A COMPARISON OF BINOCULAR AND MONOCULAR

REACTION SPEED

by

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STATEMENT BY AUTHOR

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REACTION SPEED

Gary L. Heyer

ABSTRACT

Monocular and binocular visual stimulation of approximately corresponding retinal regions was presented to three dark adapted human subjects (Ss). Ten stimulus variations were administered to the Ss at two luminances. They were: both varied, onset and offset; right on, left varied, onset and offset; left on and right varied, onset and offset; right off and left varied, onset and offset; and left off, right varied, onset and offset. The high luminance used was 996 millilamberts and the low luminance used was 100 millilamberts. Reaction time was measured as the dependent variable. The S made his reactions by releasing a lever attached to a micro switch.

The area of the visual stimulus was held constant at 20° throughout the experiment. The region stimulated was 10° on the nasal field of the right eye, and 10° on the temporal field of the left eye.

Histograms were plotted comparing the mean high and low luminance reaction times as a function of the five stimulus source onset conditions, and the five stimulus source offset conditions at both high
and low luminances. These figures show that for all conditions tested, reaction time is faster to high luminance than to low luminance, and that reaction time is faster to the onset of a stimulus than to the offset of a stimulus.

Cumulative percentage of response curves were plotted with reaction time as the axis of abscissas, illustrating monocular and binocular onset and offset conditions at high and low luminance. Inspection of these curves showed that reaction time is faster to binocular stimulus offset, than to monocular (right eye) stimulus offset at both high and low luminance.

Probability of response curves were plotted for both onset and offset conditions. Predicted curves were obtained by computing the probability of a response for the eyes operating as independent detectors; the actual probability of a binocular response was available from the obtained data. A comparison of these curves for the onset condition showed that there was a greater probability of faster reaction times predicted for the eyes operating as independent detectors than was actually obtained. A comparison of the curves for the cessation condition showed that there was a greater probability of faster reaction times for the eyes operating binocularly than was predicted on the basis of independence of the two eyes.
INTRODUCTION

Reaction Time as a Psychophysical Method

Investigators of visual phenomena have been perplexed for over sixty years with the question of whether the two eyes serve as independent detectors, or if a common sensory path, involving both eyes, central to the optic chiasma, increases sensitivity and efficiency. Binocular vision certainly improves judgments of the distance of objects, but binocular interaction for threshold, and other indices, still remains insufficiently explored.

One method of investigating this problem is reaction time, yet very few previous studies have been reported using this method as the dependent variable. As Froeberg (1907) pointed out,

"...of the methods employed in experimental psychology, scarcely any has been more useful and more extensively applied than the method of reaction time. The extensive literature on the subject shows that it has been employed in the study of the most diverse mental processes, and is at present successfully applied to such problems as the measurement of differences in sensations, individual differences, the transference of function, the psychology of the insane, etc., and that valuable data bearing on such problems are rapidly accumulating."

Woodworth (1938) said,

"...reaction time affords a means of studying the total reaction as dependent on the stimulus, the task and the conditions in which the task is performed. Variations in the total reaction time throw light on the dynamics of the performance. It is with this understanding that the reaction time
method is employed."

Simple reaction time, as used in this study, is defined as the length of some defined simple minimal response between the onset of a stimulus and the completion of some defined simple minimal response. In the latter situation, however, the offset of the stimulus is an energy change and can be regarded as a stimulus itself.

The terms "reaction time" and "response latency" are used interchangeably. The term "reaction speed" refers to the reciprocal of the latent period, and has been used as an index of the intensity of the sensation (Piéron, 1920).

Piéron (1920) has reminded us that reaction speed is not the latency of sensation, but the latency of a total reaction. The total reaction time can be divided into two components; the irreducible minimum and the reducible margin. The irreducible minimum consists of the time of receptor processes and neural conduction, and is somewhat variable depending upon the level of efficiency of the various neural units involved. Therefore, in visual excitation, the components of the irreducible minimum are the afferent and efferent transmission delays and the time required for the completion of central processes. The irreducible minimum changes from experiment to experiment, depending upon the variables which are held constant.

The reducible margin of reaction time is that portion which falls above the irreducible value--its duration is governed largely by
the independent variables in the stimulus situation. This reducible margin may be determined quite accurately by subtracting the maximum reaction time for threshold stimuli from the minimum reaction time to maximum stimulus intensities. The reducible margin may be related in systematic ways to a stimulus variable.

An example of such a function was suggested by Piéron (1920). He proposed the hyperbolic function,

\[ T = \frac{A}{(I + C)} + K, \]

as a description for the decline of reaction time with increasing flash luminance. In this equation, \( T \) = reaction time, \( A \) = the reducible latency, \( I \) = flash intensity, and \( K \) = an irreducible limiting latency.

The Relationship Between Time and Intensity of the Stimulus and Reaction Time

The variables of luminance and duration of a visual stimulus affect the reducible margin. One of the earlier studies in the United States utilizing simple reaction time to determine the effects of varied intensity and duration of a visual stimulus was conducted by Froeberg (1907). The method Froeberg used for both of his experiments was essentially the same. The source of illuminance used was daylight, reflected by Milton Bradley white baryta paper and Hering's grays. The illuminance from the Milton Bradley paper was designated as 100 and the other intensities were obtained from Hering's grays. They were compared with the white baryta paper by placing them on a color
wheel. The degree of brightness was determined by the size of the white sector, expressed in terms of percentage of the whole circle, that produced the same shade of gray as the paper to be tested. The lowest intensity used was daylight reflected off velvet black, and the other intensities were designated as 56, 25, 16, 10, 6 2/3, 3 1/2, 2 1/4 and 3/4. The stimulus durations were obtained by moving paper of a desired absorption value across an aperture varying in size from 3 to 48 millimeters. The paper was rotated at a rate of one millimeter per millisecond, therefore, each additional millimeter would add one millisecond to the duration of the stimulus. The durations for this experiment were 3, 6, 12, 24, and 48 milliseconds. Two subjects were used and 400 reactions were taken for each condition. Mean reaction times and mean variations were taken for each condition. Mean reaction times and mean variations were also computed for each of the sets of data. It was stated that the lowest intensity used was well above threshold due to the limitation of the apparatus.

The results showed that reaction time increases as the intensity of the stimulus decreases. More explicitly, the time of reaction tends to increase arithmetically as the intensity of the stimulus decreases geometrically. Reaction time was plotted against the logarithm of the stimulus intensity and a linear curve was obtained.

Hecht's (1918) work on Mya arenaria, has shown a similar relation of luminance and reaction time. Mya, when exposed to light,
retracts its siphon. Hecht used the time from the beginning of the exposure, to the beginning of the retraction, to calculate the velocity of light adaptation. He showed that reaction time is a reliable method of finding values of the increment of intensity which give the same degree of discrimination at different adaptation levels. In a similar study (1928), he found that reaction time appears to increase linearly to the logarithm of the stimulus intensity.

Hovland (1936), investigating human reaction time to flashes exposed in different background intensities of illumination, found a decrease in reaction time as the difference between the stimulus and adaptation field increased.

In a similar study, although using more comprehensive stimulus ranges, Bartlett and Macleod (1954) studied the effects of flash and field luminance upon human reaction time. They found that reaction time showed little drop with further increases in flash brightness where the stimulus luminance was clearly distinguishable from the field luminance. There was, however, a large increase in reaction time as the contrast between field and flash was reduced. The reaction time was faster for the foveal position than it was for the peripheral position, but with dim luminances the reverse was true. The functional relation of luminance to reaction time was demonstrated by fitting the following equation to the data:

$$T = \frac{1}{B \log \frac{I}{I_0}} + K,$$
where B is a slope constant, I is flash luminance, I₀ is a limiting flash intensity, dependent on the field luminance to which the subject is adapted at which reaction time approaches infinity, and K is a limiting latency which reaction time approaches as I becomes very large. The essential difference between this formulation and that of Piéron's, mentioned earlier, is that Bartlett and Macleod employed logarithmic units instead of arithmetic units. This logarithmic unit substitution more adequately described the extensive Bartlett and Macleod's data than did the formulation of Piéron.

Temporal conditions or a visual stimulus also determine the magnitude of reaction time although not all investigators agree on the amount or directions of the effect.

The first systematic investigation into the effects of duration of a visual stimulus upon reaction time was made by Froeberg (1907). His method was described earlier in this paper. From his results, Froeberg concluded that reaction time increases arithmetically as duration decreases geometrically. When comparing the effects of the duration of stimulus with the effects of luminance, Froeberg found that reaction time decreased with an increase in either variable, but for his data the increment produced by an increase in illuminance was twice that of the same increase in duration.

Wells (1913) in studying the effects of the duration of a visual stimulus on reaction time, failed to find any evidence that reaction time
increases as duration decreases beyond the shortest value he tested. Wells obtained reactions from the onset of a stimulus light 12, 25, 64, 144 and 1,000 milliseconds in duration. A plastic disc forming a retinal image of 0.014 millimeters was illuminated by a Nernst filament. The illumination at the disc was 3 1/4 candle power at a distance of 142.5 centimeters. From these results, he stated that if there was any relation between reaction time and duration of a stimulus, it was that the longer the duration of the stimulus, the longer was the reaction. The probable relationship between the reaction time and duration of stimulus would be a direct one, that is, for every unit increase in stimulus duration, there would be an increase in reaction time although not in the same proportion. Just why this should be so is not argued successfully, for obviously if a stimulus exists in strength sufficiently long to excite a response, any further continuation of the stimulus would not effect the speed of the response. At any rate, the inverse relation that Froeberg found was not substantiated in Well's data. In his discussion, Wells minimized the effects of duration in both his experiment and Froeberg's experiment because of the small differences in reaction time produced by increases in duration.

Pease (1964) determined the effects of duration of a visual stimulus upon simple reaction time, using a large range of durations from three to 500 milliseconds at luminances that ranged from near threshold to very bright values. His experiment showed that reaction time
is inversely related to an increase in duration for the two lowest luminances tested (0.42 and 0.84 millilamberts), but that reaction time is fairly constant to the higher luminances (2,670 millilamberts). Evidently three milliseconds is sufficient for the sensory impression of his brightest flashes, so reaction time was not affected by more stimulus time.

Pease also found that for the two lower luminances, reaction time decreased as stimulus duration increased up to a certain critical duration, after which, reaction time was a constant. His findings suggest that the critical duration seems to depend upon flash luminance, and that as higher luminance levels are reached, increases in duration (beyond some critical period) do not affect the reducible margin or the reaction time.

