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THE EFFECT OF BACKGROUND LUMINANCE ON THE BRIGHTNESS OF FLASHES

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INTRODUCTION

IF A SPOT of light, of luminance ΔI, is added to a large steady background of luminance I, the smallest value of ΔI at which the spot is visible is the "increment threshold". We know that increasing I raises the increment threshold. We can also measure the brightness[2] of a superthreshold increment by, for example, comparison with a reference stimulus in the other eye. It is not immediately obvious what effect increasing I will have on the brightness of a constant increment ΔI. SCHOUTEN and ORNSTEIN (1939) assumed that the brightness would increase because the background luminance would add to that of the superimposed light. However, FRY and ALPERN (1953) showed that the brightness of a superimposed light decreases. Thus the background reduces the sensitivity of the visual system, whether sensitivity is measured with a threshold or a superthreshold criterion. But what is the exact relationship between the threshold and superthreshold effects? This question is relevant to a number of long-standing problems in sensory psychology: in general to the relation of data on thresholds to the perception of superthreshold stimuli, which are after all the rule both in everyday vision and in physiological experiments; and in particular, to von Kries' "Law of Coefficients", to "automatic gain control" models of adaptation (e.g. RUSHTON, 1965), and to "simultaneous contrast".

There is already evidence that the relation of superthreshold to threshold effects is not the simplest possible: attenuation of all inputs by a constant factor. For instance, STEVENS and DIAMOND (1965) showed that an intense peripheral source of glare raised the threshold ΔI (for steady lights) by a larger factor than it raised the value of ΔI required for a given superthreshold brightness. Since glare acts by producing a background of scattered light in the eye (RUSHTON and GUBISCH, 1966), we may expect that measurements of the brightness of flashes on uniform backgrounds will show the same effect.

One of the simplest situations in which to study the relation between threshold and superthreshold effects is that in which a small short test flash is added to a large steady background. The use of short flashes avoids complications associated with adaptation to the test stimulus. Further, although objects in our natural environment do not often flash on or off for 200 msec (the duration we used), eye-movements cause their retinal images

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[2] We shall use the word "brightness" to refer to the sensation. The physical quantity is "luminance".

to do so. Most fixations last between 100 and 800 msec (e.g. YARBUS, 1965). The results of brightness measurements of flashes with durations within that range do not differ appreciably, in regard to the features we shall discuss, from those presented here.

We have therefore measured for a wide range of background luminances, both the increment threshold and, by interocular brightness matching, the luminances required to produce various different brightnesses. The experiments reported here are restricted to increment flashes, in cone vision and achromatic light, of one size, duration and position on the retina.

METHODS

Choice of display

Making a brightness match between patches on backgrounds of different brightnesses is a subjectively difficult task, both for flashes and for steady lights. BURGH and GRINDLEY (1962) report the comments of some subjects. Thinking that this difficulty may have been responsible for some of the problems in the literature on brightness contrast, we have used a display in which matching is subjectively easier than usual. This display is shown in Fig. 1. Its unusual feature is that the two monocular backgrounds, generally of different luminances, are seen superimposed in the binocular field rather than, as is more usual, side by side. The test patches thus appear to be on the same background, a binocular mixture of the separate monocular backgrounds. This type of display has been used previously by PITT (1939), and FRY and ALPERN (1953, 1954). It introduces the complication that each patch is seen through the contralateral background. In the second part of this paper we discuss to what extent this is a serious complication.

This display not only makes matching subjectively easier, but also produces an important simplification in the results. It is convenient to describe only experiments with increment flashes, because our procedure for decrements (that is, light taken away from the background) was different, but the real justification is empirical: with this display, our subjects never made a brightness match between an increment and a decrement. Even a weak increment on a dark background looked brighter than the weakest decrement on a very bright background. It can be objected that the present experiments do not provide convincing evidence of this, because the apparatus was usually set for increments in both eyes, so that subjects did not have a free choice. However, in earlier experiments with the same display (but with steady lights) we did give this free choice. The subjects controlled the luminance of a patch that could be made either dimmer or brighter than its surround, and we were careful not to bias them in favour of either. In these experiments no subject, neither naive nor sophisticated, ever matched an increment in one eye with a decrement in the other, for any combination of luminances. Essentially the same observation was made by ASHER (1950) with a similar display. We have not critically tested this result with flash stimuli, but have assumed that since increments and decrements appear more strikingly distinct as flashes than as continuously visible stimuli, the result would hold for flashes too. In a large number of subsequent experiments with flashes we have found no reason to doubt this assumption.

Several lines of evidence, both psychophysical and electrophysiological, suggest that the brightness of a uniform region is determined by neural activity arising in or near the retinal image of its edge. The separation of increments and decrements fits this idea well, since they are qualitatively distinct (as steady lights) only at their edges. More generally, we can say that the visual system responds primarily to spatial and temporal transients. The perception of the test patch will depend on its own transients, and therefore, to obtain the simplest results, only those should be present. This is our reason for presenting the test stimulus as a small flash on a uniform background.[3,4]

The clear separation between increments and decrements is not usually obtained with the displays commonly used in studies of simultaneous contrast the (effect of the luminance of a surround on the brightness of a patch). In these studies the backgrounds of the test and comparison stimuli are usually side by side in the binocular field (see Discussion). Nor, of course, is it obtained when the test patch has a non-uniform surround, even when the surrounds are binocularly superimposed (e.g. HOREMAN, 1963; SAUNDERS, 1968). Indeed, for steady lights the terms "increment" and "decrement" are hardly relevant in the absence of a uniform

[3] This procedure cuts across the traditional distinction between "adaptation" and "contrast". But these concepts, at any rate in the senses in which they are often understood, are the wrong ones to use in thinking about perceived brightness, if it is the spatial and temporal transients which are all-important. For instance, they suggest experiments in which, to isolate "adaptation", an adapting light is switched off just before a test light is presented. Correspondingly, in space, a "contrast inducing" field is not allowed to overlap the test patch. But these procedures, while necessary for answering some questions, provide the preceding or neighbouring stimuli with transients of their own, and so lead to a more complicated situation, which will be harder to understand, than one in which the only transients present are those of the test stimulus.

[4] The approach in terms of increments and decrements, and the separation between them, are not new. They date back at least to the work of HERING (e.g. 1920).

