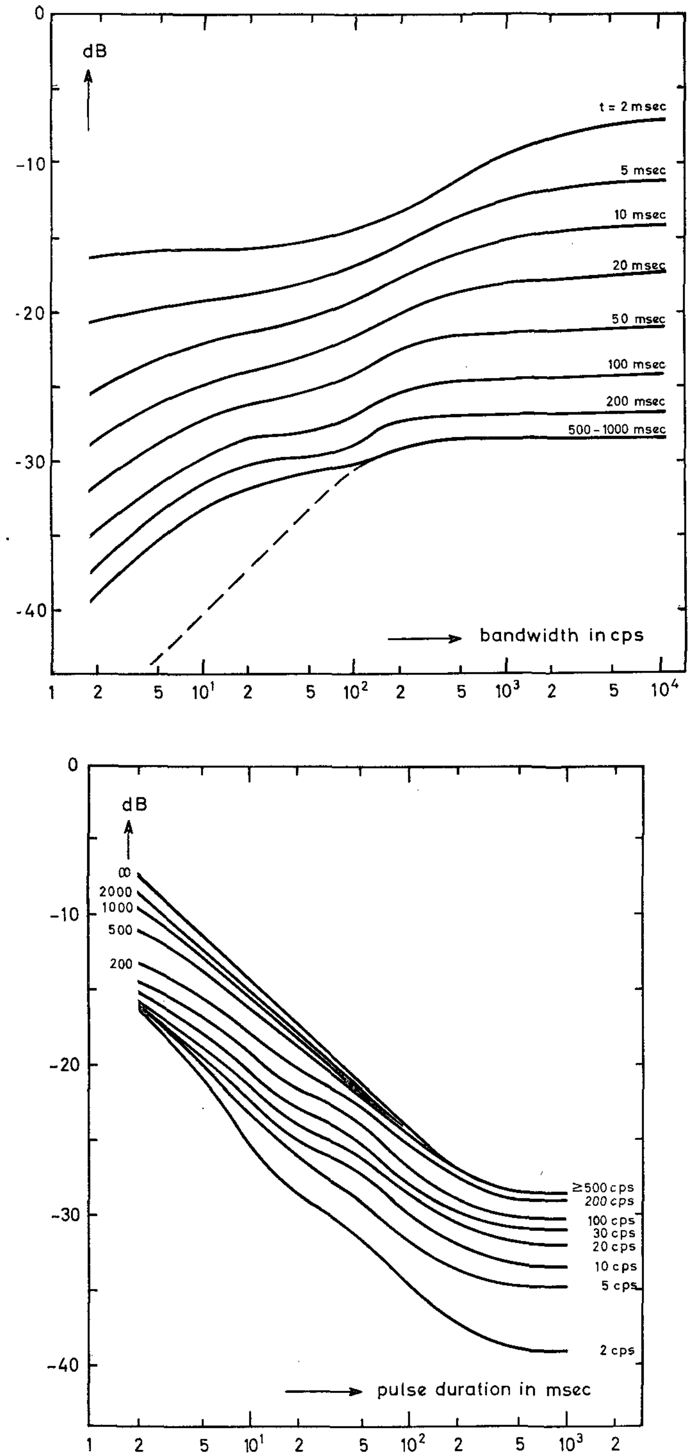
den Brink, 1964a). For details of the method used in this study we refer to this publication. It may be mentioned only, that filters were used in a bandwidth range between 2 and 2000 cps for the masking noise. The side slopes of the filters were more than 100 db per octave. Noise, filtered in this way,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

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

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

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

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



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

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

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

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