Froeberg and Wells used a wide range of durations which would lie within the critical duration for low luminance but their intensities were too high to allow duration to determine much of the response. To explore adequately the effects of duration upon reaction time, near-threshold luminances should have been employed.

Pease and Sticht (1965) investigated reaction time as a function of onset and offset stimulation of both the fovea and periphery. Four luminance values were used (31,400 ml., 314 ml., 3.14 ml., and 1.98 ml.). They found that reaction times to the offset of a light in the fovea, at the lower luminance values, is faster than to the onset of that same
light. However, in the periphery, the reaction time to the offset of the stimulus is longer than that to the onset. They thus concluded that at low luminance levels, the offset reaction times are faster than the corresponding onset reaction times, and this difference may be eliminated, or possibly even reversed, by increasing the luminance to a high level.

In the periphery, the onset reaction times were faster than the offset reaction times at all but the very highest luminance level. Thus, in the periphery, there is not only a reversal of the effects obtained with foveal stimulation, there is also an increase in the differences between onset and offset reaction times. Pease and Sticht point out that these differences tend to persist over a wider range of luminance values than do the foveal effects. This lends support to the electroretinogram studies of other animals where investigators have shown that the off-effect is more conspicuous in cone than in rod electroretinograms. Their findings also suggest still another functional differentiation between the fovea and the periphery.

A Comparison of Binocular and Monocular Reaction Times

As mentioned earlier in this paper, only a few investigators have used reaction time to investigate the question of the existence of a common sensory path involving both eyes. One of the first was Poffenberger (1912).
Poffenberger (1912) reported the reaction time to light to be about 0.015 seconds faster for each of three subjects he used when both eyes were stimulated than when only one eye was stimulated. Only foveal stimulation was used during the tests. He felt that this difference was not due to the retinal apparatus, but due to central factors, that is, due to a difference in the speed of conduction through the brain centers. Each fovea is represented on each occipital cortex, so that a stimulus striking the fovea of one eye would react upon both visual centers in the cortex. A stimulus falling on the fovea of each eye would act as a double stimulus upon each visual center. The greater energy set free by this double stimulus would therefore account for the decrease in reaction time.

Miles (1936) found that an appreciable difference appeared in the eye-movement reaction latency when the stimulation, which was peripheral, was changed from the monocular to the binocular. The latency measurements were made by the photographic corneal-reflection method. The stimulus apparatus consisted of a special lamp box with a front about 30 cm. square which faced the subject. It was fitted with four mm. openings for stimulus presentation. Monocular stimulation was achieved by covering the left eye opening with a dark cardboard screen. The stimulus openings were illuminated from within the box by the use of four clear 40-watt, 120-volt Mazda lamps mounted in a quadruple socket and equipped for diffusion purposes with two
spaced thicknesses of ground glass interposed between the lamps and the openings. With the fall of a screen which turned the recording beam on the eye, a resistor in the lamp circuit was suddenly short-circuited and the lamp filaments, which had been heated to a dull red, instantaneously came up to full brilliance. From ten to 35 reactions could be measured on the photographic plates. The recording was always made from the right eye in both binocular and monocular stimulation.

The monocular-stimulation series used showed a mean for 256 eye reactions that was 26.3 milliseconds longer than that for the 196 reactions in the binocular-stimulation series. However, Miles felt that this difference did not offer conclusive evidence of binocular summation at a higher level. Certain features inherent in his eye-reaction recording technique prevent any definite answer. First, registration was always taken from the right eye. At the moment the stimulus appeared, a narrow, nearly parallel, actinic beam of light was turned on the right eye from a position (reflecting mirror) 22° to the right, and about 10° down, from the primary line of regard. This beam of blue light had, through the diffusion of some light in the media of the eye, the unavoidable subjective effect of suddenly dimming the field including the pre-fixation dot and the presented stimulus. Because the left eye did not receive the recording beam, it was free from the visual dimming effect produced in the right eye. This dimming effect was
much more obvious when the stimulation was monocular. "It seems not improbable that the visual interference from the recording light beam may account in large part or even wholly for the longer latency when the right eye was used alone," said Miles.

In the monocular series, reactions to stimuli occurring in the right half of the field were scarcely shorter than in the left half, whereas, in the binocular series, the difference in favor of the right side was 12.8 milliseconds. This difference was statistically significant.

Minucci and Connors (1964) measured reaction time under three viewing conditions: binocular, dominant eye and non dominant eye stimulation. They presented four photopic intensity levels (7.13, 8.06, 9.10 and 10.18 log uuL.) to their dark adapted subjects under the three viewing conditions. The stimulus was presented to a one degree area of the fovea. They found that reaction time was a negatively accelerated, decreasing function of increased light intensity. Or, phrased another way, the reciprocal of reaction time increases with the increase in log intensity.

Binocular reaction times were faster than dominant eye reaction times, which in turn were consistently faster than the nondominant eye reaction times at all intensity levels. The overall increase in reaction time from binocular to dominant eye was found to be approximately six percent, and to the nondominant eye about ten percent. Minucci and Connors also found a constant relationship between the binocular reaction
time and the average monocular reaction time for each S.

They showed that for a visual stimulus to evoke the same speed of reaction (equal latency), the light must be between .53 and .71 log units higher on the brightness scale when presented to the dominant eye, than it is when presented to both eyes. At the lower intensities, the same speed of reaction is evoked when the light is .85 log unit brighter presented to the nondominant eye, and at high intensities when the light is 1.4 log units brighter presented to the nondominant eye, than to both eyes. At the high brightnesses, the stimulus had to be .72 log unit brighter to evoke the same response in the nondominant as in the dominant eye, while at the intermediate levels, the difference in equivalent brightness averaged .35 log unit.

At the intensity levels used, summation was clearly demonstrated. The percent decrease in binocular reaction times as compared with the average monocular reaction times ranged between 5% at the highest intensity and 12% at the lowest intensity. Using a 2-cp. light, Poffenberger (1912) had found an 8% decrease in binocular foveal reaction times as compared to monocular reaction times.

Minucci and Connors found that a light stimulus to both eyes had the same effect as one ranging between .69 and 1.07 log units brighter to one eye, depending on the luminance level. The absolute log-unit difference also varied with the intensity level. There was a constant relationship of approximately 1.1 between average monocular
and binocular brightness equivalents. The log-unit differences found for equivalent reaction times between the average monocular and binocular conditions were greater than could be expected even with complete summation. To the authors, this indicated that the increase in brightness with binocular vision only partially explains the reductions in reaction time.

Unlike the monocular-to-binocular brightness ratios, the non-dominant to dominant ratios were not constant and indicated that the differences between the nondominant and the dominant eye as measured by reaction time are slightly reduced in the middle range of intensities. This implies that when only one eye is being used for observations, the factor of dominance is an important one.

Contrary to what might be expected, dominant eye visual acuity was superior to nondominant eye acuity only in four cases, the same in one, and in five cases acuity was superior in the nondominant eye. Binocular visual acuity was superior to that of the dominant eye in only six of the ten subjects.

The authors concluded that acuity is not a factor in determining the superiority of the binocular reaction time over monocular, or of the dominant eye reaction time over nondominant.
Binocular Interaction at the Threshold of Seeing

Lythgoe and Phillips (1938) showed that the smallest illumination visible during adaptation to darkness is less when observations are made binocularly than when they are made monocularly. They obtained quantitative measurements of the monocular and binocular thresholds during adaptation to darkness, for a large test patch by using a composite white light. After the preliminary period of light adaptation, the subject was plunged into darkness and a predetermined illumination was projected on a test patch which was illuminated by projecting an image of one side of an opal glass screen on a wall. The range of illumination of the test patch was from $5.6 \times 10^{-3}$ to $2.2 \times 10^{-7}$ equivalent f. c. A flash occurred every 2.5 seconds and lasted for 0.2 seconds. A small red spot of light projected at a spot corresponding to the center of the test patch served as a fixation light. Since the pupil diameter is known to fluctuate considerably in the dark, the investigators insured a uniform maximal dilatation of the subject's pupils through use of a mydriatic which was periodically administered throughout the experiments. A predetermined illumination was projected on the test patch and the subject signaled the experimenter when he saw the flash by pressing a key. The time taken for the subject to see a flash was then recorded. The illumination was then immediately reduced, and, as before, the time taken by the subject to see the new illumination was recorded.
The visual angle subtended by the test patch was 12 1/2°.

Four or five subjects completed a set of readings with central fixation, while two of the five subjects did a set of readings for the peripheral retina in which the fixation spot was 25° distant from the center of the test patch and slightly higher.

Observations with both eyes, the right eye and the left eye were made in all possible combinations. Readings for both eyes and for each eye separately were then averaged. The results were plotted on a logarithmic scale, showing both the threshold brightnesses and the average times at which they were seen. For all subjects, and for all stages of dark adaptation, the binocular threshold was lower than either of the monocular thresholds. Binocular summation was said to have occurred at all stages of dark adaptation. Also, the binocular threshold was approximately the same as the monocular for a test patch of twice the area.

Bartlett and Gagné (1939) criticized Lythgoe and Phillips' findings by pointing out that they used a small red cross in the center of the stimulus patch as a fixation point and that light adaptation was accomplished by uniformly illuminating the chamber in which the subject sat. They said that under these conditions of illumination, the subject probably focuses his eyes for far vision. Thus, it is possible that in the change from light adaptation to dark adaptation, the parallel position of the eyes would suffice for the monocular determinations, while for the binocular,
a greater amount of convergence and accommodation would be necessary. This would lead to the stimulation of different retinal areas, and the slight amount of summation found (about 0.15 log unit of intensity) might be accounted for in these terms. This weakness points out the necessity for controlling fixation conditions. Bartlett and Gagné ran three experiments with a special view of controlling the fixation factors. They made no attempt to record the entire course of dark adaptation under binocular and monocular conditions. Instead, a number of measurements were taken after a given interval in the dark, or at approximately the same point on the dark adaptation curve. Results of these experiments showed no evidence for the existence of foveal binocular summation at threshold. The results, however, were not interpreted as excluding central interaction effects under certain other experimental conditions. They pointed out that when the stimulating areas are illuminated with intensities far above threshold there occur such effects as those encountered in Fechner's "paradoxical experiment." In this experiment, a subject looks at an evenly illuminated white surface with both eyes, and then with one eye alone. In the latter condition, the brightness of the surface appears reduced. By introducing various filters in front of one eye during binocular observation, it is possible to make the surface appear either brighter or darker when the subject shifts to monocular observation.
Pirenne (1943) admits that the absolute threshold of binocular vision is slightly lower than monocular threshold, but he attributes the difference entirely to the probability of seeing at this level. Pirenne bases his argument on the findings of the quantum nature of light, in which there occurs at the absolute threshold of vision, fluctuations of a purely physical nature which are large enough to account quantitatively for the variability of the response of the organism to the stimulus.