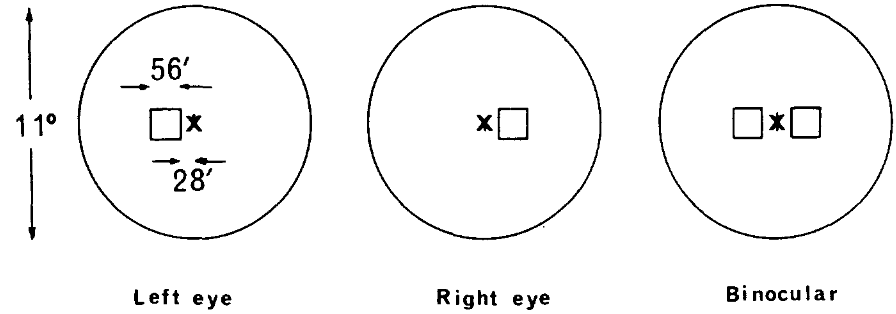

FIG. 1. The display used for the main experiments.

surround, and the probable dependence of brightness on the luminance step at the edge of the patch suggests that a non-uniform surround would not yield simple results.

To summarise, two features of the display in Fig. 1 are important. (1) The patches have uniform backgrounds. (2) The backgrounds are binocularly superimposed. A third feature may also be important: (3) The patches are far enough apart to minimise binocular interaction between their contours, a possibility that is well documented.

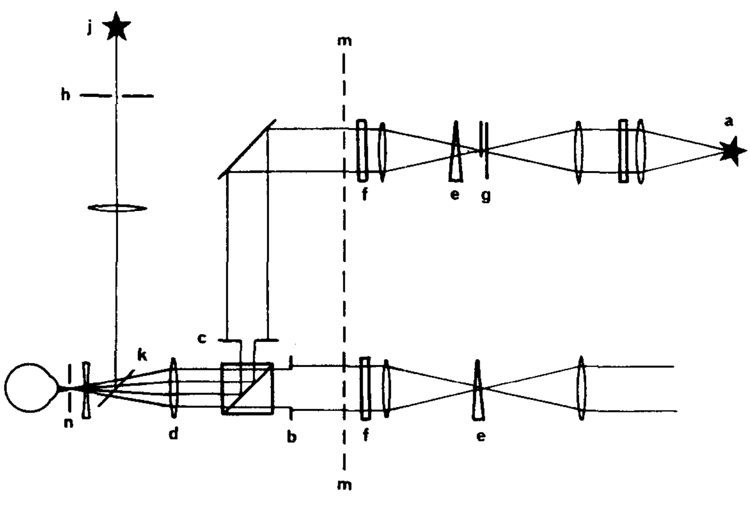

FIG. 2. A schematic side-view of the optical system for one eye.

Apparatus

The Maxwellian-view optical system is shown in Fig. 2. The two channels required to produce the display for one eye were arranged vertically above each other, for ease of access. By means of mirrors which are not shown, all channels derived their light from a single 50 W Q.I. projector bulb, *a*, run on stabilised d.c., and surrounded by four collimating lenses and heat filters. The field stops providing the edges of the background and of the test patch were at *b* and *c* in focal planes of the eye-lens *d* (focal length 100 mm). Luminances were controlled by neutral wedges at *e* and metal film filters at *f*. The wedges were sufficiently close to images of the source filament *a* to provide uniform fields without the use of balancing wedges. The upper channel provided the test patch and the lower one the background. The fixation cross, also seen at optical infinity, was an aperture in a slide at *h*, illuminated by source *j*, and seen by reflection in the coverslip *k*. The subject controlled the voltage through *j* so that the fixation cross was as dim as was compatible with its function. The design of the cross (Fig. 1) allowed the subject to judge the alignment of his eyes from the alignment of the vertical bars belonging to the right and left crosses. All channels formed filament images at the artificial pupils *n*, 1·7 mm in dia., which served to restrict the beam entering the eye to the centres of the filament images. To avoid readjusting the display for non-emmetropic subjects, auxiliary lenses were sometimes placed just in front of the artificial pupils. These reduced the size of the display by 6 per cent for PDCC, who is myopic. The displays were aligned, measured and focussed (with the help of other auxiliary lenses) by projecting them onto a screen beyond the artificial pupils. The entire system, except for the common source a, was duplicated, one for each eye. A detail omitted from Fig. 2 is that the beams were reflected through 90° in a horizontal plane at points indicated by the line mm. For the left eye all the optics to the left of mm could be adjusted laterally to suit the subject's interpupillary distance. The subject held his head steady by biting on an impression of his teeth.

The wedges were circular, mounted on shafts which also carried digitisers.[5] These were connected to a decoder[5] that displayed the position of the wedges in thousandths of a revolution. This conveniently centralised the scales of all the wedges, and, by means of a digital printer, allowed us to record the position of any wedge by pressing a switch.

Flash duration was controlled by electronic timers operating electromagnetic shutters cutting filament images at g in the patch channels. Using a silicon photocell and an oscilloscope we found that the peak-to-peak rise and decay times of the flash were about 1 msec, and that the variability of the duration was negligible.

Calibrations

Two of the neutral wedges were calibrated (with a Minus Blue filter in the beam) by a photomultiplier tube. Using the apparatus as a visual photometer, with the "white" light used in the experiments, these calibrations were checked against each other, and all other neutral wedges and filters calibrated. The transmittances of the first two wedges were also found for "white" light by flicker photometry against a sector wheel whose luminance was measured by an S.E.I. Photometer. The results of this method agreed closely with the photomultiplier measurements.

The spectral transmittances of the "neutral" wedges and filters in fact dropped sharply for wavelengths below 460 nm. This is most unlikely to affect any of our brightness measurements since blue light contributes so little to brightness.

To measure the absolute luminances, the maximum output of each channel, without filters and with minimum wedge density, was directed onto a screen coated in MgO (reflectance r) placed x cm beyond the artificial pupil. The luminance of this screen (L mL) was measured with the S.E.I. photometer. The retinal illumination in trolands is given by $10^3x^2L/r$. L was briefly measured for each channel at the end of every experimental session and found to remain satisfactorily constant over large numbers of sessions.

