

THE DEPENDENCE OF BEZOLD-BRÜCKE HUE SHIFT ON SPATIAL INTENSITY DISTRIBUTION

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INTRODUCTION

THE FACT that the apparent hue of saturated colours depends slightly on luminance was discovered independently by VON BEZOLD (1873) and BRÜCKE (1878). They gave a qualitative description of the phenomenon occurring when one observes the total spectrum. Later, this has been studied quantitatively by PURDY (1931, 1937) who compared two monochromatically illuminated fields. He determined the wavelength difference between the two fields needed for equal apparent hue when the fields have two fixed but different luminances. This wavelength difference is a measure for the Bezold-Brücke effect. It depends, as he found, on the luminance of the two fields and on the region of the spectrum involved. Only at three points in the spectrum, 476, 508 and 570 nm, is the phenomenon absent.

More recent quantitative studies were made by BOYNTON and GORDON (1965), in which they used a forced-choice colour naming technique. A theoretical analysis of the effect was made by WALRAVEN (1961, 1962), on the basis of Pitt's fundamental response curves and certain assumptions regarding saturation in the stimulus-response relation for each of the colour mediating systems.

We made measurements similar to those of Purdy. However, because of the possible influence of lateral inhibition on such saturation effects we introduced systematic variation of the size of the visual field as an extra parameter. Such a parameter also seems relevant because of analogous studies on apparent brightness. Indeed, the relation between apparent brightness and luminance, changes from a power function with exponent $\frac{1}{2}$ to one with exponent $\frac{1}{3}$, when the size of the visual field is increased from a few minutes of arc to over a few degrees (STEVENS and GALANTER, 1957).

In this paper measurements on the Bezold-Brücke hue shift are presented for stimulus fields consisting of two half fields, of various spatial frequencies, and of two circular fields, one with a variable diameter. The results are discussed in terms of the hypothesis that apparent brightness is the crucial factor for apparent hue. Predictions based on a model for lateral inhibition from VON BÉKÉSY (1960) are compared with the experimental facts.

PROCEDURE AND ARRANGEMENTS

For our experiments two stimuli of different luminances and different wavelengths must simultaneously be presented on either adjacent or, occasionally, remote areas of the retina. In Fig. 1 a scheme of the experimental setup is presented. At the location of G the

subject observed either a grating on which reflecting and transparent bars alternate, or two half-fields, or two separate circular fields.

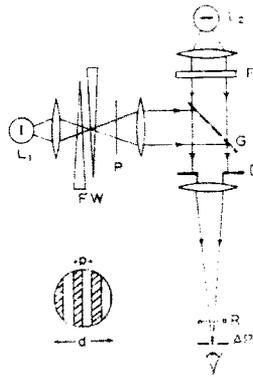


FIG. 1. Experimental arrangement to measure the Bezold-Brücke hue shift with several stimulus patterns as described in the text (not to scale).

The period of the grating and the diameter of the total visual field of the two half-field test target were parameters. In the case of the two circular fields, the size of one of them was varied as a parameter while the other one was constant and acted as reference. The luminances of the stimuli were varied by current strengths through the incandescent light sources L_1 and L_2 . The wavelength of the light from L_1 was continuously variable by two oppositely moving interference filter wedges (FW), for L_2 various single interference filters were used. The polaroid P eliminated reflection of the light from L_1 on the transparent parts of G. In Fig. 2 the various stimulus conditions are shown. With the grating (b) measurements were made for various periods which are indicated as degrees of visual angle. With the two half fields (a) measurements were made for sizes of the test field between 0.2 and 1.5 degrees. With the two separate circular fields (c) the reference had a size of 1.2 degrees, the other one was varied in diameter between 0.2 and 1.2 degrees.

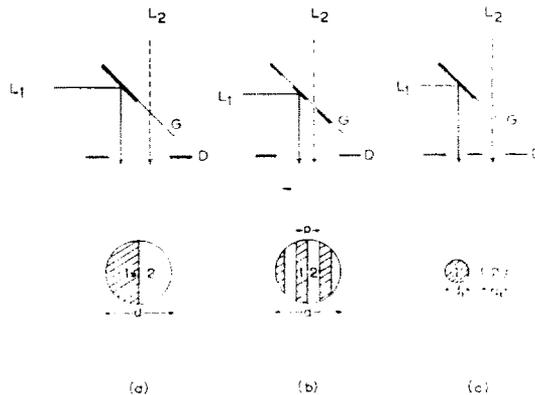


FIG. 2. The combinations of grating G and diaphragm D (see Fig. 1) with the visual fields to match.

