Brightnesses, luminances, and Fechner's paradox¹

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Monocular brightnesses were varied, without varying monocular luminances, both by means of simultaneous contrast and by means of changes in the level of adaptation. Binocular brightness was shown to change in accord with monocular brightness, independent of monocular luminances.

If the luminance of a binocularly viewed target (say, a disk of light) is equal for the two eyes, the subjective brightness of the target increases monotonically with increasing target luminance. However, when the target luminance is made unequal in the two eyes, the relation of binocular brightness to monocular luminances becomes more complex, as shown schematically in Fig. 1. If the luminance of the disk of light presented to, say, the left eye (LE) is held constant at some luminance L , that disk will have some specific monocular brightness, MB . As the luminance of the disk in the right eye (RE) is then varied upward from zero, the perceived binocular brightness of the disk follows a nonmonotonic function. At first, the binocular brightness falls below MB . After reaching a minimum, it rises again, and returns toward MB as the luminance in the RE approaches the luminance in the LE (cf., Fry & Bartley, 1933). When both eyes are illuminated by L , the binocularly seen brightness is equal to or slightly higher than MB . The region of the curve which falls below MB represents the phenomenon that classically has been named Fechner's paradox: adding light in the RE diminishes the brightness of the target. The two transition points which limit the region over which Fechner's paradox occurs have been labelled "A" and "B" for later reference.

A variety of theoretical treatments of these phenomena is available. Fry and Bartley (1933) attribute them to the interaction of a set of excitatory and inhibitory processes. The phenomena have been more usually described as shifts in eye dominance (e.g., Davson, 1949). Simple mathematical models postulating averaging mechanisms whose interocular weighting properties change with changes in the monocular luminances have also been proposed (Levitt, 1965a, b; Hurvich & Jameson, 1966). In particular, Levitt has suggested that monocular luminances may be combined in a weighted sum to yield binocular brightness. He discards (1965b, p. 6) the alternative hypothesis that monocular brightnesses, rather than luminances, are combined to yield the composite binocular brightness level.

For a variety of reasons this conclusion seemed to us worthy of further testing. First, it is known from physiological studies that in the early stages of the visual system, a non-linear, "compressing"

transformation (such as a logarithmic transformation or a power function with exponent < 1) occurs. The existence of this transformation makes it unlikely that later operations of the system would perform a process describable as the summing of luminances. Second, absolute luminances are poorly identified psychophysically. This suggests that information about absolute luminances is largely unavailable at later stages of the visual system. And third, it is possible to vary monocular brightness without varying monocular luminance, as discussed below. Therefore, Levitt's conclusion that monocular luminances alone determine binocular brightness would imply that monocular and binocular brightnesses are independently determined, in very different ways. To allow monocular brightnesses to determine binocular brightness would be more parsimonious. It is therefore worthwhile to test the generality of Levitt's conclusion by investigating binocular brightness under conditions where brightness and luminance can be varied independently. We report two such experiments.

EXPERIMENT 1

Our first experiment depends on the fact that the brightness of a test figure is influenced by the level of adaptation of the eye (Stevens & Stevens, 1963). Specifically, a test figure of a given luminance, presented to an eye adapted to a higher luminance, will look dimmer than it does when presented to an eye adapted to the luminance level of the test figure. In demonstrations of Fechner's paradox in which the difference in illumination between the two eyes is produced by momentarily placing a filter over one eye (say the RE), just such a discrepancy between adaptation level and stimulus luminance is present for that eye.

Fig. 1. The brightness of a binocularly viewed target, as a function of the target luminance presented to the right eye (RE). The left eye luminance is held constant at L (Schematic).

In such a demonstration, if the RE is covered by a filter and allowed time to dark adapt to the level of luminance created by the filter, the RE brightness of the test figure will increase. This suggests a test of the question posed by Levelt. If monocular luminances alone determine binocular brightness, binocular brightness will remain constant (as does the luminance of the test spot) over changes of RE adaptation; but if binocular brightness depends on monocular brightness, binocular brightness should increase as the RE dark adapts.