RESULTS

The effect of background luminance on flash brightness

Procedure. In any one session the luminance of the left-eye flash was kept constant. There was no left-eye background. An ascending series of right-eye background luminances, I, was presented to the subject, and for each he adjusted the luminance of the right-eye flash, ΔI, so that it looked the same brightness as the constant left-eye flash. In other sessions different luminances of the left-eye flash were used. Usually the subject made three settings of each brightness match or threshold, and the average was taken. In a few sessions a Constant Method was used: ten stimuli spaced at 0·1 log unit intervals over a range roughly centred on the matching value were presented in random order, five times each. For increment thresholds, the subject adjusted the luminance of the flash until he could see it on about 80 per cent of trials.

In these experiments the flashes were simultaneous in the two eyes and lasted for 200 msec. The inter-flash interval was increased from 1·5 sec at threshold to 8 sec at the highest brightness. The subject always fixated the crosses as steadily as he could while making the matches. With this display rod influence was negligible: dark adaptation threshold curves reached their final level in less than 10 min even after an intense bleaching light. Also the patches always had the sharp-edged and/or yellowish appearance characteristic of cone vision in our experiments.

Before each session 10 min of dark-adaptation was given. Subjects adapted to each new background luminance by looking at it for 2 min before starting to make matches.

Figure 3 gives data for two subjects. Each curve is the average of four obtained under similar conditions. The lowest curve in each set shows the increment threshold, and successively higher ones correspond to the successively brighter left-eye standards indicated by the squares. These curves are "constant-brightness" curves: each represents the set of (ΔI, I) pairs in the right eye which match a given standard in the left eye.

The constant-brightness curves are like the increment-threshold curve in that each is horizontal on the left (no effect of background) and has a slope of about 1·0 on the right (Weber's Law). The higher curves, however, have a shallower bend and are not vertically above the lower ones, but somewhat to the right. The latter feature may be described in

[5] This system was specially made by Harrison Reproduction Equipment Ltd., Farnborough, Hants., England.

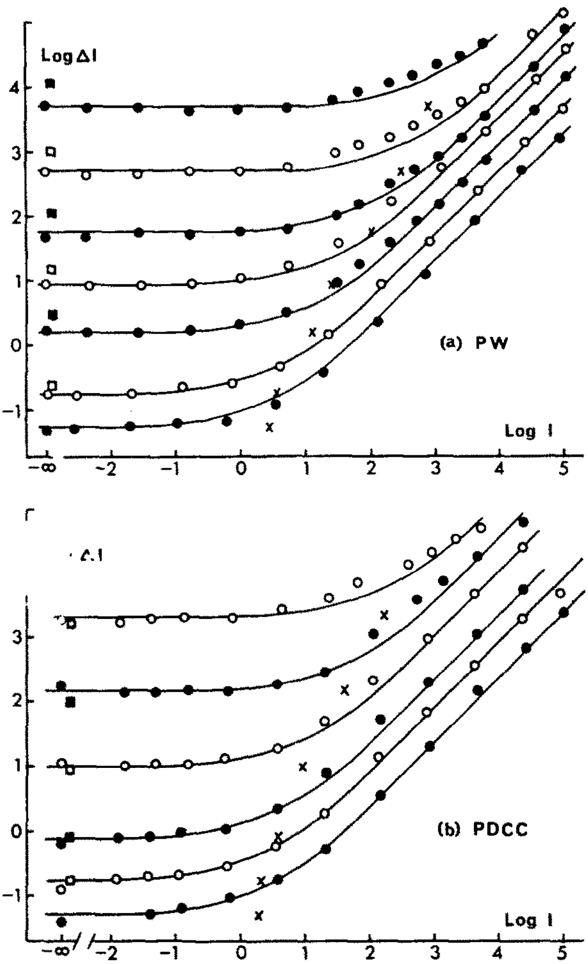

FIG. 3. Increment threshold and constant-brightness curves for two subjects. Symbols are alternately filled and plain only for clarity. Squares indicate left-eye standards. Units are trolands.

various ways: that brightness grows more rapidly with log luminance on bright backgrounds than on dim ones; or that backgrounds do not attenuate all inputs equally: they attenuate strong flashes less than weak ones. It is the effect found by STEVENS and DIAMOND (1965).

The curves drawn in Fig. 3 are all tracings of Stiles's "threshold vs. intensity" curve (WYSZECKI and STILES, 1967, p. 578), moved parallel to the axes to give the best fit at both ends, but not rotated. We have found it convenient when drawing this curve through data, to mark the point at the intersection of the two asymptotes, which we shall call the "*J*-point" (X's in Fig. 3). This point fixes the position of the curve and allows one to see at a glance the absolute threshold and the Weber fraction of the branch in question. The locus of the *J*-points shows clearly how the higher curves are related to the lower ones: whether they are vertically above them or whatever. Stiles's curve fits the threshold and the lowest constant-brightness data quite well, but does not agree with the shallow bends of the higher curves. These can be fitted by using *two* Stiles curves, reminiscent of the results of some of Stiles's two-colour threshold experiments. This treatment is not warranted by the present data, which do not show clearly defined kinks between the branches. In recent experiments, however, we have found that the two branches do have different spectral sensitivities. Even if these two-branched curves are taken seriously and attention is restricted to the left- or right-hand branches, it is still true that the higher constant-brightness curves lie to the right of the lower ones.

This greater effect of backgrounds on threshold than on superthreshold flashes may be a feature of all such brightness measurements, but there are three other possibilities. Two of these, that it is a result specific to certain durations or sizes of flash, or that it is a property of combinations of cone mechanisms but not of single ones, will not be discussed here. The third possibility is that it is due to a light-adapting effect of the bright flashes used for the higher curves: a series of these intense flashes, only 8 sec apart, might have bleached sufficient pigment to produce an "equivalent background" (see e.g. RUSHTON, 1965) which would mask the effects of changing the luminance of the real background at the lower end of the luminance range. This could produce the long plateaux shown in the upper curves. Two types of control experiment disprove this explanation. First, the curves were virtually unchanged (a) when the inter-flash interval was increased to 12 sec, or (b), more importantly, when the patches were steady lights, not flashes. Under the latter condition much more pigment must have been bleached, but it was without effect on the constant-brightness curves. Second, we found in further control experiments that the threshold 6 sec after a flash of luminance 4·0 log trolands, measured during a long train of such bright flashes occurring at 12 sec intervals, was at most 0·2 log units above its value in darkness. This corresponds to an equivalent background of about 1 troland. Such a background would not mask a real background of 10 trolands, yet the plateaux of the highest curves extend to that background luminance.

