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SIGNAL LUMINANCE AND POSITION EFFECTS
IN HUMAN REACTION TIME

by

JACK DEAN RAINS

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I hereby recommend that this dissertation prepared under my
direction by Jack Dean Rains
entitled Signal Luminance and Position Effects
in Human Reaction Time
be accepted as fulfilling the dissertation requirement of the
degree of Doctor of Philosophy

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SIGNED:

Jack D. Rains

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SIGNAL LUMINANCE AND POSITION EFFECTS
IN HUMAN REACTION TIME

Jack Dean Rains

ABSTRACT

Three well-trained subjects were presented with visual stimuli of a constant area and duration at four different intensities and nine retinal positions. The subjects reacted to the stimuli by releasing a switch upon seeing a flash. Two of the intensities employed were well above cone threshold, 3,555 millilamberts and 11.25 ml. The other two intensities were below the intensity necessary to excite the cones. One was a white light of .11 ml and the other was a blue light of .13 ml which contained no wave lengths above 520 millimicrons. The stimuli subtended a visual angle of four minutes and each flash lasted 0.0230 seconds. The flashes were presented foveally and at 5, 10, 20 and 30 degrees, measured in terms of visual angle, on both the nasal and the temporal retina of the subjects' right eyes.

Curves were plotted which describe reaction time as a function of retinal position for each of the four intensities. The finding that the nasal side of the retina yields faster reactions than the temporal side was supported. Also, as has previously been reported, with bright stimuli, foveal stimulation results in faster reactions than stimulation at any other retinal position.

The interaction between retinal position, intensity and reaction time is fully discussed. With bright flashes, above the threshold for the cones, the resulting curves were somewhat similar to density functions of retinal elements when curves for both rods and cones are summed. With dim flashes, the curves were quite similar to the curves describing density of rod elements by retinal position.

A hypothesis is advanced to account for the relationship between density counts and reaction time. It is assumed that there is a distribution of latencies among receptors in the retina. Consequently, the more receptors which are stimulated in a given sample, the higher the probability that one or more faster acting elements are included.

Comparisons are made with existing curves describing visual acuity and visual threshold as a function of retinal locus of stimulation. In general, it is noted that the superiority of the nasal retina over the temporal retina is true for the curves describing acuity and the curves describing reaction time, but not for the sensitivity function.

The functions described in the study are dependent upon the interaction between retinal locus and intensity. Also, it is noted, two other parameters are undoubtedly important in such a determination and should be taken into account before one extrapolates from these data to some application. Area of the stimulus flash and duration of the flash are critical in a study of this kind. Since the peripheral retina is capable of summation of both an areal and a temporal nature, over a

wider range than is the fovea, if larger and/or longer flashes were employed, the peripheral retina would gain some advantage over the fovea, which does not summate over such large areas and temporal durations.

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HISTORY

The use of reaction time as a dependent variable in psychological experiments has had a long and distinguished history. Since there has occasionally been some confusion regarding the time interval which constitutes the measure of reaction time, it would be well to define it here for the purposes of this study. In the following experiment, reaction time is taken to mean the interval between the presentation of a stimulus and the completion of the execution of the subject's response, release of a switch.

A reaction of the kind here employed may be divided into two main components: the sensory and the central-motor portions. The main assumption in a study of this kind is that the central-motor component consumes a finite, constant amount of time independent of the characteristics of the state of the receptor or stimulus parameters. Thus, we are here investigating the sensory component of the reaction. Differences between conditions will be assumed to be referable to retinal mechanisms and to neural mechanisms intervening between the retina and the visual cortex.

Only a few investigators have examined the relation between visual reaction time and position of the stimulus on the retina. Hall and von Kries (1879) examined nine retinal positions with respect to the reaction time yielded at each of these points. Using themselves as subjects, and a stimulus light which was above cone threshold, they

examined reaction time to stimulation at the fovea and at 30 and 60 degrees nasally, temporally, and above and below the horizontal meridian. They were the first to elucidate three basic relationships which have been since confirmed by other investigators: 1) with a light adapted eye, reaction time is shorter to bright visual stimuli whose image strikes the fovea than to similar stimuli striking any other retinal locus; 2) visual stimuli with images appearing in the nasal retina yield faster reactions than stimuli with images appearing in the temporal retina; 3) reactions to stimuli with images above the horizontal meridian are faster than to stimuli at corresponding points below the meridian.