The large magnitude of these fluctuations is due to the extreme smallness of the number of quanta which are active at the seat of action of light upon the nervous system, that is, which are actually absorbed by the retinal rods (5-14 quanta as an upper limit).

Thus, at the threshold, the magnitude of the physical stimulus varies at random from one trial to the next even when conditions are kept rigorously constant. Variations in the sensitivity of the organism may also occur, but clearly the physical fluctuations dominate the situation.

Of course this refers to the unocular threshold. In regards to the binocular absolute threshold, the random nature of the stimulus variability probably accounts for the lower threshold.

If the brightness threshold is defined as the brightness at which the probability of seeing the light flashes is, for example, 0.50, we may ask whether the binocular is not lower than the unocular threshold simply because the probability of receiving one stimulus of sufficient magnitude is greater when the subject is using two eyes than when he is using one, the two eyes acting as independent light detectors, . . .

said Pirenne.
Five experiments were conducted by Pirenne in a small peripheral region of the dark-adapted eyes. The circular test field, made of opal glass, 10' in diameter, was placed 20° below a fixation point; it could be illuminated with white light for durations of four milliseconds. Log brightness used in two of the tests was 1.0, and in a third test, 1.4. A log brightness of 1.0 corresponds to an actual test field brightness of 0.0047 e.f.c.

In each experiment, the frequency with which the subject saw the flash with the left, with the right and with both eyes, at one of several brightness levels was recorded. The natural pupils were usually used, but sometimes pilocarpine was used to contract the pupils to a fixed size. This did not alter the results over those obtained when it was not used.

Theoretical calculation of the frequency of seeing with both eyes in terms of the frequency of seeing with the left and with the right eye were made. Letting PL, PR and PB be the probabilities of seeing with the left, with the right and with both eyes, and assuming that the probabilities PL and PR are independent, it follows that from the definition of probability that,

\[ PB = 1-(1-PL) (1-PR) = PR + PL-PLPR \]

As an approximation to PL and PR, the observed frequencies of seeing with the left and with the right eye were used. In a series of \( n \) flashes, the standard deviation of the frequency of seeing to be expected theoretically on the basis of random variations is equal to,
In experiments one to four, the differences between the observed binocular frequencies and the calculated values of PB were of a magnitude to be expected with the allowable error. Pirenne concluded from these results that the two eyes act as independent detectors. He also pointed out that if complete summation were to exist, the two eyes would behave as a single unit and the same result would be achieved by exposing both eyes to a certain brightness or exposing one eye to twice that brightness. He found that doubling the brightness of the flash in one eye raised the frequency of seeing from an average of 0.38 to an average of 0.86, while the binocular frequency for the former brightness was found to be only 0.56. Pirenne felt that this ruled out complete physiological summation and showed that the possible amount of partial summation, the existence of which cannot be ruled out because of the inaccuracies of the measurements, must be small in degree.

In the experiment for the brightness level at which the largest number of flashes was tried, the observed binocular frequency agreed with the calculated one well within the standard deviation, which was less than four percent. Pirenne also found that the experimental frequency curve determined for the left eye agreed fairly well in shape with the theoretical curve he had calculated on the basis of the Poisson equation for a retinal threshold where \( n \) equals six quanta. He also found that the right eye experimental curve agreed with the calculated

\[
\sigma = \sqrt{p(1 - p)/n}.\]
curve. Theoretical curves R and L were drawn for n equals six quanta through the two points representing the unocular data of the fifth experiment. Theoretical binocular curve B of PB was then calculated in terms of the curves R and L. Curve B was then compared with the experimental points for the binocular frequency of seeing, and good agreement was found between the two. He thus found, that, notwithstanding the absence of physiological summation, the binocular threshold was about 0.1 log unit below the mean of the unocular thresholds. The binocular frequency curve was also steeper than the unocular curve, and the threshold for the two eyes was more sharply defined than the threshold for one eye.

His results showed that the barrier to be overcome by the stimulation must be situated below the fusion level of the nervous paths of the two eyes. Pirenne also stated that application of the same conceptions to the interaction between different regions of one retina also suggests itself, and is likely to have a bearing on the theory of all frequency of seeing curves.

Collier (1954) maintains that the probability of response is significantly greater for binocular vision than for monocular. He then found that this summation is significantly greater than that which would be expected by the combination of independent but nonmutually exclusive probabilities. These results were borne out of three experiments. Apparatus used for the experiments was designed to present the dark
adapted subject with a short (.001 sec.) peripheral (20°) monochromatic circular flashes of light for a 10° visual angle at a constant intertrial interval of 4.67 seconds. The brightness of the stimulus patch was continuously variable over a wide range of values. An image of the filament of a strip filament, six volt, 18 amp. lamp provided the illumination for the stimulus patch. Condensing lenses brought the image of the filament to focus at the 1-mm. strip stop located immediately before the fast blade of a three-bladed rotating shutter. The image of this stop was projected onto a ground glass screen. The visual angle of the stimulus patch was 10° produced by a circular aperture in a shim metal stop placed immediately in front of the ground-glass screen which was located in a light-tight chamber in which the subject sat.

The distances from the artificial pupils to the stimulus patch and to the fixation point were both 50 cm. The fixation point was red and subtended 10° of visual angle. The stimulus patch appeared 20° below the fixation point. The artificial pupils used were 3 mm. in diameter. The interpupillary distance of the artificial pupils and the position of the mouth bite with respect to the artificial pupils were adjustable in the vertical and horizontal dimensions, and reproducible to .5mm.

Four blanking shutters separately operated by Telechron motors were mounted between the artificial pupils and the stimulus patch.
These shutters were so located that it was possible to interrupt the visual path between either eye and the stimulus patch and the fixation point, separately, or in any combination. The subject responded, if he saw a flash of light, by means of a telegraph key.

Three fixation conditions were possible in Collier's experiments; binocular fixation, monocular fixation right eye, and monocular fixation left eye. Three viewing conditions were also possible: binocular viewing, monocular viewing right eye, and monocular viewing left eye.

In experiment 1, Collier varied the fixation and viewing conditions. In experiment two, fixation was always binocular and viewing conditions were varied. In the third experiment, viewing was always binocular and fixation was varied. Experiment four was the same as experiment one, but no artificial pupils were used. In each of the experiments, a single luminance method of stimulus presentation was used which allowed for a large number of trials and also made possible the calculation of a measure of association. The luminance for each subject was chosen to yield approximately 75% "yes" responses binocularly in the first, second and fourth experiments, and 50% "yes" responses in the third experiment.

Results of experiment 1, in which the fixation and viewing conditions were varied concomitantly, showed that the percentage of "yesses" under monocular conditions was approximately one-half of the percentage
under the binocular condition. The expected value for the binocular percentage "yesses", calculated on the assumption of independent but not mutually exclusive events \( \text{Pb} = \text{Pr} + \text{Pl} - \text{PrPl} \) from the monocular values was 59.9%. The discrepancy between the obtained (75.0%) and expected values were calculated for each subject on each day. The obtained binocular value was above the expected value in 34 out of the 36 cases tested. It was above the largest value in 35 out of 36 possible comparisons. Thus, summation was significantly present \((p < .01)\).

Results of experiment two were similar to experiment one, again indicating summation.

In experiment three, in which the fixation conditions were varied and the viewing condition was always binocular, monocular percentages of "yesses" were approximately 80% of the binocular percentages. Sixteen of the 18 possible binocular values were above the highest monocular value. Thus binocular (viewing) percentage of "yesses" with only one eye fixated is significantly less than the binocular percentage of "yesses" with both eyes fixated.

In experiment four, in which the fixation and viewing conditions were the same as experiment one, but in which no artificial pupils were used, the percentage of "yesses" under the monocular condition was again approximately one-half of the percentage under binocular condition. Twelve out of the 13 possible binocular values were above the expected value. The possibility that the significant amount of summation
reported in experiments one, two and four was an artifact of the combination of independent nonrandom sequences was checked by Collier by an empirical sampling experiment and found unlikely.

Collier (1954) reported that one interesting result occurred in three sessions for two subjects in which one of the monocular Pr's was zero, but in which the binocular Pr showed a significant amount of summation. "This," said Collier, "indicates the possibility of subliminal summation."

From the data obtained, Collier evaluated the hypothesis that binocular stimulation of corresponding points of homogeneous areas of the retinae should be considered as functionally equivalent to doubling the area of stimulation in a single eye. Monocular left eye method of limits data for each of the nine subjects were plotted on probability paper and straight lines fitted visually. The average slope over the four days of testing was calculated for each subject. From these slopes, on the assumption that the slope for binocular determinations would not differ from monocular determinations, the increment in log brightness necessary to produce the increment in percentages of "yesses" from the monocular to the binocular condition was calculated. The average for all subjects and days was .18 log uul with a standard deviation of .03. The same value was also obtained from constant method data. Ricco's law ($AI = k$) predicts an increment of .30 log uul. which is obviously too large. Piper's law ($\sqrt{AI} = k$) predicts an
increment of .15 log uul. On the assumption that .15 is the population value, a t-test of the difference between the obtained value and the population value failed to reject the null hypothesis but was very close to being significant.

Collier pointed out that the detection of summation cannot be attributed to the optimal conditions used during the experiment since Pirenne (1943) used almost identical stimulating conditions, with the exception of a longer duration of stimulation, and failed to find summation. This divergence of results might possibly be explained in that cumulative retinal changes produced by repetitive stimulation are a necessary condition for summation. In this respect, Collier's experiment differed from Pirenne's in that it used a single luminance method of stimulus presentation with a fixed intertrial interval rather than one of the more conventional methods of threshold determination.