Method

The subject (S) viewed a circular spot of white light having a luminance of 2.4 log mL (94 dB re 10⁻¹⁰L) and subtending a 2° visual angle, at a distance of 1 m. The S always began by adapting to the test target for 10 min. His LE always viewed the target directly. In the "light adapted" condition, the RE also adapted directly to the target luminance. In the "dark adapted" condition, a two log unit neutral density filter was placed between the S's RE and the target during the period of adaptation, and for re-adaptation between test trials.

For each test trial, the S was handed one of a series of neutral density filters to hold over his RE. Any adapting filters were removed. The S alternately covered and uncovered his RE with an opaque stop. He was asked to respond "brighter monocular," "brighter binocular," or "same," to indicate whether covering the RE increased, decreased, or made no difference in the brightness of the target. Thus the monocular, LE brightness of the target was used as a baseline against which to judge binocular brightness. (Such a method rests, of course, on the assumption that the brightness of the target, as viewed monocularly by the LE, does not vary significantly with the adaptation level of the RE.)

A test trial never took longer than 5 sec. Between trials the S readapted to the relevant adaptation conditions for at least 10 sec. Ten trials were presented at each of a series of widely spaced filter densities, with order randomized. Following these trials, more finely graded filters were used, again ten times each in a random series, to investigate more fully the regions in which transitions in the S's responses occurred.

Three replications of the light adapted condition and three of the dark adapted condition were performed on each of two Ss, in an ABBAAB order.

Results

The results of three replications on subject JC are shown in Fig. 2. The upper graph shows the percent of judgments "binocular brighter," and indicates the RE luminance at which transition A (Fig. 1) occurs. A lower level of adaptation in the RE produces a leftward shift of the "binocular brighter" curve.

Fig. 2. Percent of judgments "binocular brighter" and "same" for three replications of Experiment 1, Subject JC. For a given RE luminance level, the percents "binocular brighter," "same," and "monocular brighter" sum to 100. The left and right arrows above the abscissas show the adaptation levels of the RE under "dark adapted" and "light adapted" conditions respectively.

The luminance of the RE stimulus that results in Fechner's paradox is shifted downward.

It is interesting to note that for this S, when the RE is adapted downward by two log units (20 dB), viewing the target binocularly—directly with the LE and through a 2.0 density filter with the RE—makes the target appear brighter than it appears in monocular (LE) view. That is, when the RE is adapted to the luminance level at which the RE stimulus is presented, Fechner's paradox in its classic sense does not occur. To produce the paradox for this S, it is necessary to present RE luminances below the luminance to which the RE is adapted.

The lower graph in Fig. 2 shows the percent of judgments of "same," and illustrates transition B of Fig. 1. As in the upper graph, dark adaptation of the RE shifts the curve leftward, shifting downward the range of RE luminances for which Fechner's paradox is reported. There is considerable variability in this curve from one replication to the next, indicating a variability of the S's criterion of sameness. However, in each replication the dark adapted curve is clearly to the left of the light adapted curve, and none of the three light adapted curves falls to the left of any dark adapted curve.

Data from the second S confirmed those from the first in all important respects. They differed from those of the first S in showing a secondary hump in the percent "same" curve, in the luminance range over which transition A occurred; i.e., in the range where responses switched from "monocular brighter" to "binocular brighter." The first S responded spontaneously only "binocular" or "monocular" over this range, reserving "same" judgments for very dim RE stimuli.

EXPERIMENT 2

The second experiment used a second method of varying subjective brightness without varying luminance, that of brightness contrast (Horeman, 1965). If a test target is surrounded by an area of luminance greater than its own luminance, its brightness will be diminished; and the greater the ratio of surround to target luminance, the more will the brightness of the target be diminished (Wallach, 1948; Heinemann, 1955). This phenomenon makes possible a simple test of the influence of monocular brightness on binocular brightness. Each of the two eyes can be presented with a target-surround pair, and the two monocular stimuli fused to form a single target and surround in binocular view. One can then vary the luminance of the RE surround alone, and measure changes in the binocular brightness of the target. If diminishing the brightness of a monocular target diminishes the brightness of the binocular sensation to which the monocular input is contributing, then increases in surround luminance in the RE should diminish the binocular brightness of the surrounded target disk. This should be true even though the luminance of the monocular target remains unchanged.