Kästner and Wirth (1908) conducted a study which, although not directly comparable to the work of Hall and von Kries, nevertheless lends support to the three conclusions above. Their experiment involved a disjunctive reaction calling for a different response depending on which area of the retina was stimulated. Moreover, they did not stimulate the same points as Hall and von Kries. However, by taking averages of certain of their positions after their Ss were well practiced, they were able to conclude that the direction of the differences they found was not in conflict with the findings of Hall and von Kries.

The study which is most often quoted on the topic of visual reaction time and stimulus position was conducted by Poffenberger (1912). He was primarily interested in finding a means of measuring the time lost in the transmission of an impulse through a synapse. Each of Poffenberger's Ss was presented with stimuli at nine retinal positions: the fovea, and 3, 10, 30, and 45 degrees on either side of the fovea

along the horizontal meridian. The right and left eyes of each S were tested separately and Ss reacted with their right and left hands under different conditions. Poffenberger hoped, in this manner, to be able to relate differences between certain of his conditions to time lost in additional synapses. He reasoned that light striking the nasal side of the retina of the right eye, for example, would give rise to nervous activity in the left occipital lobe of the cortex. Since the left motor area of the cortex controls movements of the right hand, reactions with the right hand to stimuli appearing nasally on the right eye should be faster than left hand reactions to stimuli in the same position. The difference in reaction time between left and right handed reactions, then, should be in part attributable to time lost in synapse or synapses between the right and left motor areas of the cortex. As a result of this phase of his investigation, Poffenberger concluded that synapse time for humans was between 3.6 and 4.0 milliseconds.

The data of Poffenberger's experiment, however, which have attracted the most attention are his plots of reaction time versus position of the stimulus on the retina. His Ss were light adapted (to an unspecified intensity) and presented with stimuli subtending about one degree visual angle from a two candlepower bulb. Stimuli were of about four milliseconds duration. Poffenberger was able to draw the following conclusions:

1. With the exception of subject P at 3 degrees, the reaction time increases as the distance from the fovea is increased.
2. The nasal side of the retina gives a faster reaction than the temporal side, in nearly every case when the times for the two hands are combined.

3. This relation between the temporal and the nasal side of the retina agrees in general with the extent of the visual fields corresponding to the temporal and the nasal side of the retina; with the acuity relations of these two sides and with the appearance of flicker upon the two halves of the retina. (p. 56)

Lemmon and Geisinger (1936) reasoned that since the periphery of the retina was more sensitive than the fovea when the eye was dark adapted, foveal reaction time should be longer than peripheral reaction time in the dark adapted eye. To test this hypothesis, they measured the reaction time of 14 Ss at the fovea and 45 degrees to the left of the center of the field. Since their Ss used both eyes, the stimulus fell temporally on the right retina, nasally on the left retina. The intensity of the light used was unspecified. Ss were measured under light adapted and under dark adapted conditions. The intensity of the light was considerably weaker when Ss were dark adapted, thereby precluding the possibility of comparison of reaction times under the two adaptation conditions. Incidentally, in his excellent review article, Teichner (1954), apparently misinterpreting their findings says, "... Lemmon and Geisinger, who...used a very bright test stimulus, found shorter RT's with the light-adapted than with the dark-adapted eye." (p. 133) The only specification of light intensity was a vague one. Under light adapted conditions, Lemmon and Geisinger state, "...it was sufficient to be plainly visible against the background." (p. 140) Under dark adapted conditions, "...it was so faint as to be just barely visible on the fovea after the adaptation-period. It could not be seen at all at the beginning of this period." (p. 141)

In general, Lemmon and Geisinger found that reaction time to their visual stimulus under dark adapted conditions was faster in the periphery (if the data for all subjects were lumped together). The result was not clear cut, since half of their Ss showed a difference in the other direction. Under light adapted conditions, reliably faster reaction time latencies were achieved to foveal stimulation.

Galifret and Piéron (1948), with a dark adapted eye and a bright stimulus flash obtained faster reactions to foveal stimulation than to peripheral stimulation.