Matin (1962) summarized the binocular-monocular threshold of vision debate, by pointing out that it centers around two main points. First, concern over the existence and nature of a common sensory path for the two eyes central to the optic chiasm, and second, concern with the determination of the location of the locus or loci between stimulus and psychophysical response at which the largest barrier to threshold seeing exists. The monocular-binocular threshold comparison has seemed to offer an avenue of information on these matters, although this avenue is by no means an exclusive one. Work on
binocular vs monocular flicker, binocular vs monocular brightness matches and the influence of an adapting light in one eye on the threshold in the other eye have also been studied in this connection.

The weight of the more recent evidence on the threshold question has favored the result that the binocular dark-adapted absolute-intensity threshold is lower than the comparable monocular threshold. However, it has been pointed out by Pirenne (1943) that contrary to the classical conception of matters, a finding of a larger monocular than binocular intensity threshold would not necessarily establish the existence of a common nervous pathway for the two eyes. Simple statistical considerations which assume that the two eyes are independent detectors would predict that a larger monocular than binocular threshold will be found even though a nervous mechanism for binocular summation might not exist. Should this hypothesis of probability summation be found to hold empirically, however, nothing could be inferred regarding the existence of a common sensory pathway for the two eyes since the largest barrier to seeing might lie peripheral to the common path; the presence of nervous summation at the entrance to the common path would not in this case influence the outcome of the threshold responses. Any signal getting through the peripherally located largest barrier would also be passed into any existing common path, but any signal not getting through the peripheral largest barrier would not then enter into a summation process at the entrance to the
common path. However, should the result $P(B) > P'(B)$, where $P(B)$ is the binocular probability of seeing and $P'(B)$ is the prediction if the eyes acted as two independent detectors, be found, then it would be necessary to conclude, 1) that a common sensory path for the two eyes is being used at threshold and, 2) that the largest barrier to threshold seeing resides at, or central to, the entrance to the common sensory path.

Experimental comparisons of $P(B)$ and $P'(B)$ have resulted in conflicting outcomes. As previously discussed in this paper, all three possible outcomes have been found. $P(B) = P'(B)$ (Pirenne, 1943), $P(B) < P'(B)$ (Casperon, et al., 1950), and $P(B) > P'(B)$ (Collier, 1954).

Matin (1962), felt that an answer might be provided by performing an experiment which placed the comparison of $P(B)$ and $P'(B)$ into a framework which tests for temporal summation. Should summation exist beyond a combination of probabilities of seeing of two independent detectors, it would be clear that the magnitude would depend on how the energy is distributed in time. For example, should the test flash to one eye precede the test flash to the other eye by several seconds, it would be expected that even if a nervous mechanism for binocular summation existed, it would not be manifested. On the other hand, any nervous summation which does exist might be expected to be called into play if the flashes to both eyes occurred simultaneously. Thus, by varying the
temporal interval between the occurrence of the test flash to corresponding locations of the two eyes it would be expected that if a nervous mechanism for binocular summation exists it would be manifested in a function showing a probability of seeing which was greater at shorter time intervals and less at longer time intervals, perhaps dropping to the level predicted by the hypothesis of two independent detectors at very long time intervals. If no nervous mechanism for binocular summation exists, the probability of seeing would not change as the time interval between the onsets of the test flashes to corresponding locations of the two eyes was varied. One might also expect the constant probability of seeing to be predicted by the hypothesis of two independent detectors.

Matin made measurements of binocular probabilities of seeing for varying separations between onset of test flash to corresponding locations of the two eyes, as well as measurements of monocular probabilities of seeing. Two dark-adapted subjects were used throughout the experiment.

The optical unit used was constructed so that the stimulus flash could be presented to either eye singularly, or both together. Each eye had its own fixation target. The use of identical but separate test targets for each eye made possible an adjustment of the physical distance between them which insured that they stimulated corresponding locations in the two eyes. It also made possible the variation of the temporal
interval between the onsets of the stimuli to corresponding locations in the two eyes and permitted the luminances to the two eyes to be easily adjusted separately. The binocular view of the test target after adjustment and when lights for both stimuli were turned on consisted of a single circle, 35 minutes of visual angle in diameter. The duration of the light stimulus to the left eye was 1973 usec, and to the right eye, 1865 usec. Corresponding points of the two retinae were stimulated. The test targets were adjusted so that the subject reported complete fusion of the two views. Flash stimuli were used for the adjustment of the targets. Thirty five-min. 5-millisecond flashes of high, equal luminances were presented simultaneously, one to each eye. The target aperture serving the left eye was horizontally displaced 7° away from the fixation target for that eye. The aperture serving the right eye was then moved laterally between trials to the subject's command until the subject's response went from "two" to "one" on each trial. This adjustment was accomplished with relative ease.

When there was an interval between flashes to the two eyes, Martin reported that an interesting development appeared. With interstimulus temporal interval (ITI) at about 60 milliseconds, the subject sometimes reported that he saw two spatially separated flashes. A further adjustment of the location of the target aperture for the right eye changed the subject's report to "spatial superposition with temporal
separation." For this adjustment, when the two flashes were simultaneous, fusion was maintained.

For larger interstimulus temporal intervals of about 150 to 200 milliseconds, it proved impossible to obtain an adjustment which resulted in a consistent report of spatial superposition. Instead, the two flashes appeared to overlap somewhat, but the amount of overlap changed from trial to trial. At ITI values of 200 milliseconds, the best that could be done was to obtain a report of "complete overlap" about ten percent of the time, "3/4 overlap" about thirty percent of the time, and "1/2 overlap" about sixty percent of the time. The adjustments were made separately for each of the two subjects with about the same results.

During the lateral movement, the test target appeared to move back and forth in the third dimension. Adjustment was to a criterion in which both test and fixation targets appeared to the subject to lie in the same apparent frontal plane.

Matin's experiment was designed to provide measures of binocular frequency of seeing as a function of the time interval between two flashes, one to each of a pair of corresponding points in the two eyes, and a comparison of measured binocular frequency of seeing with a prediction from monocular measurements on the hypothesis of physiological independence of the two eyes. Each monocular stimulus presentation consisted of a single flash to either the left or right eye. Each
binocular stimulus presentation consisted of two monocular flashes presented together with a predetermined time interval between them. The time interval was the main independent stimulus variable of each experiment. On each trial, the subject received a flash to the left eye, or a flash to the right eye, or a binocular presentation with a particular value of ITI. The subject reported on whether he saw a light, did not see a light, or saw more than one flash. Interstimulus temporal intervals ranged from 0 to 275.75 milliseconds.

Matin found that $P(B) > P'(B)$ for ITI values smaller than about 100 milliseconds. The hypothesis that the two eyes behave as two independent detectors at the absolute threshold can predict only one possible outcome for Matin's experiments. $P(B)$ should not vary with ITI. Since this prediction did not hold, the hypothesis cannot be right. Matin thus concluded that the main component in the difference $P(B)$ and $P'(B)$ at ITI values less than about 100 milliseconds involves a process of nervous summation occurring in a common sensory path in the visual system central to the optic chiasm. Seeing thus occurred on some binocular trials in which seeing would not have resulted had the flash been presented to the left eye alone or to the right eye alone. This is equivalent to the significant result that subliminal processes (those below the threshold of seeing) can travel in each monocular system at least as far as the lateral geniculate synaptic layers. Such a conclusion means that the largest barrier to seeing at threshold must lie central to
the retina, and any treatment of threshold phenomena must consider events at this barrier.

Matin also reported some indications that the magnitude of binocular summation at the absolute threshold is less than the magnitude of summation of intensities within one eye. At an ITI equal to 0, two 35-min. 2-millisecond flashes each producing a given probability of seeing, resulted in a greater probability of seeing when both were presented to one eye than when one flash was presented to one eye and the second to the other eye. It also seemed that the probability of seeing-ITI function for one eye was unimodal rather than bimodal as was the case for the $P(B)$-ITI function. The most striking aspect of the $P(B)$-ITI function was found in the dip at about 70 milliseconds and a secondary rise at about 90 milliseconds. The bimodal form of this function makes it clear that the value of $P(B)$ for a fixed mean luminous energy presented to both eyes depends on how the energy is distributed in time between the two eyes up to ITI values of about 100 milliseconds. Thus, in binocular vision, intensity and time are not reciprocally related quantities for a fixed response. Such a result is different from that found for small areas in monocular vision in which the temporal distribution of a fixed quantity of energy in a single flash up to a critical duration is irrelevant to threshold seeing.

The time-intensity reciprocity in monocular vision has been interpreted as a process going on at the retina, and the fact that a
similar reciprocity and similar values of critical duration have been observed in the optic nerve supports such a conclusion.

Matin's (1962) data indicate the presence of a summation process at regions beyond the retina. It seems that any interpretation must require that the first flash in every binocular stimulus sets up an excitability cycle at some post-retinal location(s) in the visual system. The form of the $P(B) \text{ vs } ITI$ function is then determined by the fact that the optic nerve response to the second flash taps in on different phases of this cycle at different ITI values.

We must remember that absolute thresholds are not precisely measured with the method of limits technique. The frequency technique is much more precise. Some of the results of the early experiments might be expected if stimulation of corresponding retinal locations in the two eyes was not assured and/or if correlation between measurements of monocular probabilities of seeing were to occur. These factors were carefully eliminated in Matin's experiments. While the magnitude of binocular summation appeared to be less than the magnitude of summation in one eye that has been previously reported, it is not altogether clear that such would continue to be the case were results compared for equal sensory areas stimulated under stabilized image conditions.
Masking and Metacontrast

The brightness of a flash of light is reduced when it is followed by a second flash in an adjacent region of the field. This effect, metacontrast, depends upon, among other things, the luminance, duration, exposure asynchrony, spatial separation of the two flashes and the region of the field in which the flashes appear.

Alpern (1953) conducted a detailed series of studies on this phenomenon using both binocular and monocular stimuli. His results showed that the magnitude of the effect increased as the luminance or duration of the second flash increased, as the luminance or duration of the first flash decreased, and as the angular separation of the two flashes in space decreased. He also showed that if the two flashes were confined to the two degree center of the visual field, the effect disappeared, but as they were moved gradually out into the peripheral field the effect quickly appeared.