Each measurement, except for the condition *c* (Fig. 2), started with a brightness match by the observer for equal λ_1 and λ_2 of the two stimuli from L_1 and L_2 . Afterwards the luminance in the L_2 beam was increased by a factor between 1.7 and 10. The observer now changed the position of the interference wedge until the hues of both stimuli matched. In case the difference between λ_2 and the new λ_1 was so large that, relative to the luminance step, the change in spectral sensitivity of the test subject became significant, appropriate corrections were made for L_1 and a new match in hue was taken. In condition *c* (Fig. 2) the λ -differences needed for a match in hue between fields of different diameter, but equal either in luminance or in apparent brightness, were also determined.

To prevent errors caused by the Stiles-Crawford effect, precautions were taken so that the light beam passed through the central area of the pupil. To accomplish this an illuminated narrow ring *R* (Fig. 1) of large diameter was used concentric with the optical axes. The eye position is correct when the ring is just invisible. With improper alignment some part of the ring is visible, hence the observer can correct his position.

The subject observed the stimuli in Maxwellian view through an artificial pupil (AP) with a diameter of 1 mm.

All brightness values are given in relative units: $B_1=1$. The absolute value of the brightness B_1 is a few hundred photopic trolands.

EXPERIMENTAL RESULTS

There are two main features to be distinguished in the results as presented in Figs. 3 and 4.

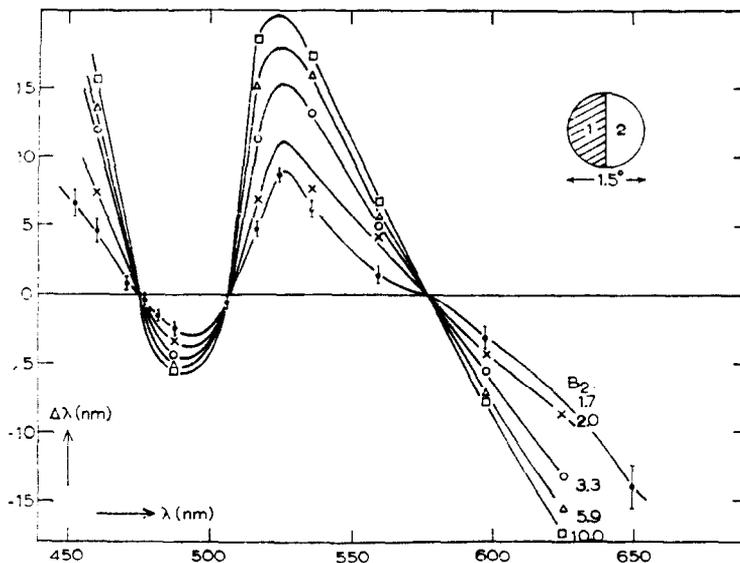


FIG. 3. The wavelength difference $\Delta\lambda$ corresponding to the Bezold-Brücke hue shift caused by several values of the luminance B_2 of field 2 as a function of the wavelength λ . Two half circular fields are used. The diameter of the total circular visual field was 1.5 degrees (visual angle). B_2 is given in relative units ($B_1=1$). Each point is the mean of at least three measurements.