The apparent conflict between the findings of Lemmon and Geisinger and of Galifret and Piéron was successfully resolved by Bartlett and MacLeod (1954) who investigated reaction time as a function of different flash and field brightnesses. They tested both the fovea and the peripheral retina ($11^{\circ} 20'$ below the fovea) with different flash and field intensities. The equation they derived to describe the curves obtained by plotting reaction time against intensity of the flash contains three constants. The values of the constants in their single equation differed slightly from one subject to the other. More significantly, however, they differed depending on the retinal area stimulated. The three constants required for their hyperbolic equation to fit the data were: 1) a limiting latency which the data approached as an asymptote with high stimulus intensity; 2) a threshold constant for the minimum intensity visible; and 3) a slope constant. With bright flashes, foveal reactions were found to be faster

than reactions to peripheral stimuli (as had been reported by Galifret and Piéron), but with dim flashes, peripheral reactions are faster than foveal (as had been found by Lemmon and Geisinger). To repeat, all of Bartlett and MacLeod's observations were fitted by a single theoretical equation by a choice of constants depending, primarily, upon the retinal area.

Reviews of the general area of reaction time studies have been written by Woodworth (1938), Johnson (1923) and, most recently, by Teichner (1954).

Since the introduction of modern electronics, the problems of the investigator in the reaction time area have been greatly reduced. Older studies such as Poffenberger's (1912) were fraught with difficulties involving calibration of intensity, instability of timing mechanisms, and inability to illuminate and extinguish the light source rapidly. For example, Poffenberger's study utilized the movement of a mechanical shutter mechanism across the light source as a means for exposing and occluding that source. Obviously, the entire stimulus area could not be illuminated at the same instant since the shutter mechanism consumed some finite length of time in totally exposing or occluding the patch of stimulus light. Also, the duration of the flash of light was dependent upon the accuracy of the mechanical system in question. A contemporary device such as the Sylvania Glow Modulator tube (R1131C) which is used in this study obviates these difficulties since no mechanical devices are used to present and terminate the stimulus flash. It reaches full brightness in .0001 seconds and can

be extinguished with equal rapidity.

The earlier investigators used, as a common method of measuring response time, the Hipp chronoscope. Woodworth and Schlosberg (1954) describe this instrument as follows:

It consisted of two basic parts:

1. A rapidly moving clockwork mechanism, which was started and allowed to reach normal speed well before the stimulus was given, and stopped after the response. A weight furnished the power to operate the clockwork; the speed was controlled by a reed which vibrated 1,000 cycles per second, taking the place of the pendulum or balance wheel escapement found in ordinary clocks.
2. A very light tooth and train of gears, to move the hands which actually measured RT. The tooth was thrown against the drive gear at the moment of stimulation and back to the brake gear on the response. The distance the hands moved between the moments of stimulation and response was the RT. The starting and stopping of the clutch was accomplished by a pair of electromagnets and springs in balance, and it was customary to check the chronoscope every 50 reactions or so. (p. 12)

The early reaction time experimenters, then, were confronted with the vagaries of this mechanical system. As a consequence, it was customary to calibrate the apparatus with a gravity-type chronometer set to deliver a standard time at the approximate mean of the reaction time distribution. It should be pointed out that the Hipp chronoscope, when it was working accurately, had an error considerably below one percent (Woodworth and Schlosberg, 1954). However, the instruments were subject to terminal errors, the result of inertial lag in starting or overshoot in stopping, and running errors, due to fluctuations in the speed of the running mechanism. As a consequence, some experimental sessions had to be discarded, a factor which mitigates against the

ability of the experimenter to make meaningful statements concerning variability of his Ss' responses.

Today, one instrument commonly used for measuring elapsed time is an electronic pulse counter. If a known frequency source (such as a crystal or frequency oscillator) is driving the counter, it becomes an events-per-unit-time meter, or a time interval meter. It is a highly stable and accurate device and its accuracy is not affected by minor fluctuations in voltage frequency of house current.

In the experiment which follows, we have used these two electronic devices to examine the reaction time of dark-adapted Ss to visual stimuli at four different intensities and nine different retinal positions. Two of the intensities were chosen so as particularly to elucidate the rod function across the retina. These intensities were below cone threshold. The other two intensities were well above cone threshold and it was expected that they would yield a mixed rod and cone function.

METHOD

Apparatus

The response timing apparatus was a custom designed unit manufactured by The Psychological Instruments and Research Laboratory of Rome, New York. It employs a Berkeley Electronic Counter to measure the delay in responses with a precision of 0.0001 seconds. The unit also contains provision for delivering a flash of controlled duration and intensity and for measuring the duration of the flash for calibration purposes. A flash duration of 0.0230 seconds was employed in this experiment. The duration was recalibrated prior to each day's experimental sessions.