Alpern showed that metacontrast is a U shaped function of $\Delta t$, with maximum suppression occurring in the region of $\Delta t = -100$ milliseconds. By this, Alpern means that a second flash, following a test flash by 100 milliseconds, exhibits maximum suppressive power over the test flash brightness. Alpern was unable, however, to demonstrate interocular induction of metacontrast although some previous investigators have claimed to observe this phenomenon.
Kolers and Rosner (1960) found that with asynchronous presentation of adjacent black figures on lighter backgrounds there is masking of the prior stimulus. Using disc-ring experiments in which the disc (target) and ring (mask) have equal luminance and equal contrast, detection of the disc is a U shaped function of $\Delta t$. Visual masking differs from metacontrast in that two visual forms are presented in sequence for brief supra-threshold durations and the presence of the first form is not reported at certain durations of the pause between them. Kolers and Rosner investigated the masking phenomenon monocularly, binocularly and dichoptically. Dichoptic presentation differs from monocular and binocular presentation in that two different stimuli are presented to each eye at the same time. They encountered no great difficulty in obtaining dichoptic masking using disc and ring as stimulus figures, as did Alpern, who utilized rectangular-shaped stimulus figures. Alpern was unable to obtain dichoptic masking in his experiments.

Boynton (1961) points out that in experiments where the eye is completely adapted to the conditioning stimulus, no bilateral interaction occurs, which suggests a total independence of left and right-eyed visual nervous systems. The threshold for a monocular flash is affected by contralateral excitability, but only when the latter is changing. This would suggest that the two systems are largely independent so far as sensitivity is concerned. Boynton stated, however, that although the
locus of the ipsilateral effect is largely peripheral, the contralateral experiments show that masking can also take place higher in the visual system. Thus, a fraction of the ipsilateral interference may occur at higher levels--most likely at the visual cortex.

In order for the entire ipsilateral effect to be cortical, a much larger signal-to-noise ratio would seem to be required for discriminability at the cortex than at the periphery. This implies that, although a "discernible" signal is sent from the eye to the brain, the visual brain is not able to make use of that signal. It appears most unlikely that the visual system, which seems peculiarly adapted to preserve and enhance small differences in contrast, could operate in such a way.

Boynton also noted that the relative size of the conditioning stimulus compared to the test flash is very important. A small test flash upon a large conditioning field allows discrimination to be made between the brightness of the test spot and the surrounding area even if the two are flashed simultaneously. However, if the conditioning stimulus is of the same size and retinal position as the test spot, the discrimination can be made only by successive comparisons in time. The experimental differences between ipsilateral and contralateral conditions become smaller and may disappear altogether for stimulation of the peripheral retina when the onsets are near one another in time.

The implications of these results are that although the ability of the higher visual centers (presumably the visual cortex) to mediate
spatial discriminations based on intensive differences is very good, these centers are relatively poor at mediating discriminations based upon time alone. An important and very significant exception is the contralateral equal-area condition, in which one eye is completely adapted to the conditioning stimulus. In this case, the test-flash threshold is no different from the threshold for complete dark adaptation of the two eyes, regardless of the areas involved. One interpretation is that under steady-state conditions of adaptation, the prevailing rate of activity in the cortex produced by the conditioning stimulus is so low as to exert a negligible effect upon the perceptibility of the contralateral test flash.

Boynton (1961) firmly believes that the notion of an input quantization of time in vision is compatible with experimental results available. The basic idea is that the visual input may be packaged in successive time frames and that, therefore, any two events that occur within a given time frame, and that depend upon a temporal discrimination alone for their perception, cannot be discriminable. This idea accords with the familiar fact that the visual presentation of sixteen still pictures each second, the standard rate for "motion" picture projection, provides a rather satisfactory illusion of continuous time-flow. Such time packages also appear consistent with what might be expected, from the standpoint of communication theory, or an efficient detection-transmission system.
Is reaction time correlated with the apparent brightness of a
flash of light subjected to various degrees of metachronal masking?

Fehr and Raab (1962) have shown that reaction time depends
on stimulus characteristics rather than on the phenomenal appearance
of the stimulus. They discovered this while dealing with the relation
between reaction time and the apparent brightness of light flashes as
contingent on their duration. Normal reaction times (approximately
160 milliseconds) could be evoked by flashes which were phenomenally
absent. Under appropriate circumstances, subjects can respond with
normal latency to a stimulus whose probability of detection is near
chance.

Reaction time is a convenient measure of retroactive masking
since the masked stimulus is the one presented first. For example, if
the reaction time chronoscope is started when the first stimulus is
presented, it is possible to compare the reaction time to the first
stimulus when it is presented alone with the reaction time to the first
stimulus when it is followed by a masking stimulation.

In their present experiment, masking of a square target was
achieved by subsequent flashing of two adjacent squares. Stimulus on-
set asynchronies were studied over a range from 0 to 75 milliseconds.
Phenomenal suppression of the first flash varied from none (0 asyn-
chrony) to maximum (75 millisecond asynchrony). With both foveal
and peripheral vision, they found no effect of phenomenal brightness on
reaction time. Reaction time to the target, flashed alone, was never faster than reaction time to the target followed by masks. They thus concluded that it was the physical dimensions of the stimulus, rather than its phenomenal characteristics, that determined reaction time.

When the conditioning stimulus is presented to one eye and the test flash to a homologous position in the other eye, backward masking of the latter is still found.

Battersby and Wagman (1962) obtained visual excitability changes from two trained observers by measuring threshold with a test flash of light at varying temporal intervals from a supraliminal conditioning flash. In monocular observation, the two flashes were presented to the same eye; in binocular observation, the conditioning flash was exposed to one eye and the test flash to the homonymous location in the other eye. The conditioning target size was varied while the concentrically placed test flash was held constant. In all instances, thresholds fell to an asymptote, returning to resting level only after termination of the conditioning flash.

Both monocularly and binocularly, an increase in the magnitude of threshold rise was produced by making the conditioning target smaller, the greatest proportionate effect being obtained binocularly. These findings indicate that central (retrochiasmal) processes are critical with respect to spatial interaction in the visual system, a conclusion compatible with recent studies on the cortical receptor field.
Several authors (Kolers and Rosner, 1960; Schiller and Wiener 1963) have reported that perception of a visual pattern can be masked either monoptically (both stimuli to the same eye) or dichoptically (the two stimuli to separate eyes), when the masking stimulus is also a visual pattern. Masking also occurs when a visual form is followed by a stimulus having essentially no figural characteristics, such as a bright flash of light (Lindsley, 1961).

Schiller (1964) performed three experiments to determine whether masking by pattern and masking by flash reflect identical processes, or whether different mechanisms were involved.

In the first experiment, the extent of monoptic and dichoptic masking was investigated as a function of interstimulus interval in order to see if this temporal variable affects masking by pattern and flash in the same, or in a different manner. Results of this experiment showed that the extent of backward masking is a complex function of the interstimulus interval duration. In some cases, masking declines steadily with increasing interstimulus interval; in others, it increases at first and then declines. This is in accord with the results of Alpern (1953) which were presented earlier in this paper. Masking with the pattern occurred both monoptically and dichoptically. The extent of this masking was slightly less dichoptically. With the flash, masking occurred primarily on monoptic presentation. A slight masking effect was also found dichoptically with an interstimulus interval of
three milliseconds.

The visual masking effects reported by Schiller seem to be different from the interference which takes place by metacontrast (Alpern, 1953). In metacontrast, interference with the first stimulus is minimal at short interstimulus intervals, and reaches a maximum between 75-100 milliseconds, then declines again. In Schiller's masking experiments, interference declined steadily with an increasing interstimulus interval. Although a small degree of masking with a dichoptic flash was reported by Schiller, the extent of this masking varied with subjects, and two subjects did not show a significant effect at all. Therefore, it is difficult to draw any conclusions from these findings.

It should be noted, however, that small but reliable dichoptic effects, using flashes of light for both masked and masking stimuli, have also been reported by Battersby and Wagman (1962).

Schiller found that the extent of masking by pattern was slightly less dichoptically than monoptically. He states that this difference can apparently be magnified when the monoptic and dichoptic conditions are presented in separate series of trials, rather than being presented randomly. "It is possible," said Schiller, "that when these conditions are not randomized, the eye receiving the pattern under dichoptic conditions becomes inhibited with practice, thereby decreasing the extent of masking."
The second experiment dealt with the differences observed in visual masking when either a pattern or a flash was used as the masking stimulus. The results show that a decrement in threshold with the pattern was much greater than the decrement with the flash. The extent of masking by the pattern was somewhat greater monoptically than dichoptically. Also, the extent of masking by the pattern was less with an interstimulus interval of 20 milliseconds, than with an interstimulus interval of three milliseconds. This difference was much greater for the monoptically presented flash.

Schiller's third experiment employed various combinations of flash and pattern in the masking situation in a further attempt to assess the processes underlying masking and the relationship between the two kinds of masking situations. He found that presenting flash and pattern together to one eye significantly increased the masking effects. This occurred both upon monoptic and dichoptic presentation, but masking on monoptic presentation was significantly greater than on dichoptic.

As a result of these experiments, Schiller feels that there are two distinguishable processes of masking involved. The one for flash seems to occur in the central visual pathways prior to the mixing of the two monocular representations. The process for pattern occurs at levels where the two monocular fields interact. The decline in masking by pattern on repeated trials further suggests complex processes of perception in which learning might play a role.
Physiological Evidence for Binocular Interaction

Our discussion would not be complete without a brief survey of the physiological evidence for binocular interaction. Fillenz (1960) has shown that, in the cat, there is evidence to suggest that the lateral geniculate body is an important integrative center. In studying the interaction of impulses coming from the two eyes of anaesthetised, dark-adapted cats, she found that the lateral geniculate body was arranged in three zones. Two zones contained units which responded to illumination of the contralateral eye, separated by a middle zone which responded to illumination of the ipsilateral eye. Sixty-six units of the lateral geniculate body were isolated for study. Each unit was subjected to light stimulation of the two eyes. Only seven units could be activated from each eye separately. The rest responded only to either the ipsilateral or the contralateral eye. In the seven units which responded to both eyes, the responses to the two eyes were different.

A second approach was tried by Fillenz by giving various combinations of binocular stimulation. Out of nineteen total units investigated, there were thirteen units where illumination of only one eye produced a response, but illumination of the other eye, even though by itself it produced no response, modified the response of the unit to illumination of the first eye. When a light was applied to the ipsilateral eye, all the bursts following this stimulus were delayed. The earlier the ipsilateral stimulation occurs, the more marked this effect.
In a second experiment, Fillenz investigated the problem of optic nerve fibre distribution in the lateral geniculate body of the cat by using the Glees silver staining method. Three types of cats were used: normal cats, cats surviving for three to seven days after removal of one eye, and cats surviving for fifty-seven to three hundred and fifteen days after eye enucleation.