Accuracy and repeatability of matches

PW obtained three constant-brightness curves using a Constant Method, at brightnesses corresponding to ΔI=0·0, 0·5 and 1·0 log trolands on a dark background. The average increase in ΔI required to go from 25 to 75 per cent judgements "right-hand patch brighter" was 0·11 log units at all three brightness levels (averaged over the 15 background luminances used at each level). This quantity was slightly but significantly larger for the seven brightest backgrounds than for the seven dimmest (0·13 and 0·09 respectively, $p<0{\cdot}002$ by a Mann–Whitney U-test). Curves repeated by one subject under identical conditions in different sessions, using the usual Method of Adjustment, differed from each other by horizontal and/or vertical shifts over a range of up to 0·3 log units. The variability tended to be higher at the higher brightness levels. The accuracy and repeatability of data at medium brightness levels were little, if any, worse than we found for threshold measurements. We have not, however, gone into this question systematically.

In the course of various experiments we have obtained constant-brightness curves under similar conditions from another four subjects. They did not differ in any important respect from the authors' data in Fig. 3.

Form threshold

We also measured the "form threshold": the least luminance at which the test patch was usually seen as a square, though not always with sharp edges. For both subjects the locus of this form threshold was a curve of the same shape as the threshold curve shown, about half a log unit higher and to a first approximation a member of the family of constant-brightness curves.

Only above form threshold does the patch have a uniform brightness. Since the judgements both of form threshold and of brightness below form threshold are rather arbitrary, there would be little point in asking whether the form threshold curve fitted exactly into the family of constant-brightness curves.

What is meant by "brightness"?

Figure 3 might suggest that the subjects were matching the patch/surround *contrasts* of the two patches. It is important to realise that this was not so subjectively. We tried to ignore the backgrounds and the edges of the patches and to match only the apparent intensities of light in the centres of the patches. It was sometimes helpful to think of the two patches as windows into the same lighted room; the task was to adjust the luminance of the test window so that the room looked evenly illuminated. That is how it seemed to us as subjects, and that seems to be how people naturally interpret the instruction to "make the patches look equally bright". To deliberately match apparent contrast is in fact very difficult with our display; it is just possible, because each patch appears with a halo the brightness of its own monocular surround. The luminances required for a contrast match are in general different from those required for a brightness match.

A flash on a bright background adjusted to look the same brightness as one seen in darkness did not look the same in other respects. The one in darkness looked slower and yellower.

The effect of a background in the other eye

In all the above experiments each patch was seen through a background of light present to the other eye. Does this have any effect either on the brightness of the patches or on the measurements of threshold?

Threshold measurements. There is quite general agreement in the literature that a steady background in one eye has no effect on the threshold of the other. FIORENTINI and RADICI (1961) give references, to which may be added the experiments of CRAWFORD (1940). A slight elevation of threshold has sometimes been reported (see above references).

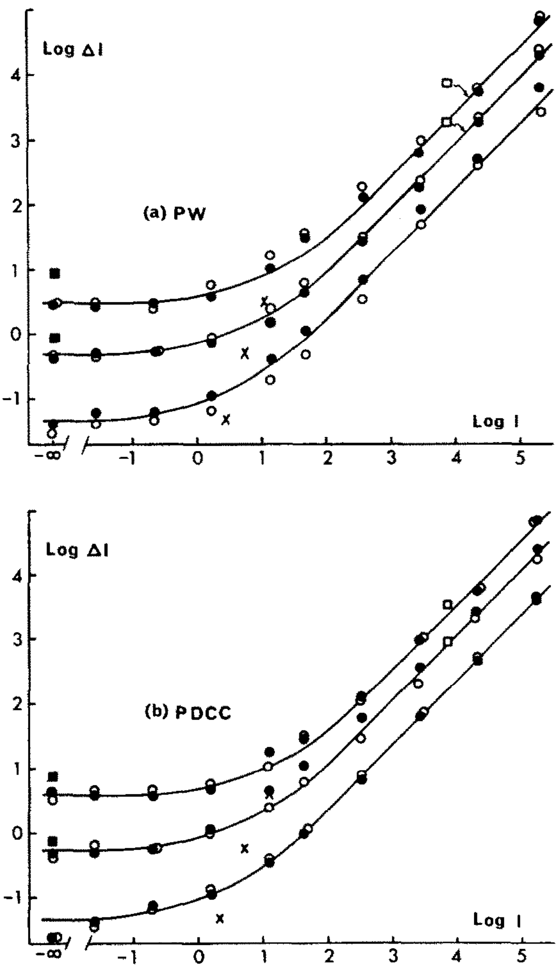

FIG. 4. More increment threshold and constant-brightness curves. Filled circles are matches to filled squares left-eye standards. Plain circles match plain squares. Conditions as for Fig. 3 except that each set of points represents only a single experimental run. Units are trolands.

We also have failed to find any effect. The lowest curves in each set in Fig. 4 show measurements of the right-eye threshold (method of adjustment; each point average of three settings) both with the left eye dark-adapted (filled circles), and with a background of 3·87 log Trolands in the left eye (plain circles). The two sets of points were obtained in separate sessions. It can be seen that for subject PDCC the results coincide almost exactly, while for PW the threshold with a bright contralateral background was slightly lower. This small difference is in a direction opposite to that to be expected, was not repeatable, and is of a size which occasionally occurred when measurements were repeated under supposedly identical conditions. We conclude from these data and other similar observations made in the course of various experiments, that any effect of a contralateral background on threshold is small compared to our experimental error.

Brightness matching. The effect of the contralateral background on patch brightness is well-known to be small (e.g. HERING, 1920). If one closes one eye when looking at the display of Fig. 1 the brightness of the remaining patch changes very little if at all, however bright the background in the closed eye. PITT (1939) made this observation, and describes an experiment in which matches made with a display like Fig. 1 but with no left-eye background were compared with matches made in a modified display in which the left-eye patch was arranged to fall within a black region put in the right-eye background. The differences between the two sets of matches "could be readily attributed to experimental error". Pitt also reported an independent test by W. D. Wright. "His method was as follows. A small patch of light was viewed by the left eye, and a larger patch of considerably higher brightness was viewed by the right eye. The light entering the right eye could be switched on and off rapidly, and Dr. Wright states that, by memory matching, he could discern no appreciable difference in the apparent brightness of the small patch of light whether the larger field was on or off".