Method

The S viewed two pieces of ground glass, one with each eye, through a set of mirrors. Two squares of opaque white cardboard were glued to the fronts of the pieces of ground glass, and illuminated by the room illumination. These were fused by the S and appeared as a single square subtending a visual angle of 1° . The ground glass was illuminated strongly from behind. Filters placed just behind the ground glass of the RE field varied the luminance of the RE surround; whereas a filter placed between the LE stimulus field and the eye could be used to vary the luminances of the LE target and surround simultaneously.

The luminance of the RE target was always 1 mL (70 dB re $10^{-10}L$). The luminances of the LE target and surround were held constant respectively at 1 and 10 mL (70 and 80 dB) for Condition 1, or at 0.1 and 1 mL (60 and 70 dB) for Condition 2. Before the test trials began, the S adapted for 10 min. to these luminances, with the RE surround luminance set at

10 mL (80 dB). For each test trial, the experimenter changed the luminance of the RE surround for 5 sec. or less. As before, the S viewed the target alternately with the LE alone and with both eyes together. He judged whether the target appeared brighter monocularly or binocularly. Ten test trials were presented at each of five luminances of the RE surround.

Results

The results of Experiment 2 for subject JC are shown in Fig. 3. Under the conditions used, the brightness of the RE target falls below the brightness of the LE target when the RE surround luminance exceeds about 10 mL (80 dB) (Wallach, 1948). In each of the two conditions, increasing the luminance of the RE surround toward and beyond this level results in decreasing percentages of "binocular brighter" judgments. That is, when the brightness of the RE target is less than the brightness of the LE target, the presence of the RE target diminishes the binocular brightness of the target. This result is directly analogous to the original statement of Fechner's paradox, provided that the existence of Fechner's paradox depends on brightness (and not luminance) differences between the two eyes.

This result is particularly striking when the second condition (dotted curve) is considered. In this case, the luminance of the RE target is greater than the luminance of the LE target; while, due to the presence of its surround, the brightness of the RE target is below the brightness of the LE target. For high surround luminances, the S reliably reports that the target appears brighter in monocular than in binocular

Fig. 3. Percent of judgments "binocular brighter" for two conditions of Experiment 2, Subject JC.

view. Again, Fechner's paradox depends on brightness and not luminance.

Results from a second S were more variable, but confirmed those of the first S in all important respects.

CONCLUSIONS

The results of the two experiments have implications for the understanding of binocular brightness phenomena. First, they limit the conclusion drawn by Levelt (1965a, b) that monocular luminances are combined in a weighted sum to yield binocular brightness. Although Levelt's model describes data taken under his experimental conditions, a different model is required to describe the determination of binocular brightness for varying levels of adaptation and for variations in inducing field luminances. When monocular brightness and monocular luminance are not perfectly correlated, it is the brightness that appears to determine the binocular effect.

Second, much has been learned in recent years about the functioning of the mammalian visual system at the physiological level. Both summatory and inhibitory neural interactions are known to exist in mammalian visual systems (Hubel, 1963), as are neural units that change their functioning as the luminance level of the visual stimuli changes (Barlow et al, 1957). Cortical units having inputs from both eyes are known to exist (Hubel, 1963). A variety of post hoc combinations of such model units can be designed to produce a unit whose output rate varies with input in the manner shown in Fig. 1 (cf., Fry & Bartley, 1933). Thus, with the addition of the weak assumption that the rate of firing of such a unit is the physiological correlate of perceived brightness, Fechner's paradox can be explained. Our main conclusion is simply that for any such models to be successful, the input to the model system cannot be correlated solely with the luminances of the stimuli presented to the two eyes. These inputs will correlate more closely with the perceived monocular brightnesses of the stimuli, as influenced by such factors

as brightness contrast and monocular adaptation levels.

The present results remain consistent with the conclusion drawn by others on the basis of other kinds of evidence, that adaptation (Rushton, 1963; Barlow, 1964) and brightness contrast (Ratliff, 1965) both occur at early stages of visual information processing; that is, before information is combined from the inputs to the two eyes.

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Notes

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