The results showed that two interlaminar layers existed in the sagittal section of the geniculate body in addition to the three layers classically known. These interlaminar layers consist of a fibre plexus containing optic tract fibres derived from both eyes. In cats where the fibres from one eye are in the process of degeneration, the presence of degenerating synaptic terminals in both interlaminar layers of both sides demonstrates that these interlaminar layers contain synaptic terminations from both eyes. Fillenz states, however, that, "the presence of degenerating and normal synaptic terminals of the interlaminar layers is suggestive but insufficient evidence for binocular convergence on to a given neurone. Such convergence, however, is implied by the electrophysiological findings."

Burns, Heron and Grafstein (1960) recorded surface potentials and single unit potentials in the cat's cerebral cortex in response to diffuse visual stimulation. They found that surface responses produced by stimulation of the contralateral eye are larger in amplitude than those produced by stimulation of the ipsilateral eye, while those produced by
binocular stimulation are larger still. The amplitude of the surface responses increased to a maximum with increasing intensity of stimulation. For any given single cell, there was a constant ratio between the average number of unit discharges in response to contralateral, ipsilateral and binocular stimulation. At different stimulus intensities, this ratio was found to be constant, although the absolute numbers of discharges may be different. It was possible for them to divide the cells into functional groups according to: which eye produces the larger number of discharges; (i.e. which eye is dominant) and, whether binocular stimulation produced more, fewer, or as many discharges as stimulation of the dominant eye alone. All the functionally different types of neurons were found in all the cellular layers of the cortex. The latency of the unit responses was found to be shorter with binocular than with monocular stimulation, and was also shorter when brighter stimuli were used.

Auerbach, et al., (1961) investigated the electric potentials of the retina and cortex of cats evoked by monocular and binocular photic stimulation. They found that surface responses produced by stimulation of the contralateral eye are larger in amplitude than those produced by stimulation of the ipsilateral eye, while those produced by binocular stimulation are larger still. One way to explain this phenomenon is to assume that the uncrossed pathway of the cat's visual system is of smaller diameter than the crossed, which means that it consists of a
smaller number of individual fibers. This would imply a wider
cortical projection of the crossed connections. Electrophysiological
support has been found for this view, but anatomical support has not.

Their measurements showed that the cortical response to
binocular stimulation results from the linear summation of the electro-
motive forces of cortical responses to both monocular stimulations.
In other words, upon simultaneous stimulation of both eyes, cortical
potentials produced by impulses propagated along contralateral path-
ways sum algebraically in the visual cortex with cortical potentials
produced by impulses propagated along ipsilateral pathways.

The electric potentials were evoked by photic stimuli and were
measured at one position on the visual cortex of one hemisphere, and
at both retinæ.

White, blue, blue-green and red light flashes were used over
an intensity range of six logarithmic units. The stimulus was applied to
both eyes simultaneously and to each eye separately and measurements
were made from photographic superimpositions of eighty individual
sweeps.

Monocular stimulation of either eye evoked electroretinograms
with larger positive deflections (b-wave) than following binocular sti-
mulation. This phenomenon demonstrates neural interconnection
between both eyes and mutual inhibition of the electric responses of
the two retinæ. The retinal effect is presumed to be brought about by
subcortical control via centrifugal fibers.

Monocular stimulation elicited an electric response in the dark eye as well. This response was of reversed polarity and of much lower amplitude than the electroretinogram elicited in the stimulated retina. Up to a certain level of intensities, amplitudes increased linearly and latencies decreased linearly with log intensity. Stimulation above this level of intensity produced an inhibitory effect both in the retinal and in the cortical response. It elicited potentials, the amplitudes of which leveled off and sometimes decreased with further increase of intensity, while latencies continued to decrease.

The retino-cortical time was determined for the different kinds of stimulation used with the exception of red. Within the intensity range employed, the retino-cortical time was shortest for white, blue and blue-green test lights after binocular and contralateral stimulation with a slight tendency to be still shorter for the binocular. The retino-cortical time was shortest after white, and longest after blue stimulation.

Additional evidence for binocular interaction comes from Shortess' (1963) work with the retina of the frog. Using intact frog-eye preparations, Shortess exposed the back of the eyeball and inserted a micro-electrode into the retina. Both the intraretinal electroretinogram and the responses of single-ganglion cells were recorded when the eye was stimulated with light flashes in the range of 0.3 to 1.5 seconds duration. The responses in the test eye were compared when this eye alone was
stimulated to when both eyes were stimulated.

Shortess found that, under certain conditions, the magnitude of the negative intraretinal ERG was reliably increased when stimulation to the contralateral eye accompanied the test-eye response. Shortess concluded that this effect is the result of neural interaction between the two eyes, since it cannot be attributed to the consensual pupillary response, or to such experimental artifacts as light scatter or of direct response potentials from one eye to the other.

It is the purpose of this study to compare simple reaction times to monocular and binocular stimulation of approximately corresponding retinal regions, under both onset and offset stimulus conditions. Two luminances will be used, one of low and one of medium, intensity.

Previous studies involving reaction time as the dependent variable have used the same-sized stimulus objects in both monocular and binocular measurements. This method is not satisfactory, since an appropriate comparison between monocular and binocular magnitudes of summation requires that equal sensory areas be stimulated, rather than just the use of same-sized stimulus objects. Equal areas will be utilized in this study.

All previous studies involving monocular-binocular comparisons have been limited to the onset stimulus condition. This study will also investigate the offset stimulus condition under monocular and binocular (right eye) conditions.
It is reasoned that if reaction time to binocular stimulation is significantly shorter than to monocular stimulation, when duration and intensity of stimulus flashes are held constant, that evidence for binocular summation would be indicated.
METHOD

Apparatus

Stimuli.

The stimulus was neon light, presented in a light-proof room to a dark-adapted subject. As illustrated in figure 1, two independent cylinders (A), five inches long and four inches in diameter, provided the housings for the stimulus sources. The cylinders were mounted at an angle of 10° from the fixation source (B) which was directly in front of the subject (S). The stimulus sources consisted of six neon (NE 51) bulbs mounted in the rear of each cylinder. Adequate light diffusion was provided by lining the inside of the cylinders with heavy-duty tin foil, and covering the front of the cylinders with 1/8" opal glass. The stimulus sources were reduced to 7/16" in diameter each by using 1/16" thick aluminum diaphragms which were placed over the opal glass fronts. The center-to-center distance between these diaphragms was the same as the interocular distance of S's eyes. Light from the stimulus sources subtended a visual angle of twenty minutes of arc at each eye.

Due to the interocular distance of the S's, the cylinders were positioned at slightly different angles in relation to S's eyes, so that approximately corresponding retinal regions could be stimulated. This
Figure 1. Top view of apparatus as described in text.
difference in angle between the two stimulus sources also enabled
the experimenter (E) to stimulate either eye separately, or both eyes
simultaneously, without providing the subject with any "cue" which
might affect his performance.

The two stimulus source cylinders were mounted on a piece of
half-inch plywood measuring \(15\frac{1}{2}\)" X \(11\frac{1}{2}\)". This whole assembly was
firmly mounted on a 24" X 36" wooden table which extended 29" in
height. This positioned the two stimulus sources at eye level to \(S\) when
he sat comfortably in the reaction chair which will be described later.

Power for the two stimulus sources was supplied by a Heath-
kit Regulated Power Supply (model W-PS-4), (C). A constant output
current of 150 volts was supplied to the stimulus sources. With both
stimulus sources on, the twelve NE 51 bulbs drew 25 ma. Prior to
the experiment, new bulbs were inserted in the stimulus sources and
seasoned for four hours at 160 volts. A periodic check every two or
three minutes was maintained by E to make sure that the voltage and
amperage remained constant throughout the experiment.

Midway between the stimulus sources and \(S\) was a quarter-inch
plywood shield (D), 24" X 48", which was mounted on a 29" high, 36"
X 24" wooden table. This shield was angled back 10° from the center
and contained a round hold (F) 1 3/8" in diameter at eye level between
\(S\) and the stimulus sources. A camera iris diaphram was utilized for
this aperture. The area surrounding the plywood shield was covered
with heavy cloth on both sides and above, to prevent light from the experimental equipment from being visible to S. This, in effect, divided the experimental room into two halves, with the aperture between.

A filter housing (G) constructed of quarter-inch plywood, was attached to the back of the aperture so that E could insert and remove the Wratten neutral density filter which transmitted 10% of the incident light.

The two luminances used may be generally described as of medium bright and of low intensity. The lowest luminance presented (one stimulus source with filter) was bright enough to enable S to see it 100% of the time. The lower luminance was provided by the insertion of a Wratten neutral density filter (density 1.00) at the aperture. Without the filter, each stimulus source provided a light intensity of 995 millilamberts (ml.). Thus, with the Wratten neutral density filter inserted, each stimulus source provided a light intensity of 100 ml. The luminances were calibrated with a MacBeth Illuminometer.

**Visual fixation.**

The foveal fixation display consisted of a cross subtending a visual angle of 1° 50' at the fovea. The light source for this fixation was also a NE 51 bulb. It was mounted in a closed metal cylinder, one end of which was covered with white celluloid. The white celluloid was masked off with black tape so that only the cross was visible to S. A
Wratten neutral density filter was attached to the front of the fixation light source so that when S was completely dark-adapted, he could barely see the fixation cross. The complete fixation assembly was mounted 4.8" out from the plywood shield so that it was on a plane parallel to both eyes of S.

The subjects task and provisions for his response.

S sat in a chair with a right arm-rest. The chair was securely mounted on a 30" X 24" X 3/4" plywood base, and was positioned so that S's eyes were 72" from the foveal fixation point. Extending up from the back of the chair was a \(1\frac{1}{2}\)" X \(7\frac{1}{4}\)" wooden brace. Attached to this brace was an adjustable head rest (H) constructed of one-half inch by three inch plastic, curved in the shape of a "U." The inside of the head rest was covered with 1/8" sponge rubber for comfort. S maintained a steady position by seating himself well back in the chair with his head firmly held against the back of the U-shaped head rest. To prevent head movement, a one-inch rubber strap was placed from one side of the head rest, across the forehead of S, and tightly secured to the other side of the head rest. The complete head rest assembly could be adjusted vertically to accommodate each S.