The stimulus was a flash from a Sylvania Glow Modulator tube (R1131C) which has a rise and decay time of less than 0.0001 seconds. The face of the tube was masked down so that the crater yielded a patch of light subtending a visual angle of four minutes at S's eye. Intensity of the light was controlled by Wratten neutral density filters placed directly in front of the tube.

Four intensities were employed in this study. Two of the intensities were chosen so as to be well above cone threshold. The other two intensities were below cone threshold.

The brightest light (corresponding to intensity A in Table I) was produced by interposing no filters between the glow tube and S's

eye. The luminance of this light was calibrated with a Macbeth Illuminometer at 3,555 millilamberts. Intensity B was achieved by interposing neutral density Wratten filters to drop the apparent luminance by 2.5 log steps to 11.25 ml. Intensity C represented a drop of 4.5 log steps from the full intensity to 0.11 ml. Intensity D was chosen to serve as a check on the data obtained from the dimmest white light, C. It was achieved by interposing neutral density filters to drop the intensity to 2.7 log steps below the full value and an additional filter (Wratten No. 48). This is a blue filter which passes no wave lengths above 520 $m\mu$. Its peak transmittance is at about 460 $m\mu$. This filter serves to reduce the overall intensity by an additional 1.74 log steps. Thus the fourth intensity was a blue light of 0.13 ml.

Nine retinal positions were tested: one was the center of the fovea and the other eight were at 30, 20, 10 and five degrees along the horizontal meridian in both the nasal and temporal retina. The device for fixating so that the image of the stimulus flash fell at each of these peripheral positions consisted of four pinpoint holes drilled in the end of a small cylindrical can containing a neon bulb (NE 51) and a red filter (cut from a Polaroid Dark Adaptor Goggle 1084). Each pinpoint represented one corner of a square whose diagonals measured 17 mm, so that each diagonal subtended one degree visual angle. The pinpoint holes were positioned in such a way that one diagonal was horizontal and the other was vertical. Thus, the fixation array formed a diamond shape, chosen to minimize S's eyeball drift.

During the course of the trials for each experimental session, S was housed in a light-tight, sound-deadened room whose interior dimensions measured nine and one half by seven feet. In one corner of the room, four feet above the floor, a plywood board, four by four feet, was mounted horizontally. The stimulus apparatus and fixation devices were affixed to this board on the perimeter of a semicircle with a radius of 87.63 centimeters. The center of each fixation device was 5.4 centimeters above the board.

The foveal fixation device presented a special problem. Figure 1 depicts the side view of the central fixation apparatus, the stimulus lamp, and the filter system. Light from the Sylvania Glow Modulator tube (A) passes through neutral density filters (B), then through E, a double-prism beam splitter which was in place during all trials, to F, S's right eye. Light from the foveal fixation device (C), after passing through the red filter contained in the can (D), is reflected from the surface of the double-prism beam splitter (E) to S's eye. The image of the fixation points in the foveal position appeared 5.4 centimeters above the board, and the stimulus light was judged to fall in the center of the four fixation points.

In order to minimize variability in positioning S's head, plastic dental impressions were made of each S. Prior to each day's run, the dental plate was affixed securely to the plywood board at the appropriate position with C clamps. S then positioned his head by aligning his teeth with the impressions in the dental plate.

FIGURE 1

Foveal fixation apparatus and stimulus lamp.

The figure is fully explained in the text.

S's right arm rested on a table to which a microswitch (Type Z) was affixed. His response consisted of the release of this switch. He was instructed to hold the switch just below the detent and to release it immediately upon seeing the flash. When S held the switch as instructed and released it, the switch button traversed only .05 centimeters. A force of approximately 150 grams was necessary to maintain the switch in the required position.

S's right foot rested on a pedal. By depressing this pedal switch, he could energize a Hunter Interval Timer, thus initiating the foreperiod.

The experimenter was able to communicate with S via a microphone outside the experimental room and a loudspeaker inside the room.

SUBJECTS

Three psychology graduate students served as subjects in this study. Each was an emmetrope and had been well practiced on reaction time tasks.

PROCEDURE

Subjects wore red Polaroid Dark Adaptor Goggles for 30 minutes prior to entering the experimental room. They remained in darkness in the room for five minutes prior to reacting. During the course of all trials, S wore a patch over his left eye.

Trials were administered in blocks of 12. Each experimental session consisted of eight or nine blocks of trials, all at the same stimulus intensity. Each block represented a different retinal position.