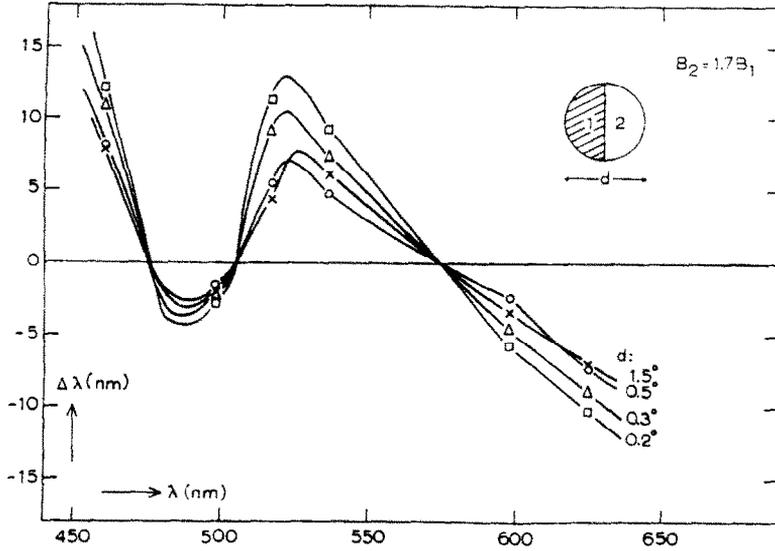


FIG. 4. The wavelength difference $\Delta\lambda$ corresponding to the Bezold-Brücke hue shift caused by an increase of the luminance by a factor 1.7, as a function of the wavelength λ for several diameters (d) of the visual field. d is expressed in degrees of visual angle. Each point is the mean of at least three measurements.

1. The locations in the spectrum of the three wavelengths at which the Bezold-Brücke hue shift is absent, are invariant despite variations in geometrical relations in the visual field. 2. The decrease of the diameter of the visual field has the same effect on the amount of hue shift as an increase of luminance difference between the two half fields. From recent measurements by LURIA (1967) we also know that an increase of temporal frequency,

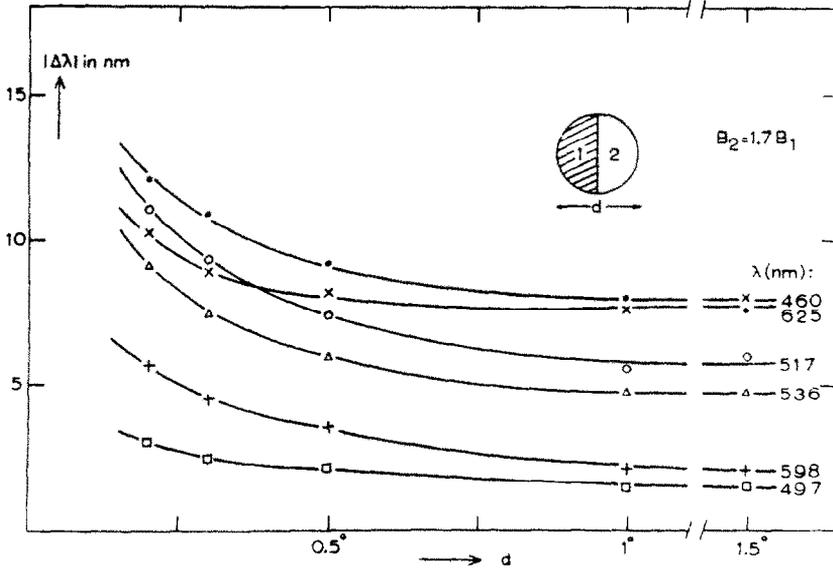


FIG. 5. The absolute value of the wavelength difference $\Delta\lambda$ vs. the diameter of the visual field using a stimulus of two half circular fields, for several wavelengths.

as obtained by a decrease of the time of presentation, has effects on hue that are analogous to the influence of luminance increase. However, Luria made his experiments by means of colour-naming techniques so the results are not quantitatively comparable with those presented in this paper.

In the Figs. 5, 6 and 7 the absolute values of the wavelength difference corresponding to the hue shift are shown as a function of a fixed increase of B_2 (by a factor of 1.7) and changes in the geometry of the several stimulus patterns.