The transitivity of brightness matching. We have carried out two types of experiment in an attempt to confirm this absence of binocular interaction. The first is to obtain a right-eye constant-brightness curve using one left-eye background luminance, and then to see if it can be replicated with a different left-eye background. The two left-eye standard patches are chosen to be the same brightness, by matching them to the same right-eye stimulus. This amounts to testing the transitivity of brightness matching in our situation. If we denote left-eye stimuli (i.e. (ΔI, I) pairs) by A_L, B_L, C_L, etc. and right-eye ones by A_R, B_R, C_R, etc. and "matches in brightness" by "$=$", then we are asking whether $A_L = A_R$, $A_L = B_R$ and $B_L = A_R$ together imply $B_L = B_R$ (1).

Figure 4 shows the results of some of these experiments, for two subjects. The filled and plain circles on each curve represent matches made to different left-eye standards, which are shown by filled and plain squares respectively. Clearly, constant-brightness curves can be replicated quite precisely with very different left-eye background luminances.[6]

However, although these results confirm that our constant-brightness curves reflect only the behaviour of the right-eye, they do not show that the brightness of a patch is unaffected by a contralateral background. To understand this, consider the possibility that the brightness of the right-eye patch is the sum of two functions: $f(A_R)+g(A_L)$, $f(A_R)$ depending only on the right-eye luminances and $g(A_L)$ only on the left. Correspondingly the brightness of the left-eye patch would be $f(A_L)+g(A_R)$. If this were so then the transitivity statement (1) above would hold, and so the results of Fig. 4 would be expected. Our "constant-brightness" curves would be curves along which $(f(A_R)-g(A_R))$ was constant; that is, not "brightness" but a more complicated function.

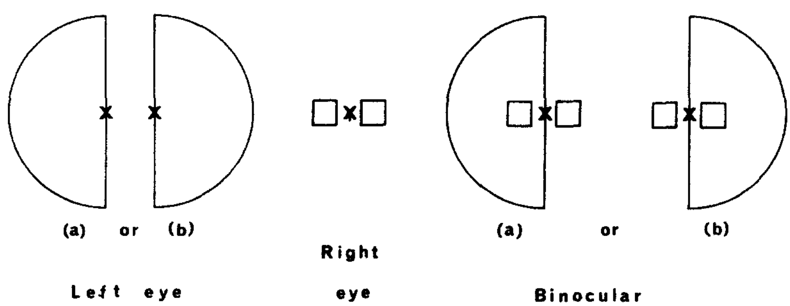

FIG. 5. Display used to study interaction with the contralateral background. Dimensions as in Fig. 1.

[6] A similar experiment by SAUNDERS (1968) gave a different result. Saunder's display, however, was such that part of the edge of the test patch coincided with the inner contour of the contralateral surround. Binocular interaction between contours is well established; it probably explains the difference in the results.

Experiments showing "summation" with the contralateral background. We have therefore tried to find out by a more direct test whether the brightness of a patch is affected by the contralateral background. We used the display shown in Fig. 5. Two square patches were presented to the right eye. The subject adjusted the luminance of the right-hand patch to match the left, under two conditions: with a large continuously illuminated semi-circular background, visible to the left eye only, overlapping either (a) the left-hand patch alone or, (b) the right alone. We compared these two conditions rather than background versus no background to equalize factors such as glare and pupil constriction (though the artificial pupils should make the latter unimportant). The patches were exposed as usual for 200 msec, with 4 sec inter-flash intervals. There was 4 min preadaptation to each left-eye background.

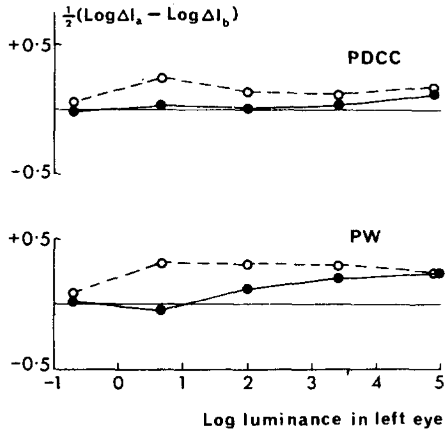

FIG. 6. Effect of a contralateral background. Plain circles and filled circles represent matches about 1·0 and 3·0 log units above threshold, respectively. Each point is the average of twelve settings made in four blocks arranged in an ABBA pattern. Units are trolands.

The results showed a small but usually repeatable effect in the sense to be expected from brightness summation between the left-eye background and the patch which it overlapped. That is, in condition (a) the subject set the right-hand patch to a higher luminance (call it ΔI_a) than in (b) (ΔI_b). An index of the amount of summation is given by $\frac{1}{2}(\log \Delta I_a - \log \Delta I_b)$. This quantity is plotted in Fig. 6 against the luminance of the left-eye background. Data are given for two subjects, and for two different brightness levels, about 1·0 and 3·0 log units above threshold. It can be seen that the effect is small, 0·3 log units at the maximum, and that bright patches are affected less than dim ones. In a number of other experiments we found that (1) this effect occurred to about the same extent for steady lights as for flashes of 200 or 30 msec. (2) The effect tended to increase with the separation of the patches up to about 2° between the near edges. (3) The matches made with no left-eye background were usually between those made in conditions (a) and (b) above. (4) The effect was rather variable. In some sessions we did not obtain it under conditions that usually produced it.

A negative result in this experiment would have been quite strong evidence that a contralateral background had no effect on patch brightness. But the small effect actually found does not allow us to conclude the opposite. For, the patches in the display of Fig. 5 do not differ only in that one is overlapped by the contralateral background whereas the other is not. They also differ in that the patch which is overlapped *appears to the subject* to be on a much brighter background than the other, although in fact the two are on the same monocular background. This is in contrast to the display of Fig. 1 in which the backgrounds of the patches appear to be the same but are actually different. Thus the effect found (Fig. 6) could be due either to the overlap with the contralateral background or to the patches being apparently on different backgrounds. Now the main experiments used the display of Fig. 1. Therefore, if the effect were due to the overlap it would be present in the results of the main experiments (Fig. 3), but if it were due to the apparent difference between the backgrounds it would not.