Fifteen seconds elapsed between trials. After every 12 trials, retinal position was changed by selecting the proper fixation lamp, and during this interval, S rested for one and a half minutes.

Prior to each block of 12 trials, S was given five warm-up trials. On these five trials, he was informed of the duration of his reaction. After the warm-up trials, E informed S that he was ready to begin the block of experimental trials. Each trial proceeded as follows: E gave S a ready signal over the loudspeaker system. When S was ready, he depressed his response key, holding it just below the detent. Then, S depressed the foot pedal, initiating the foreperiod for the reaction. At various random intervals ranging from 2.0 to 3.5 seconds later, the flash was delivered and at the same instant, the electronic counter began timing. When S saw the flash, he released his response key, stopping the counter, then released his foot pedal. E recorded the reaction time, waited fifteen seconds, then gave S another ready signal. Foreperiods were distributed in a predetermined random order in 0.1 second steps throughout the range of 2.0 to 3.5 seconds.

Table I describes the experimental design. Each day, intensity was held constant and 12 reactions were taken at each retinal position. A total of 48 reaction times were taken for each S at each retinal

TABLE I

THE EXPERIMENTAL DESIGN

Temporal retinal positions are denoted by T, Nasal by N, Foveal by F. At every experimental session each subject was given 12 reactions at each retinal position listed, yielding a grand total of 1632 reactions per subject.

<u>Experimental Session</u>	<u>Intensity</u>	<u>Retinal positions, in degrees, in order of presentation.</u>
1	A	30N, 20N, 10N, 5N, F, 5T, 10T, 20T, 30T
2	B	20N, 10N, 5N, F, 5T, 10T, 20T, 30T, 30N
3	C	10N, 5N, 5T, 10T, 20T, 30T, 30N, 20N
4	D	5N, 5T, 10T, 20T, 30T, 30N, 20N, 10N
5	D	30T, 20T, 10T, 5T, 5N, 10N, 20N, 30N
6	C	20T, 10T, 5T, 5N, 10N, 20N, 30N, 30T
7	B	10T, 5T, F, 5N, 10N, 20N, 30N, 30T, 20T
8	A	5T, F, 5N, 10N, 20N, 30N, 30T, 20T, 10T
9	D	5T, 10T, 20T, 30T, 30N, 20N, 10N, 5N
10	C	10T, 20T, 30T, 30N, 20N, 10N, 5N, 5T
11	B	20T, 30T, 30N, 20N, 10N, 5N, F, 5T, 10T
12	A	30T, 30N, 20N, 10N, 5N, F, 5T, 10T, 20T
13	A	F, 5N, 10N, 20N, 30N, 30T, 20T, 10T, 5T
14	B	5N, 10N, 20N, 30N, 30T, 20T, 10T, 5T, F
15	C	10N, 20N, 30N, 30T, 20T, 10T, 5T, 5N
16	D	20N, 30N, 30T, 20T, 10T, 5T, 5N, 10N

position and each intensity. On days when the intensities which were above cone threshold were used, S yielded 108 reactions (12 trials at each of nine retinal positions). Since the dimmer intensities were below cone threshold, no foveal reactions could be recorded on the days when they were employed. On these days, S yielded 96 reactions (12 at each of eight retinal positions).

The four intensities were varied in an ABBA order. Also, retinal loci were varied systematically throughout the course of the 16 days of the experiment to prevent a position bias.

RESULTS

Figure 2 summarizes the data for one S, HK, at the three intensities of white light: intensity A, 3,555 ml; intensity B, 11.25 ml; and intensity C, .11 ml. The photopic threshold lay between intensities C and B. An approximate threshold measurement was taken for one S, JR. The foveal threshold is at approximately 1.59 ml when the area and flash duration are at the previously specified values. Absolute threshold measures for the same S, taken at the 10 degree nasal position resulted in a value of .040 ml. for the area and flash duration employed in this study.

Three main effects should be noted here: 1) the effect of the intensity of the stimulus light upon reaction time; 2) the effect of retinal position upon reaction time; and 3) the effect of the interaction between intensity and retinal position.

The curves for each intensity are clearly separate on the graph, demonstrating the general principle that, at least in the lower range of intensities, the stronger a sensory stimulus, the faster is the reaction. Many investigators have commented upon this general finding (Froeberg, 1907; Steinmann, 1944; Teichner, 1954). The curves for intensities A and B are separated by from 30 to 50 milliseconds at all points. Intensity B produces a curve which is separated from that produced by intensity C by an average of 70 milliseconds.