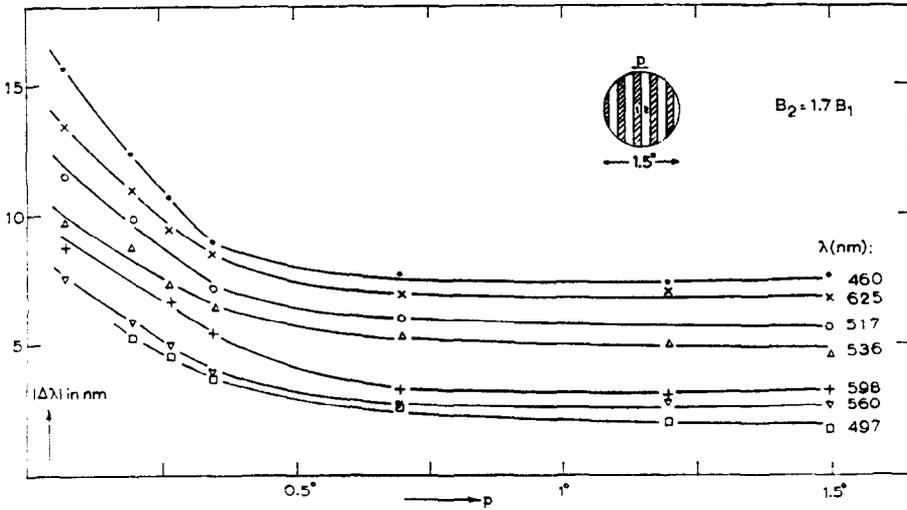


FIG. 6. The absolute value of the wavelength difference $\Delta\lambda$ vs. the period, p , of a grating of alternately rectangular light and dark bars of equal width, for several wavelengths.

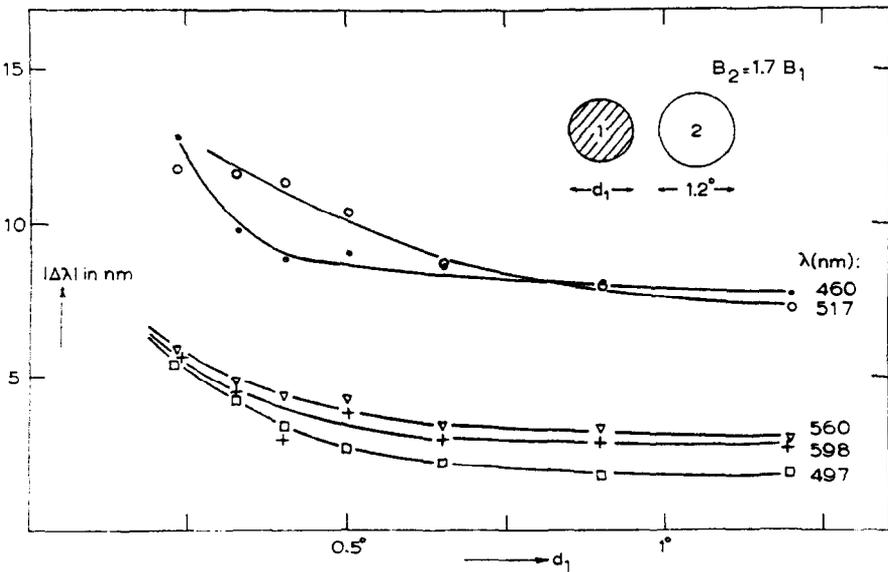


FIG. 7. $\Delta\lambda$ vs. the diameter of field 1 for several wavelengths. Field 2 is used as reference. Two separated circular fields, of different fixed luminances are used as stimuli.

DISCUSSION AND THEORETICAL ANALYSIS

In view of the conformity of the set of curves obtained for several luminance ratios and those obtained for several dimensions of the stimulus, we start from the assumption that there must be a relation between them such that, for instance, a decrease in the size of the visual field introduces an increase in the apparent brightness ratio of the stimuli which in turn causes a change in the hue shift. It appears in Fig. 5, 6 and 7, that for larger values of the geometrical parameters the wavelength difference is nearly constant, while for smaller values it increases, although the luminance difference in the stimulus stays constant.

If this increase of hue shift is caused by a change in apparent brightness difference there must also be an increase of brightness difference due to a decrease of the diameter of the field or of the period of the grating. There is something which could be responsible for this, namely the phenomenon of the Mach bands [RATLIFF (1965), MATTHEWS (1966)]. In Fig. 8 we show schematically the response to a rectangular shaped luminance pattern. The bands are present only in the neighbourhood of a change in the luminance and consist of an increase in brightness contrast.

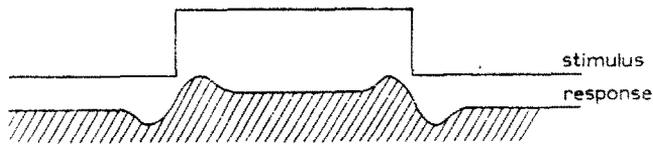


FIG. 8. Response to a rectangular shaped brightness pattern (schematic).