As S sat in the fixation position, he placed his right arm on the arm-rest. A micro-switch (BZ-2RWB80) was mounted on the front of the arm-rest so that S could comfortably operate the switch with his right index finger. A lever was attached to this switch and bent so that
the lever was parallel with the base of the switch and was stopped by a metal plate which limited the distance to which the lever could be depressed to 2 mm. To execute a reaction, S held the lever against the stop until the onset (or offset) of the stimulus source(s) and then S lifted his forefinger as rapidly as possible.

Response measurement and stimulus presentation sequence.

A Hewlett-Packard Electronic Counter (model 522B) (I), measured reaction latencies to 0.0001 seconds. Reaction time was recorded in milliseconds directly from the counter by E. Two Hunter Decade Interval Timers (model 100C) (J) controlled the duration of the foreperiods. These timers have an accuracy at 100-500 millisecond intervals of ±5 percent. S initiated the foreperiod by depressing a foot switch which closed the timer circuits. At the end of the foreperiod, the timer devices triggered the counter and stimulus light(s) simultaneously, and the counter was stopped when S released the reaction lever, opening the counter circuit.

E controlled the presentation of stimulus source combinations through using a ten-position rotary switch (K) which was conveniently placed near the two Hunter timers. E was also positioned so that he could observe both stimulus lights on every presentation, thus allowing him to keep a constant check on stimulus presentation conditions.
Subjects

Subjects were three male graduate students. Each practiced this reaction time task for ten hours prior to the test trials. All three were highly motivated and worked on a volunteer basis. Two of them had participated in numerous previous reaction time studies.

Procedure

Prior to each session, each S dark adapted thirty minutes in the experimental room. He was comfortably seated in the reaction chair with his head strapped in place. After S was adapted, he was instructed to direct his vision to the fixation cross and to attempt to hold his fixation on it. E then turned on the left stimulus source and asked S to close his right eye. If S was in the correct position, i.e. the correct angle from the stimulus source, the stimulus source could be made to "disappear" by S closing his right eye. The same instructions were given to S for the left eye, after E had turned out the left stimulus source and turned on the right source. When S confirmed that he could make each stimulus source "disappear" by closing the appropriate eye, the experiment was ready to proceed. S was then instructed to keep his eyes fixated on the fixation cross and to react to any change in the stimulus source(s) that he noticed.

S reacted to the stimulus changes, each of which was preceded by a foreperiod. The duration of the foreperiod was changed from trial to trial. Durations ranged from two to four seconds, in steps of tenths
of a second, and were predetermined by use of a table of random numbers. To determine a reaction latency, E set the foreperiod on the Hunter timers, and then said, "ready," which was the signal for S to depress the reaction key and, when he felt ready to react, the foot switch. The foot switch initiated the foreperiod by closing the timer circuit. S held this foot switch down until the reaction (lifting off the finger in response to the stimulus change) had been executed. When S lifted his finger from the microswitch lever, the counter was automatically stopped. E then read the reaction time and recorded it. He then changed the rotary switch to the next desired position, and, after setting the interval timers, initiated the next trial a few seconds thereafter by calling "ready" to S.

Since two stimulus sources were used, they could be presented to S in several ways, which were: both, right on and left varied, right varied and left on, right off and left varied, and right varied, left off.

Five reaction times were recorded during each session for each of the stimulus source conditions, at two luminances, for both onset and offset conditions. The order of presentation was counterbalanced and systematically varied to prevent any order effects. Thus, one hundred reaction times were recorded for each S, each session. Each session lasted about forty-five minutes and no S complained of fatigue for this period of time. After each twenty-five reactions, S was given a five minute rest period before the experiment was continued. The alignment
of both eyes with the two stimulus sources was re-checked after each rest period. The five minute rest period was also adequate for S to re-adapt to a low-luminance condition after receiving a series of high-luminance stimuli.

Periodically, E inserted "catch" tests, i.e., he gave the ready signal, but did not vary the stimulus source(s). This was to ensure that S was not anticipating his reaction to the stimulus.

A grand total of fifty reactions per condition, per luminance, was collected for each S during the ten sessions in which he contributed recorded data.

In Table 1 "location" shows whether both eyes were stimulated simultaneously, or whether a change in stimulation was presented to only one of the two eyes. "Varied" shows which one of the two eyes received a change in stimulation, and "onset-offset" shows how the change in stimulation occurred. For example, "right on, left varied, offset" tells us that both eyes were being stimulated with the two stimulus sources, and then the left eye stimulus source was turned off. "Left off, right varied, onset" tells us that both stimulus sources were off, and then right eye stimulus source came on. As previously mentioned, each of these conditions was presented at two luminances, referred to in the table as "high and low," and each subject received each condition five times during each of ten sessions. The presentation of the location changes was given to each S in a counterbalanced order. When comparing
### TABLE 1
THE EXPERIMENTAL DESIGN OF THE EXPERIMENT

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>BOTH EYES VARIED</th>
<th>RIGHT ON LEFT VARIED</th>
<th>LEFT ON RIGHT VARIED</th>
<th>RIGHT OFF LEFT VARIED</th>
<th>LEFT OFF RIGHT VARIED</th>
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<tbody>
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<td>Onset</td>
<td>Offset</td>
<td>Onset</td>
<td>Offset</td>
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</tbody>
</table>

Subject 1
Subject 2
Subject 3
conditions, it is important to keep in mind that \( S \) was fixating straight ahead, and that the changes in stimulation were occurring 10° in the periphery. The \( S \) could not look at the stimulus source(s) and was reacting only to a "change" in stimulation.
RESULTS

The design of this experiment was constructed so that a five way analysis of variance could be performed on the data. The main effects to be tested were sessions, onset-cessation, stimulus source variation, luminance and subjects. The analysis was performed on mean reaction time scores since the mean and median scores were nearly identical for all stimulus source variations throughout the experiment. The F ratio for the analysis of variance was tested at the .01 level of confidence.

Figures two and three present the mean high and low luminance reaction times plotted as a function of the five stimulus source onset conditions for three subjects. Inspection of these histograms reveal that reaction time is considerably faster to high luminance than to low luminance. Note that reaction times are about as fast when the subject reacts to one stimulus source light coming on, as when he reacts to two stimulus source lights coming on simultaneously. This occurs at both the high and low luminance condition.

Figures four and five present the mean high and low luminance reaction times plotted as a function of the five stimulus source(s) offset conditions for three subjects. These figures show that reaction time is faster when both stimulus source lights are on, and both go off
Figure 2. Mean high luminance reaction times plotted as a function of the five stimulus source onset conditions for three subjects.
1 BOTH ON
2 RIGHT ON, LEFT VARIED
3 LEFT ON, RIGHT VARIED
4 RIGHT OFF, LEFT VARIED
5 LEFT OFF, RIGHT VARIED
Figure 3. Mean low luminance reaction times plotted as a function of the five stimulus source onset conditions for three subjects.
Reaction Time In Milliseconds

1  BOTH ON
2  RIGHT ON, LEFT VARIED
3  LEFT ON, RIGHT VARIED
4  RIGHT OFF, LEFT VARIED
5  LEFT OFF, RIGHT VARIED
Figure 4. Mean high luminance reaction times plotted as a function of the five stimulus source cessation conditions for three subjects.
1 BOTH OFF
2 RIGHT ON, LEFT VARIED
3 LEFT ON, RIGHT VARIED
4 RIGHT OFF, LEFT VARIED
5 LEFT OFF, RIGHT VARIED
Figure 5. Mean low luminance reaction times plotted as a function of the five stimulus source cessation conditions for three subjects.
REACTION TIME IN MILLISECONDS

STIMULUS CONDITIONS

1. BOTH OFF
2. RIGHT ON, LEFT VARIED
3. LEFT ON, RIGHT VARIED
4. RIGHT OFF, LEFT VARIED
5. LEFT OFF, RIGHT VARIED
simultaneously, than when both stimulus sources are on, and only one of them goes off. This is true in both the high and low luminance conditions. Further inspection of these two figures shows that reaction times are nearly as fast when the subject reacts to one stimulus source being on and then going off, as when he reacts to two stimulus source lights being on and both going off simultaneously. At low luminance, the cessation condition (figure five) yields longer reaction time than the onset condition (figure three).

Figure six presents the cumulative percentage curves of one monocular (right eye) and binocular offset conditions at both high and low luminances. This figure shows that binocular offset reaction times are considerably faster than the monocular offset conditions. Notice that the monocular high luminance and low luminance baseline positions differ from each other more than do the binocular high and low luminance baseline positions. The monocular curves not only show that reaction time is longer than binocular but also that there is more variability. This is most readily seen by comparing the relative slopes of the two conditions.

Binocular onset and monocular (right eye) onset conditions, at both high and low luminance, are presented in the cumulative percentage curves of figure seven. This figure shows generally, there are more faster reaction times to the left off, right varied, onset conditions of the stimulus source(s) than to binocular onset of the stimulus source(s)
Figure 6. Cumulative percentage curves of monocular (right eye) and binocular offset conditions at high and low luminance.
Figure 7. Cumulative percentage curves of right eye and binocular onset conditions at high and low luminance.
at both high and low luminances. When comparing the relative slopes of the binocular and right eye curves, it can be seen that the right eye condition is more variable than the binocular condition.

Figure eight shows the mean reaction times plotted as a function of sessions for both onset and offset conditions at high and low luminance. This was the only interaction that the analysis of variance proved significant at the .01 level of confidence.

Figure nine shows that for the low luminance, onset conditions, that generally the calculated theoretical probability of response within the specified reaction time limits, is greater for the eyes acting as independent detectors, than was actually obtained in this experiment with the eyes operating binocularly.

Figure ten, however, shows that for the low luminance offset reaction time conditions, the obtained probability of response is greater for the binocular condition than the theoretical calculation for the eyes acting as independent detectors.