FIGURE 2

Data for one S, HK, showing reaction time as a function of
retinal position for three intensities of white light.

Similarly, the effect of retinal position upon reaction time is clearly demonstrated by these curves, although it is more difficult to discuss this effect in isolation from the more interesting finding of the effect of the interaction between stimulus intensity and retinal position. However, with the curve for each intensity, there is a retinal position which yields the fastest reaction time. In general, also, the nasal side of the retina is superior to the temporal side with respect to speed of the reaction.

The interaction between stimulus intensity and retinal position is clearly manifest. The shape of the curves for the two brighter stimulus lights, intensities A and B, is similar. The fovea is the point at which stimulation produces the fastest reaction with photopic stimuli; the 30 degree temporal retinal locus yields the slowest reaction in both cases. However, with stimulus intensity C, a light too dim to be seen by the cones, the relative reaction time to stimuli at various retinal positions is radically altered. Foveal reaction time is infinite with a light of this intensity; in other words, S could not see the stimulus at that position on his retina. The fastest reaction for this S was at 20 degrees on the nasal retina; the slowest reaction was elicited by stimuli falling at 30 degrees on the temporal retina. The shape of the curves for photopic and scotopic stimuli is sufficiently different to suggest two separate functions, dependent upon different mechanisms. This possibility will be explored below in the more detailed presentation.

Table II shows the means and standard deviations for each S independently for each retinal position and flash luminance. A few general statements may be made concerning differences within and between Ss.

Subject HK was, in general, the fastest S. This sweeping statement cannot be supported at all intensities and retinal positions. However, HK had the shortest reaction time means at 29 of the 34 possible comparison points, although not all these comparisons were statistically significant. The other two Ss were approximately equal with respect to reaction latency at most retinal positions and intensities.

Subjects HK and JR were approximately equally variable at all intensities. Subject LH was more variable than the other two Ss, although this difference was not statistically significant.

In general, the variability increased as the intensity of the stimulus was decreased. This was true for all Ss between intensities A, B, and C, though it did not reach statistical significance at the .05 level.

Figures 3 and 4 represent the mean reaction times at all retinal positions for the two stimulus intensities which were above cone threshold. The general shape of these two curves is very similar. For all Ss, the foveal reaction time was fastest with both stimulus intensities. With intensity A, however, this difference was not as marked as with intensity B, where reaction time increases more sharply between the fovea and five degrees on either side of the fovea. Since intensity A was an

TABLE II

Means and standard deviations in milliseconds for
each subject by intensity and retinal position

INTENSITY A 3,555 ml	30°N		20°N		10°N		5°N		FOVEAL		5°T		10°T		20°T		30°T	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
SUBJECT HK	184	17	175	12	171	13	175	14	168	11	182	13	176	16	182	13	188	16
LH	196	21	192	17	192	17	192	18	183	18	195	14	195	17	196	19	204	20
JR	193	13	194	17	195	12	194	18	180	19	200	23	195	16	199	16	209	17
INTENSITY B 11.25 ml																		
SUBJECT HK	221	15	209	15	208	20	215	16	200	15	225	22	218	21	233	18	241	17
LH	243	21	240	21	236	21	232	19	208	25	232	21	234	23	236	15	253	21
JR	244	20	235	16	229	20	223	14	194	26	231	13	238	17	243	17	253	23
INTENSITY C .11 ml																		
SUBJECT HK	290	25	274	19	278	31	292	30			296	25	285	15	308	22	308	21
LH	307	23	299	29	291	22	326	26			314	19	298	19	300	23	333	39
JR	300	24	316	31	305	19	323	21			320	21	311	23	305	23	317	22
INTENSITY D BLUE .13 ml																		
SUBJECT HK	273	20	260	15	256	20	271	18			278	19	273	13	281	16	296	20
LH	290	25	280	22	281	17	301	24			304	23	284	22	279	20	290	24
JR	279	19	286	16	279	16	294	19			294	20	279	17	273	19	296	14

FIGURE 3

Reaction time as a function of retinal position
at stimulus intensity A, 3,555 ml.