There is good reason for favouring the second alternative. The lower constant-brightness curves, for which the effect of Fig. 6 should be largest, are almost identical to and vertically above the threshold curve. We have concluded that the overlap of a contralateral background has no effect on threshold. Therefore it seems unlikely that it affects patch brightness.

A second, weaker, support for this view will appear below where we discuss evidence that the results of brightness-matching with displays in which the backgrounds are seen side-by-side in the binocular field are more variable and subject to effects of "attitude" than are results with our display. This would agree with our finding the effect in Fig. 6 variable and sometimes elusive only if the side-by-side matches did include the effect while ours did not.

FRY and ALPERN (1954) performed a similar experiment. Using a display like Fig. 1 they compared brightness matches (steady lights) made with the right-eye background (a) overlapping the left-eye patch or (b) not overlapping it. This experiment differed from ours in that one of the patches was in the same eye as the background, raising the possibility that in changing the size of the background might affect the brightness of that patch. Fry and Alpern, however, denied this possibility. Their results show a small effect, of about the same magnitude as ours, and open to the same two alternative interpretations.

DISCUSSION

Effect of flash duration

The previous experiments most comparable to ours used steady lights as test patches, not flashes (and required steady fixation), so we must digress a little to consider the effect of this difference. The use of steady lights, without changing the display, makes surprisingly little difference to results like Fig. 3. As we pointed out in the introduction, the separation of increments and decrements is found also for steady lights. Further, the constant-brightness curves are little changed. The plain circles in Fig. 7 represent brightness matches made under the same conditions as for Fig. 3 but with steady lights instead of flashes. The curves drawn through the points are Stiles t.v.i. curves belonging to the family of Fig. 3a, which was for the same subject.[7] The curves fit the points quite well.

Comparison with other experiments on brightness matching

The most similar is by PITT (1939) who matched steady lights in an overlapping display like Fig. 1 except that the patches were adjacent in the binocular field. His results appear to resemble ours but a precise comparison is difficult. It is not even possible to say with certainty whether his subject agreed with ours in always matching increments with increments. FRY and ALPERN (1953, 1954) carried out similar experiments at one brightness level. Their data when plotted against the same axes as Fig. 3 lie on a curve of exactly the same shape as our lower constant-brightness curves.

HEINEMANN (1955, 1961) made interocular brightness matches with steady lights using a display in which the annular surrounds to the left- and right-eye patches were seen side by side in the binocular field rather than overlapping as in Fig. 1. Some of his own data (1955) are shown as filled circles in Fig. 7. They agree extraordinarily well with ours. Since there were many differences between Heinemann's conditions and ours, this is welcome evidence for the generality of our results. The data for his other subjects, however, do not

[7] These curves are not actually among those drawn in Fig. 3a, because the brightness levels used in these two experiments were not the same. The curves in Fig. 7 are t.v.i. curves with their J-points on the straight line which best fits the set of J-points in Fig. 3a. For a given luminance, the actual subjective brightness produced by a steady light is of course less than that of a 200 msec flash (the Broca–Sulzer effect); it is the pattern of constant-brightness curves which is almost unchanged.

agree so well. Nor do those of HOREMAN (1963) in an attempted replication of Heinemann's experiment.

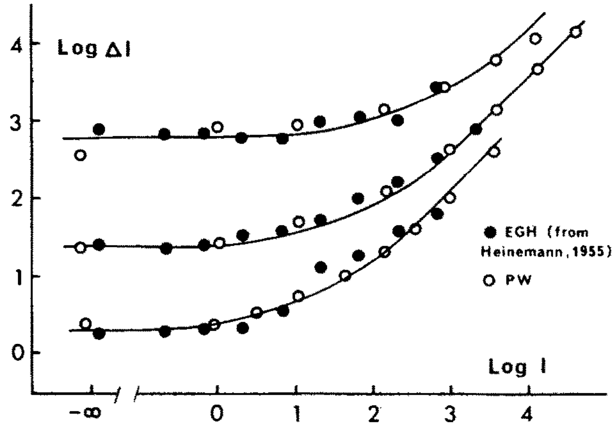

FIG. 7. This figure presents a triple comparison. The points are constant-brightness data for steady lights, from two different experiments. PW's two upper sets of points have been moved down 0·1 log units for better comparison of the shapes of the curves. That our experiment and Heinemann's used so nearly the same three brightness levels is a fortunate coincidence. The lines are Stiles t.v.i. curves with their *J*-points on the locus of *J*-points in Fig. 3a, and are therefore approximately constant-brightness curves for PW with 200 msec flashes.

Theory

In attempting to explain the influence of a background on superimposed lights, we can separate three effects of the background. First, it is itself light energy and adds physically to the superimposed light. Second, it lowers the sensitivity of the retina. Third, it produces a sensation of brightness. In this discussion we examine which of these three effects is responsible for our results.

The physical background of light. The physical addition of the background light is probably irrelevant, except as noise, to threshold measurements, in which the task is to detect an *increment*. The background light where the patch appears, although physically and visibly present, is "nothing there". But for judgements of the brightness of superimposed lights, one would expect it to be relevant. Because now the question asked of the subject is not "How much brighter than the background is the patch?" but "How bright is that part of the visual field?", that part of the field being made up of patch *plus* background. One would expect, as did Schouten and Ornstein, that the light in the background would contribute to this brightness. But in fact, it doesn't. Even on the brightest right-eye background further light must be *added* in the patch to match even the weakest left-eye patch (on no background). The pedestal on which the right-eye patch is presented does not seem to have raised it up at all. The obvious suggestion is that this is because the binocular overlap in our display has effectively put the left-eye patch on the same pedestal. But if that is the case, we are no longer considering physical addition of background light, and must turn to discussion of the other two effects of the background.

The retinal "Gain Control". The second and third effects of the background, reducing sensitivity and producing a sensation of brightness, are to a large extent independent. Some factors that affect the brightness of the background but not its luminance, such as giving it a brighter surround or stabilising it, do not alter sensitivity, as measured by the increment threshold at the centre of the background (CORNSWEET and TELLER, 1965;

BURKHARDT, 1966). These and other lines of evidence lead to two generalisations: that the brightness of the background depends mainly on events at its edge, while the increment threshold for a small spot in its centre depends on the local luminance but not at all on the edge. The dependence of increment threshold on local luminance agrees with our finding that this threshold is unaffected by a background in the other eye. Further, curves of the same shape as the psychophysical increment threshold versus intensity curve can be obtained from a retinal ganglion cell (e.g. DONNER, 1958). Thus, the threshold curve is probably determined by the local retinal "gain control" (e.g. RUSHTON, 1965).