Table 2 shows the results of the analysis of variance performed upon these data. The effects of onset-offset, stimulus source variation (location) and luminance were significant at the .01 level of confidence. As shown in figure eight, there was a significant interaction between sessions, onset and offset of the stimulus source(s) and luminance. Variance of the stimulus source(s) and luminance were significant at the .05 level of confidence, as was an interaction of
Figure 8. Mean reaction times plotted as a function of sessions for both onset and offset conditions at high and low luminances.
Figure 9. The probability of onset reaction times, at low luminance, obtained for binocular (PB) and as calculated for independent detector (PI) vision.
PROBABILITY OF RESPONSE

ONSET REACTION TIME IN MILLISECONDS

○ = PB
● = PI
Figure 10. The probability of offset reaction times, at low luminance, obtained for binocular (PB) and as calculated for independent detector (PI) vision.
PROBABILITY OF RESPONSE

OFFSET REACTION TIME IN MILLISECONDS

○ = PB
● = PI
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<th>SOURCE OF VARIATION</th>
<th>DEGREES OF FREEDOM</th>
<th>MEAN SQUARES</th>
<th>F RATIO</th>
<th>SIGNIFICANCE AT 0.01 LEVEL</th>
</tr>
</thead>
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<tr>
<td>S X L</td>
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<td>72</td>
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</table>
onset-offset, stimulus source(s) variation (location) and luminance.

Tables 3 and 4 present the reaction time data for the experiment in the forms of means, medians and standard deviations for all three subjects. Means and standard deviations were computed on the basis of 50 reactions for each condition. It will be noticed that means and medians do not differ from one another to any great degree. Although practiced subjects were used, the standard deviations seem a little higher than those found in the average monocular reaction time experiment.
<table>
<thead>
<tr>
<th>Subj.</th>
<th>BOTH EYES VARIED</th>
<th>RIGHT ON LEFT VARIED</th>
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<tr>
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</tr>
<tr>
<td>Mean</td>
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<td>290  327</td>
<td>271  314</td>
<td>255  295</td>
<td>240  289</td>
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<tr>
<td>Median</td>
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<td>290  328</td>
<td>266  316</td>
<td>253  292</td>
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<tr>
<td>Median</td>
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<td>298  350</td>
<td>261  306</td>
<td>258  315</td>
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<td>38   36</td>
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<td>305  354</td>
<td>277  310</td>
<td>268  317</td>
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<tr>
<td>Median</td>
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<td>315  350</td>
<td>300  368</td>
<td>275  303</td>
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<td>348</td>
</tr>
<tr>
<td>S. D.</td>
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<td>51</td>
<td>54</td>
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<td>Subj.</td>
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<tr>
<td>Mean</td>
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<td>340</td>
<td>354</td>
<td>387</td>
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<tr>
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<td>334</td>
<td>347</td>
<td>383</td>
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</tr>
<tr>
<td>S. D.</td>
<td>59</td>
<td>63</td>
<td>50</td>
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</table>
DISCUSSION

The principle purpose of this study was to compare binocular and monocular reaction speed. Two stimulus sources were used in this study, so that under binocular stimulation, one eye might sometimes be stimulated independently of what was happening to the other. Previous studies (Poffenberger, 1912, Miles, 1936), investigating monocular versus binocular reaction time, have used only one stimulus source. In comparing monocular with binocular reaction time, equal sensory areas must be stimulated so that an appropriate comparison between the two magnitudes of summation can be properly made. Also, all previous studies involving binocular-monocular comparisons have been limited to the stimulus onset condition. This study has investigated both the onset and the offset conditions of stimuli with various combinations of stimulus sources.

Several previous investigators have used the threshold of seeing technique to determine if the eyes act as two independent detectors, or if there is some retinal or central summation involved between them.

In threshold studies, the probability of seeing is an important factor. In the present study, luminances were well above threshold, so that the subject reacted to stimulus variations 100% of the time.
There have been three principle findings of previous absolute threshold studies regarding binocular summation, two of which are contradictory. Pirenne (1943) concluded that the two eyes acted as independent detectors. He stated that if a complete summation occurred, the two eyes would operate as a single unit. He felt that exposing both eyes to a certain luminance would be the same as exposing one eye to twice the luminance. But in his experiment, he found that by doubling the brightness of flash in one eye, that the frequency of seeing was raised from .38 to .86, whereas the binocular frequency of seeing for the halved brightness was only .56. Pirenne felt that these results ruled out complete physiological summation, but that, "partial summation may be present in a small degree."

This writer feels that physiological summation cannot be ruled out on the basis of Pirenne's findings, due to the known effects of luminance. Doubling the luminance to one eye may actually activate more retinal units in this one eye than a luminance of half the intensity would activate in both eyes. Pirenne also overlooked the fact, mentioned previously, that an accurate comparison between binocular-monocular conditions cannot be made unless twice the area of stimulus size is presented binocularly as that presented monocularly.

Collier (1954) holds that the probability of response is greater for binocular vision than for monocular vision. He found that the probability of response for monocular vision was only 50% the probability
of response of binocular vision using the same luminance values.

Collier stated that a

"...finding of a significantly lower (.01) binocular than monocular threshold implies that the population of events involved cannot be exclusively retinal in origin and excludes, therefore, an interpretation of the probability of response function entirely in terms of retinal or physical events."

As Martin (1962) pointed out, Pirenne's hypothesis of "probability summation," even if found to hold empirically, could not infer the possibility as to the existence of a common sensory pathway for the two eyes, since the largest barrier to seeing might lie peripheral to the common path. The presence of nervous summation at the entrance to the common path would not in this case influence the outcome of the threshold response, i.e. any signal getting through the peripherally located largest barrier would also be passed into any existing common path, but any signal not getting through the peripheral largest barrier could not then enter into a summation process at the entrance to the common path." Martin was the first investigator of the three so far discussed who recognized the need of using identical but separate test targets for each eye. As previously noted, this experiment also met this requirement. Martin's results showed that the eyes did not behave as two independent detectors at the absolute threshold, since the binocular probability of seeing was greater than the monocular with interstimulus temporal intervals of varying amounts. These results indicate that the largest barrier to seeing at threshold must lie central
to the retina, and any treatment of threshold phenomena must consider events at this barrier.

Both Collier's (1954) and Matin's (1962) results support the findings of the present study. In the present study, faster reaction times generally were obtained to binocular than monocular stimulation. Collier and Matin obtained a greater probability of seeing with binocular than monocular seeing at threshold. The present study extends this support to a low luminance which was seen 100% of the time (100 ml.) and to a high luminance value of 995 ml.

Poffenberger (1912), using reaction time as the dependent variable, found that binocular reaction time was only about 15 milliseconds faster than monocular reaction time for foveal stimulation. He felt that this slight difference was due not to the retinal apparatus, but to "the speed of conduction through the brain centers." However, we would expect this difference in reaction time for both binocular and monocular stimulation to increase when the stimulus is presented in the periphery of the subjects, even if presented at a lower luminance than that used by Poffenberger. This would be expected on the basis of the anatomical difference between receptors in the fovea and the periphery. It is to be expected that more summation would take place in the periphery since there are more receptors connected to one optic fiber than in the fovea. Poffenberger's results should therefore not be discounted as evidence for binocular summation.
Miles (1936) in measuring peripheral eye movement reaction latency, found that binocular latencies were shorter than the monocular latencies. However, Miles qualified his findings by stating that this was not conclusive evidence for summation at a higher level. His results were further obscured by procedural difficulties which have been previously detailed in this study.

It is evident that the differences in the results obtained in the studies so far discussed may well be due to: the nature of the threshold as a psychophysical measure (reaction time has been demonstrated to be a more accurate and reliable psychophysical method); the various stimulus conditions employed in the conflicting experiments, such as the use of one as compared to two stimulus sources for both binocular and monocular presentation; the different stimulus intensities employed, and whether foveal or peripheral stimulation was utilized.

Previous reaction time studies have not explored the binocular offset condition, nor have they been able to present the stimulus source to one or both eyes without the subject being aware of which eye was being stimulated. The present study has met both of these requirements.

Pease and Sticht (1964), in investigating reaction time to monocular stimulus offset, found that, in the periphery, the reaction time to the offset of the stimulus is slower than reaction time to the onset of the stimulus. The present study carried this offset condition to the binocular domain and found the same results. Binocular stimulus onset
reaction time is truly slower than monocular, at both high and low luminance.

The probability of response (figure ten) for binocular vision is greater than the probability of a response for the eyes acting as independent detectors, for the offset, low luminance condition. This lends additional support for binocular summation.

The apparent reversal of this finding for the probability of response under onset, low luminance conditions, shown in figure nine, possibly suggests that the probability of seeing either binocularly or independently may depend upon onset or offset stimulation. It may be recalled that Pease and Sticht (1964) demonstrated a significant difference between onset and offset stimulation at lower luminance.

One interesting finding in the present study was that reaction time to one light alone coming on to one eye is faster than that when one light is exposed to one eye, then the second light comes on to the corresponding retinal region of the other eye. Likewise, reaction time is faster to one light alone going off, than to when one light is on and the second light goes off. This may indicate that some type of inhibitory effect is taking place on the fibers being activated.

All cumulative percentage curves show that the high luminance stimulation is less variable than the low luminance stimulation. This is to be expected from the results gained from many previous signal detection experiments. It has been shown that the higher the luminance,
the more the possibility of detection.

This study has demonstrated that, under the experimental procedures utilized, there would be predicted a greater probability of faster reaction times occurring for the eyes operating as independent detectors than was actually obtained with the eyes operating binocularly under stimulus onset conditions. On the stimulus offset conditions, however, there was a greater probability of faster reaction times for the eyes operating binocularly, than was predicted for them as independent detectors.
SUMMARY

Reaction times have been recorded for various combinations of stimulus source(s) which were presented either binocularly or monocularly to the peripheral retina of three human subjects. Presentation was made at both a low luminance of 100 millilamberts and at a high luminance of 995 millilamberts. Recordings were made both to the onset and offset of the stimulus source(s).

The results are summarized as follows:

1. Reaction time is faster to binocular than to monocular stimulation, at both high and low luminances, for the stimulus offset conditions.

2. Reaction time is faster to high luminance than to low luminance.

3. Reaction time to onset stimulation is faster than reaction time to offset stimulation.

4. Reaction time is faster to a stimulus onset to a single eye, than to a condition, where a light flashes to stimulate one eye during the time when a second stimulus is presented to the other eye.

5. Reaction time is slower to a cessation of a single stimulus to a single eye, than to a condition where two lights are extinguished simultaneously, one to each eye, in corresponding retinal regions.
6. The high luminance stimulation results in less variability than the low luminance stimulation.

7. The lowering of luminance on the offset condition increased reaction time more than the lowering of luminance on the onset condition.

8. The probability of binocular seeing response curves, at low luminance offset conditions, is greater than is predicted by calculating the probability on the basis that the eyes act as independent detectors.