FIGURE 4

Reaction time as a function of retinal position
at stimulus intensity B, 11.25 ml.

extremely bright light, it induced a great amount of entoptic light in the eyeball. The stray light would have the effect of increasing the area of the flash and it is probable that some of this stray light struck the fovea. Consequently, the difference between reaction time to the foveal stimuli and reaction time to the nearby stimuli was not as marked when this intensity was employed as when intensity B, a less intense flash, served as the stimulus.

Intensities C (.11 ml) and D (a blue light of .13 ml) were below cone threshold. Intensity D was used to serve as a check on the data obtained with intensity C and to elucidate more clearly the rod function. Since intensity D was a blue light containing no wave lengths above 520 m μ , it would be more likely to stimulate only rod elements since, with the dark adapted eye, the rods are far more sensitive than the cones to light in this spectral region. Figures 5 and 6 represent the mean reaction times at all retinal positions for stimulus intensities C and D. Reaction time in the rod-free fovea was infinite since the flash was not an effective stimulus with foveal fixation. With the exception of a few reversals, the resulting curves on both sides of the fovea are U-shaped, with high reaction times to stimuli at five and 30 degrees and the lowest reaction time to stimuli appearing at either 10 or 20 degrees.

With the two brighter intensities, HK showed a characteristic upturn at the five degree positions on both the temporal and nasal retina, and statistical significance was achieved for one of the four

FIGURE 5

Reaction time as a function of retinal position
at stimulus intensity C, .11 ml.

FIGURE 6

Reaction time as a function of retinal position
at stimulus intensity D, a blue light of .13 ml.

comparisons. Subject JR also showed this five degree elevation in response latency on the temporal side of the retina with intensity A, the brightest light. This difference was not statistically significant at the five percent level of significance. Although the differences mentioned above could have occurred by chance, it should be noted that similar findings have appeared in the literature before. Poffenberger's three degree position on both sides of the fovea yielded a similar reversal with one of his Ss, P. Poffenberger made no attempt to explain this reversal. More recently, Bartz (1961), measuring latency of eye movements in highly trained Ss, noted in all three of his Ss, a greater latency for eye movements to read a signal at five degrees than at 10 degrees, his next position outward. His Ss were viewing the field with both eyes, and although this was true of both the left and right five degree positions, the difference was significant for the five degree right of center position only. Lichtenstein (1961) had two Ss tap in synchrony with a regularly flashing neon light at different retinal loci. The stimulus light subtended two degrees visual angle. One of his Ss showed "...a depression of latency at five degrees in the nasal and temporal positions along the horizontal meridian of the visual field. The other subject showed a rise in latency at those two points, but this elevation was not inordinate."

With intensities A and B, the general finding that reaction time to stimuli on the nasal retina is shorter than reaction time to stimuli impinging on the temporal retina is clearly supported. In 20

of the 24 comparisons between corresponding points on the two sides, this relationship holds. Fourteen of these 20 comparisons were significant at the .05 level using a one-tailed t-test. In two of the comparisons, temporal reactions were shorter, though not significantly so. In two other comparisons, the reaction time was equal in the corresponding points. Reactions to stimuli of intensity below cone threshold appearing on the nasal retina are not so clearly superior. Of the 24 comparisons between nasal and temporal stimuli, nasal stimuli elicit shorter reactions in 16 of the 24, of which nine are significant at the .05 level. Temporal stimuli yield shorter reactions in five cases, three of them significant. In the remaining three comparisons, the means for the corresponding points on the temporal and nasal sides are identical. However, the 30 degree nasal points yield faster reactions than the 30 degree temporal points in 11 out of the 12 possible comparisons. Of these 11, all but one are significant at the .05 level. The twelfth comparison is between identical means for subject LH with intensity D.

DISCUSSION

In the previous section, we have outlined the various findings of the experiment. In our discussion, we will attempt to show how our data support the findings of previous experiments and suggest possible mechanisms underlying the results.

The general finding of faster reactions elicited by stimuli appearing on the nasal retina has been in the literature since 1879 (Hall and von Kries). Poffenberger noted this relationship and, although he did not speculate as to its possible cause, he did examine various data which were available to him at that time such as Kirschmann's data on sensitivity, Koester's acuity data and Exner's data on critical flicker frequency. These studies examined these three variables with respect to position in the retinal field. In all cases, the nasal retina was found to be superior to the temporal side. Poffenberger also noted that the extent of the visual field on the temporal side is greater than that on the nasal side of the visual field (corresponding to the temporal retina) because the field is cut off by the nose at about 60 degrees or sooner depending upon the size of the nose and the depth of the eye sockets in the head. However, he does not make it clear what effect he believes this greater extensity of the observational field would have upon reaction time.