When the period of a rectangular grating with alternately light and dim bars is decreased, i.e. the width of the bars becomes smaller, the Mach bands could overlap each other resulting in an increase of brightness of the light bars and a decrease of the brightness of the dark bars. This fits in with our assumption.

To make a more quantitative comparison of this hypothesis with the experimental data, it is possible to construct Mach bands by means of a model of lateral inhibition described by VON BÉKÉSY (1960) as a "neural unit." In Fig. 9 (a) such a neural unit is given schematically. The stimulus produces an area of sensation and a refractory area in which a neighbouring stimulus is inhibited.

A simplified pattern of the neural unit is shown in Fig. 9 (b). S and R are the area respectively of sensation and inhibition. With this rectangular neural unit it is possible to construct the response to a stimulus as given in Fig. 9 (c) in the manner described by von Békésy. This is as follows: the stimulus pattern is sliced into vertical sections of the width of the sensation area of the neural unit and the sum of the refractory areas is subtracted from the sum of the sensation magnitude.

Similarly it is possible to construct the response to a one-dimensional periodic luminance distribution such as given by the gratings.

To ensure that the overlap of the Mach bands begins at the same values of the period, p , for which the increase of the hue shift starts, we take for the width, r , of the refractory area of the neural unit of von Békésy (see Fig. 9 (b)) the value of 4 min of arc. Von Békésy found an $r=12$ min of arc. Our value, however, is more in agreement with those found by BAUMGARTNER (1960), KORNHUBER and SPILLMAN (1964), GLEZER (1965), BRYNGDAHL (1964, 1966). They found for the diameter of the receptive fields (neural units) in the fovea

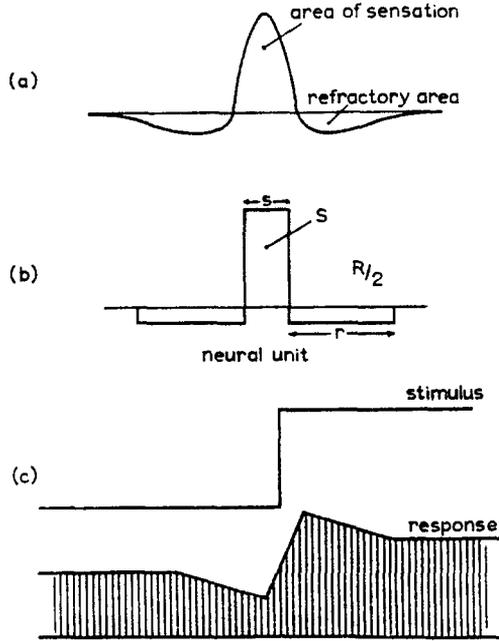


FIG. 9. (a) Neural unit, (b) a simplified version of the neural unit, (c) the response to a step-function in brightness, constructed by means of the simplified neural unit (b).

of the human eye values between 4 and 5.5 min of arc. From the responses constructed with this corrected neural unit of von Békésy, we can determine the apparent brightness difference between the bright and the dim parts as a function of the period.

The results are given in Fig. 10. In order to compare these results with the experimental data, the following procedure was used.

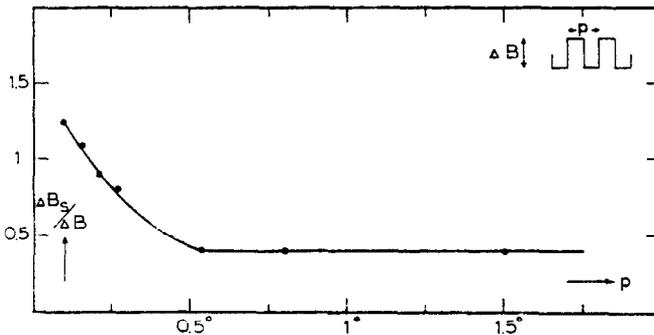


FIG. 10. ΔB_s is the subjective brightness difference calculated by means of the neural unit of von Békésy, for a rectangular grating of alternative light and dark bars with a luminance difference between the light and dark bars ΔB , and several periods p . p is given in degrees of visual angle.