Now, the superthreshold constant-brightness curves in Fig. 3 are obviously similar in shape to the threshold curve. They are also unaffected by a background in the other eye. It therefore seems very likely that they too are determined by the retinal gain control. In addition, there are three reasons why the only other relevant effect of the background, its apparent brightness, can have little effect. First, if there were any such effect, one would expect it to be greatly reduced in our display in which both test and standard patches appear to be on the same background. Second, Fig. 4 shows that when the subject can hardly see what the monocular background brightness is, because it is binocularly mixed with a bright background in the other eye, the results are unaltered. Third, the most direct evidence for the existence of an effect of apparent brightness is provided by Fig. 6, and we have already argued that that effect is absent in Fig. 3. Finally, two quite different types of experiment have also produced superthreshold constant-response curves determined by the retinal gain control and resembling the results in Fig. 3. ALPERN and RUSHTON (1967) measured the luminance required to just overcome a masking surround flash of fixed luminance, on steady backgrounds (under only the test flash) of various luminances. Their constant response curves about 1·0 and 2·0 log units above threshold are the same shape as and vertically above the increment threshold curve. BARLOW (1968) has obtained increment "threshold" and superthreshold constant-response curves for single cat retinal ganglion cells. His results are very similar to Fig. 3 (and they do show the more rapid growth of response on bright backgrounds). There are therefore several reasons for believing that all the results in Fig. 3 reflect the action of the retinal gain control on the response to the luminance increment ΔI.[8,9]

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[8] We will not discuss in more detail here the fact that the higher constant-brightness curves are to the right of, and different in shape from, the lower ones. This, as was pointed out above, is the effect found by STEVENS and DIAMOND (1965) for glare. It seems likely that this detail is also produced by the retinal gain control, since the other two effects of the background, physical luminance addition and brightness, would be expected to produce a difference between the threshold data and the results for *dim* stimuli. Both the shift to the right and the change in shape are, on the contrary, most marked for the brightest patches. This effect requires data for different colours, sizes and durations of test patch for its proper evaluation.

[9] "*Simultaneous Contrast*". We have shown above that the results in Fig. 3 hold also for steady lights. Our argument suggests, then, that the effect of a background on the brightness of a steady superimposed light, which has classically been called "simultaneous contrast" (the background having been regarded as a surround with a hole in it, which for steady lights is just a different description of the same stimulus pattern), when measured in a display like Fig. 1, also reflects only the action of the retinal gain control on the luminance increment ΔI.

This is a slightly unusual view of simultaneous contrast. It suggests that most of the effect arises because ΔI, rather than $(I+\Delta I)$, is the physical correlate of brightness. In physiological terms, that the neural correlate of the brightness of a patch of light is the size of the signal produced by the edge of the patch rather than, say, the average activity of cells (at some level) whose receptive fields fall within the patch. This, as mentioned in the introduction, fits with the other evidence, such as the behaviour of stabilised images (see, e.g. YARBUS, 1965, p. 82), that the brightness of a patch depends on the receptors stimulated by its edge. On this view the role of "lateral inhibition" is less obvious than usually assumed. It is involved in determining the size of the edge signal, but simultaneous contrast could in principle be just as great in a system without lateral inhibition, in which an edge signal was produced, for example, by the combined effects of small eye-movements and rapidly adapting "private lines".

The effect of background brightness. There are at least three reasons, however, for believing that the apparent brightness of the background does sometimes influence the brightness of a superimposed patch, though probably not in displays like Fig. 1. It seems worth going into this question in some detail. Even though it is not relevant to the explanation of our main results, it is the key to understanding their relation to much of the previous work on brightness, and also leads to suggestions as to how the output of the retina is processed at higher levels of the visual system.

The first reason is that, as we have already argued, Fig. 6 appears to show such an effect, which must be independent of both the retinal gain control and the physical addition of light, because the background and test patches were in opposite eyes. Second, it seems likely *a priori*. The argument is similar to that already put forward for an effect of the physical addition of background light. The superimposed patch is seen on a pedestal of brightness. One would expect judgements of patch brightness to take some account of the height of the pedestal when it can be clearly perceived. Third, the existence of some such effect does in fact seem necessary to explain the difference between our results and those of other brightness-matching experiments.

Heinemann's results in Fig. 7 agree well with ours, and thus apparently show no effect of background brightness. But these results imply a surprising paradox. Consider an extreme example. Arrange a dim patch of light, *A*, near a larger and much brighter patch, *B*. In *B* set another patch, *C*, whose luminance can be adjusted to be greater or less than that of *B*. Let us try to adjust it so that *A* and *C* look equally bright. If we follow the rule we have found with our overlapping display we would match the increment *A* with another increment, and so set *C* brighter than *B*. Now the surprising thing is that this is what subjects often do in the side by side situation (e.g. Fig. 7) even though such a match then creates a paradox: *C* brighter than *B*, *B* much brighter than *A*, but *C* and *A* the same brightness. Heinemann's data show very few instances of a decrement being matched to an increment (none for EGH) but many of the paradox. WALLACH'S (1948) claim that brightness is a function of the ratio of patch/surround luminance implies a similar finding. We ourselves, in this situation, vacillate between accepting a match between increments, and setting *C* to be a decrement. Different "attitudes" to the task seem to produce different matches, and it does not surprise us that some subjects do one thing and others another. Heinemann's subject ECP matched increments with decrements under these conditions and so did, to a greater extent, HOREMAN (1963), and so did all BURGH and GRINDLEY'S (1962) subjects.[10] Effects of attitude and previous experience on brightness judgements have been well demonstrated by BURNHAM (1953). The comments of Burgh and Grindley's subjects seem particularly appropriate here.