From Fig. 3 we obtained the relation between the hue shift $\Delta\lambda$ and B_2 by making vertical cross sections for different wavelengths (see Fig. 11). We used the stimulus of two

half-fields since, with them, there can be no question of an influence of Mach bands on the subjective brightness differences.

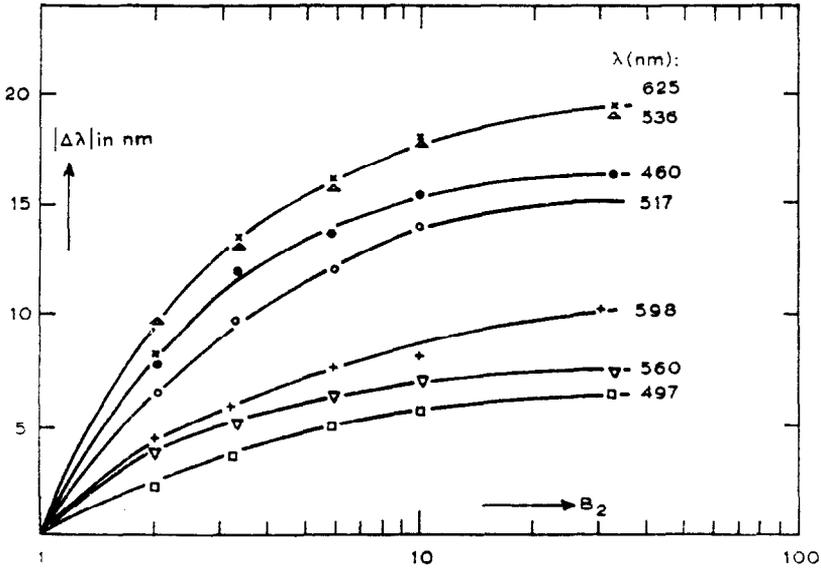


FIG. 11. The wavelength difference $\Delta\lambda$ (absolute value) corresponding to the Bezold-Brücke hue shift as a function of the luminance B_2 (rel. units; $B_1=1$) for several wavelengths.

Now it is possible to obtain from Fig. 11 the values of luminance difference, B_2-B_1 ($B_1=1$), necessary to explain the increase of the hue shift as a function of the grating period p (see Fig. 6) in the absence of an apparent brightness enhancement due to the

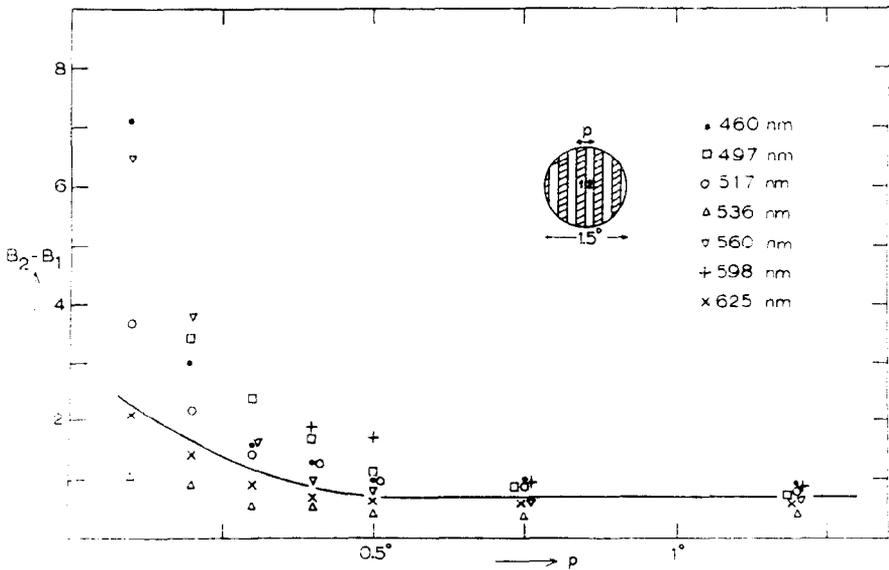


FIG. 12. Luminance difference needed to cause the same hue shift in the two half-fields (obtained from Fig. 11), as measured for the grating with variable periods. The curve is theoretical.

Mach bands. The data obtained in this manner are given in Fig. 12 for several wavelengths. The curve is the theoretical one from Fig. 10 except that it is normalized to agree with the data for the large periods. As is evident from this figure, the theoretical curve has the same general shape as the curve constructed from the measurements of the hue shift.

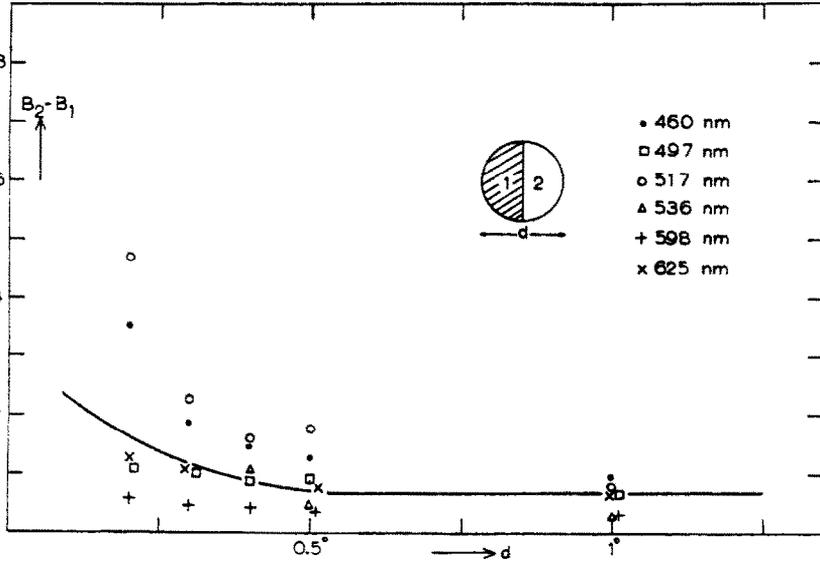


FIG. 13. Luminance differences which produced, for a large field diameter (1.5°), the same hue shift as measured for several smaller diameters, compared with the theoretical curve for the gratings when $p=d$.

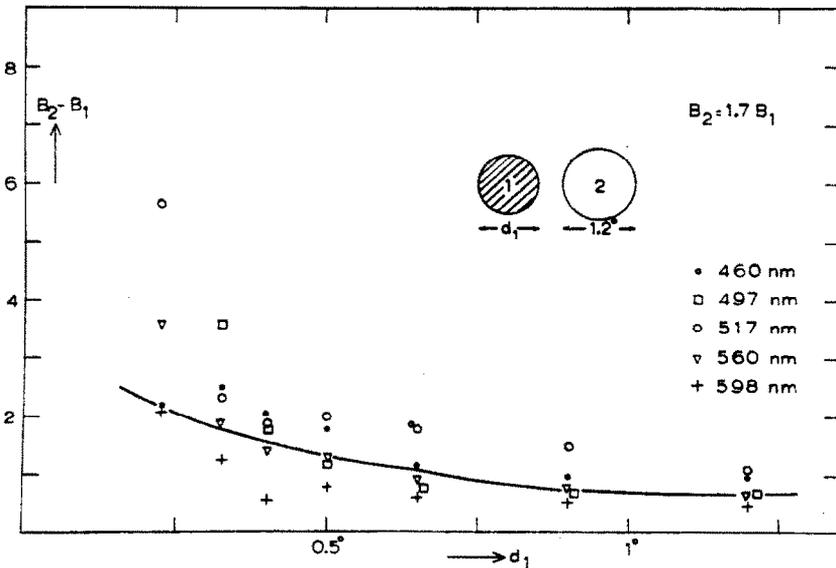


FIG. 14. Luminance differences which produced, for a large field diameter (1.5°), the same hue shift as measured for several smaller diameters when $B_2 - B_1 = 0.7$. The curve is the theoretical one from Fig. 10 when $p = 2d_1$.