We suggest that these changes of "attitude" correspond to taking account, or not, of the apparent brightness of the background as a baseline to which to relate the brightness of the patch, either consciously or unconsciously. If it is taken into account, then the brighter the background the brighter the patch. So that to achieve a given brightness the

[10] Only quite low-contrast decrements are set in this situation. Darker ones only match other decrements. With centre-surround displays the generalisation commonly found in textbooks that simultaneous contrast occurs mainly when the surround is brighter than the centre is misleading. Figure 7 shows large effects, entirely for surrounds less bright than the centres. When the surround is made brighter than the centre the effect is not so much a quantitative decrease in brightness, as a qualitative change. A different type of comparison stimulus is necessary. This point, though often made, is obscured by the results with side-by-side displays in which the occurrence of matches between increments and decrements suggests that the change is merely a large quantitative one. In the underlying retinal processes it is probably qualitative.

patch luminance can be lower than would be required if the signal produced by ΔI, attenuated by the retinal gain control, was alone determining the brightness; even to the extent of a decrement matching an increment. This is in fact the direction in which the data of Heinemann's subjects, and of Horeman, etc., deviate from ours; we know of no data deviating in the opposite direction, that is, showing a greater effect of background than is shown in Fig. 3. These data therefore suggest, on our hypothesis, that most subjects are influenced by the background brightness in side-by-side displays, and therefore in normal vision. The effect shown in Fig. 6 may be this effect of background brightness.

These hypotheses seem more plausible if one reflects that information about light intensity must be processed in different ways to achieve different perceptual goals. For example, taking account or not of the background brightness could correspond to two different types of brightness constancy, both of which seem to occur. Constancy first with respect to changes of background alone such as occur with relative movement of the object and its background, and second with respect to changes in the illumination of object and background together. The second type, represented in Fig. 3 by the parts of the constant-brightness curves with slope 1·0, is a much larger effect than the first (Fig. 6), which is reasonable because the range over which background luminance is likely to change while object luminance remains constant is small compared with the range through which the overall illumination changes. The reader may at first think that we have these types of constancy the wrong way round. Constancy with respect to changes in the background would appear to be simply achieved by ignoring the background. But we cannot do that. The early stages of the visual system code relative luminance (corresponding to the other, dominant, type of constancy), so that to achieve a perception independent of background luminance, the signal has to be referred to the background brightness as a baseline. That is, because of the way the visual system is designed we have to take account of the background brightness in order to ignore it. Loosely speaking, the visual system differentiates the input, and to achieve certain perceptual goals we have to integrate it. It is not surprising that judgements of "brightness" fluctuate or differ widely between individuals, in situations in which no one type of processing is imposed. Nor is it surprising that results obtained in a situation (Fig. 1) that apparently imposes a particular type of processing on the subject, by depriving him of the information about background brightness required for integration, should be obtained also (Fig. 7) in a freer situation by taking up some "attitude", presumably equivalent to setting up the particular perceptual goal that was imposed in the former situation.

Summary

The following tentative picture emerges from this discussion.

1. In everyday vision, and in experiments in which brightness matches are made between patches whose different backgrounds are seen side by side, the effect of background luminance on perceived brightness depends on both retinal and central mechanisms.

2. Our main experiments (Fig. 3) measure the effect of the retinal mechanism alone—the "retinal gain control".

3. An example of the action of the central mechanisms alone is given by Fig. 6.

4. A necessary condition for the central mechanisms to operate is that the subject can see the difference in apparent brightness between the backgrounds of the test patches.

5. The extent to which the central mechanisms are involved depends also on the subject's perceptual goals, and hence on his knowledge of the situation, his attitudes, assumptions and previous experience.

6. The central mechanisms act in opposition to the retinal ones: increasing the brightness of the background increases the brightness of a superimposed light relative to the level set by the retinal gain control. The retina differentiates; the brain can integrate.

7. When background luminance is varied over a wide range, the influence of the retinal gain control is quantitatively much greater than that of the compensating central mechanisms. Thus, for large changes in background luminance, perceived brightness is more closely correlated with the relative luminances of the patch and the background, which is what is encoded by the retina, than with absolute luminance.

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Abstract—Interocular brightness matches were made between flashes of light, one to each eye, added to large steady uniform backgrounds of different luminances. The backgrounds were binocularly superimposed. Under these conditions, constant-brightness curves (Log ΔI vs. Log I) were of approximately the same shape as the increment threshold curve. The brightness of a flash in one eye was unaffected by a background in the other. It is argued that these experiments measure only the contribution of retinal mechanisms. Further experiments provide some evidence of central influences. The relation between retinal and central mechanisms in the perception of brightness is discussed.

Résumé—On réalise des comparaisons interoculaires de luminosité entre des eclairs de lumière, présentés chacun dans un oeil, et superposés à un grand fond uniforme et permanent de luminance réglable, vu binoculairement. Dans ces conditions, les courbes de luminosité constante (Log ΔI en fonction de Log I) ont à peu près la même forme que la courbe de seuil différentiel. La luminosité de l'éclair dans un oeil n'est pas affectée par le fond de l'autre. On pense que ces expériences mesurent seulement la contribution des mécanismes rétiniens. D'autres expériences fournissent quelque évidence d'influences centrales. On discute la relation entre mécanismes rétiniens et centraux dans la perception de la luminosité.

Zusammenfassung—Man verglich interokulär die Helligkeiten zweier Lichtblitze, deren einer in je ein Auges fiel, und welch beide einheitlichen Hintergründen verschiedener Beleuchtungen aufgesetzt waren. Die Hintergründe waren binokulär überlagert. Unter diesen Umständen waren die Konstanthelligkeitskurven (Log ΔI vs. Log I) und die Erhöhungsschwellenkurve ungefähr gleichförmig. Die Blitzhelligkeit in einem Auge war vom Hintergrund des anderen unabhängig. Man behauptet, dass diese Versuche nur die Beteiligung der Netzhautmechanismen messen. Weitere Versuche bezeugen die Gegenwart zentraler Einflüsse. Das Verhältnis zwischen zentralen und Netzhautmechanismen wird besprochen.

Резюме — Сравнивалась светлота вспышек света, которые давались на каждый из глаз, в добавление к большому постоянному однородному фону различной яркости. При бинокулярном восприятии, яркости фонов налагались одна на другую. При этих условиях кривые соотношения контраста к светлоте (Log Δ J к Log J) имели примерно ту же форму, что и кривая порогов различения (инкрементных порогов). На светлоту вспышки в одном глазу не влиял фон другого глаза. Оспаривается, что эти эксперименты могут количественно характеризовать только участие в восприятии ретинальных механизмов. Проведенные позже эксперименты дают некоторое доказательство и центральных влияний. Обсуждается вопрос о взаимодействии периферических (сетчаточных) и центральных механизмов в восприятии светлоты.