The experimental data, however, show a dependency on wavelength. For instance, for $\lambda=460$ nm, the increase of the hue shift caused by diminishing the period of the grating is larger than that which can be expected from the effect of the Mach bands. There are several possible explanations for this. In the first place we have constructed the Mach bands by means of a very simplified model of a neural unit assuming an independence, in these Mach bands, of brightness and wavelength, while WATRAWIEWICZ (1966) has found a relation between the Mach bands and these very parameters. Secondly, we compared (Fig. 12) intensity with a sensation magnitude using a linear relation between them.

In the Figs. 13 and 14 the theoretical curve is compared with experimental data obtained with the stimulus with two half-fields and the two separated circular fields respectively. In Fig. 13 the data for a fixed diameter of the visual field is compared with the value of the theoretical curve for a period equal to this diameter. In Fig. 14 the period of the theoretical curve is correlated with twice the diameter of the circular field. While the theoretical curve was calculated for a grating, it also concurs with the experimental data from the two other stimulus patterns.

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Abstract—Measurements on the influence of the geometrical proportions of the stimulus on the Bezold-Brücke hue shift are reported. The hue shift is measured by a comparison of the colour of two fields, illuminated by monochromatic lights of different intensity. Various two-half field arrangements and gratings are used as stimuli.

For each of the patterns the Bezold-Brücke hue shift showed an increase with a decrease of the geometrical parameter, i.e. field diameter or bar-width. In explaining the results, it is assumed that a decrease of the geometrical parameter results in an increase of apparent brightness difference which, in turn, produces an increase of apparent hue difference. The experimental data were compared with theoretical predictions made with the aid of a model of the 'neural unit' of von Békésy.

Résumé—On mesure l'influence des proportions géométriques du stimulus sur le décalage de tonalité de Bezold-Brücke. Ce décalage est déterminé par comparaison de la couleur de deux champs, éclairés par des lumières monochromatiques d'intensité différente. On utilise comme stimuli divers arrangements de champs bipartite et des réseaux.

Pour chacun de ces tests le décalage de Bezold-Brücke augmente quand diminue le paramètre géométrique, c'est-à-dire le diamètre du champ ou la largeur des traits. On explique ces résultats en supposant que la diminution du paramètre géométrique a pour résultat d'augmenter la différence apparente de luminosité, ce qui produit de ce fait un accroissement de la différence apparente de tonalité. On compare les données expérimentales avec les prédictions théoriques fondées sur le modèle de l' "unité neurologique" de von Békésy.

Zusammenfassung—Es wird über Messungen zum Einfluß der geometrischen Abmessungen des Reizes auf die Brücke-Bezold'sche Farbtonverschiebung berichtet. Die Farbtonverschiebung wird durch Vergleich der Farben zweier Felder gemessen, die durch monochromatische Lichter unterschiedlicher Intensität beleuchtet werden. Verschiedene DoppelHalbfeldanordnungen und Gitter werden als Reize verwendet.

Für jedes der Muster zeigte die Farbtonverschiebung eine Zunahme, wenn die geometrischen Parameter abnahmen; so z.B. der Gesichtsfelddurchmesser oder die Balkenbreite. Bei der Deutung der Ergebnisse wird angenommen, daß eine Abnahme bei den geometrischen Parametern eine Zunahme in der scheinbaren Helligkeitsdifferenz bewirkt, die ihrerseits einen Zuwachs in der scheinbaren Farbtonverschiebung hervorruft. Die experimentellen Werte wurden mit theoretischen Voraussagen verglichen, die mit Hilfe eines Modells der "Neurologischen Einheit" von von Békésy, gewonnen wurden.

Резюме — Сообщается о влияниях, которые оказывают геометрические пропорции стимула на сдвиг в восприятии цветового тона (феномен Бецольда-Брюкке). Сдвиг измерялся путем сравнения цвета двух полей, освещаемых монохроматическим цветом различной интенсивности. В качестве стимулов были использованы различные величины двух половин поля и различные решетки.

Для каждого из паттернов сдвиг цветового тона Бецольда-Брюкке увеличивался с уменьшением геометрического параметра, т.е. диаметра поля или ширины полосы. При объяснении результатов предполагается, что уменьшение геометрического параметра проявляется в увеличении видимого различения светлоты, которое, в свою очередь, вызывает увеличение видимого различия цветового тона. Экспериментальные данные были сопоставлены с теоретическими предсказаниями делаемыми с помощью модели «неврона», предложенной Бекешы.