When Poffenberger evaluated the results of his experiment, adequate data on the relative density of rods and cones in the human retina were not available, although Poffenberger felt that such data might have been of assistance to him in helping to explain some of his results. The data of Østerberg (1935) on density of retinal elements at various retinal loci bear directly upon this problem. Østerberg counted the number of retinal elements in one human retina. Along the horizontal meridian, he found the cone count to be relatively constant in the periphery, rising sharply from about eight degrees on either side of the center of the fovea to a maximum of about 147,000 cones per square millimeter in the center of the fovea. Rod count in the center of the fovea was zero. Beginning at about $\frac{1}{2}$ degree from the center of the fovea, the density along the temporal meridian rose rapidly to a maximum at about 18 degrees and then began a slow decline to the ora serrata. Nasally, the rod count rises steeply to its maximum at about 22 degrees from the center of the fovea, then declines steadily to the ora serrata.

With regard to nasal versus temporal retinal positions, Østerberg points out that the "...nasal part of the retina is equipped more plentifully with rods than...(is)...the temporal (quadrant)." (p. 91) Since the density of cones is approximately constant from the ora serrata (except on the nasal side where cone density rises somewhat near the ora serrata), this means that the retinal units are more closely packed together on the nasal retina than on the temporal retina. If we assume

a distribution of latencies among retinal elements, then the more retinal elements we stimulate, the greater the probability that one or more rods or cones in the sample may fire more rapidly than others. With an area not so densely packed with rods and cones, fewer retinal elements are excited, consequently the probability of firing one or more elements with a short latency is less. On the basis of this hypothesis, one would expect that there would be a positive relationship between number of retinal elements in a particular location and speed of reaction. Lichtenstein has elaborated on this hypothesis and, indeed, he obtained significant fits to his data on synchronous tapping responses with an equation of the general form $L = k + aR + bC + cRC$, where L represents the response latency in milliseconds, R represents the rod density, C is the cone density, k is a constant in milliseconds, and a , b , and c are constants which presumably depend upon various factors such as area, duration, color of the flash, etc.

On the basis of this density hypothesis, one would expect that with photopic stimuli, the determining factor would be the total density of both rods and cones at any particular retinal locus. On the other hand, for a feeble light in the scotopic range (our stimulus intensities C and D), the sample would consist entirely of rods, since the stimulus intensity is below cone threshold. Consequently, the determining factor in the reaction would be the density of rods at the particular retinal locus stimulated.

Recent curves of sensitivity across the horizontal meridian of the human retina (Sloane, 1947; de Groot, Dodge and Smith, 1952; Riopelle and Bevan, 1953) have shown sensitivity of the dark-adapted eye to be less in the nasal than in the temporal retinal positions. Considering Østerberg's counts of density mentioned above, together with our data and that of Poffenberger and others, such a finding with regard to sensitivity would seem to imply that two different mechanisms are operating to influence reaction time and sensitivity. In other words, the reaction is not faster merely because the flash appears brighter to the subject. The reaction time curves, when plotted against retinal position, match the Østerberg density functions fairly well, at least with respect to the nasal vs. the temporal retinal position. Further, the reaction time curves fit the appropriate distribution. That is, for photopic stimuli, the curves are similar to the combined rod and cone density functions; for scotopic stimuli, the rod density function alone appears to be the determining factor. One might expect, on the surface, that scotopic sensitivity would also be a function of the density of the rod elements but, apparently, there is no such simple relationship. It is evident that reaction time curves do not closely follow sensitivity curves for the dark-adapted eye in this important respect. Reaction time is shorter to stimuli striking the nasal retina, whereas the dark-adapted temporal retina is more light sensitive.

Visual acuity is a function which is, in some measure, dependent upon the density of retinal elements. Wertheim (1894) has shown the nasal

retina to be slightly superior to the temporal retina with regard to its power of spatial resolution. With photopic stimuli, Wertheim's curves show visual acuity to be greatest in the fovea and to drop very rapidly as the stimulus is presented farther and farther out in the periphery. With the exception of two points near the center of the fovea, Wertheim found the nasal retina to be superior to the temporal retina with respect to its visual acuity. The density of retinal elements, which we have shown to be a critical factor in reaction latency, is also one of the critical variables affecting spatial resolution.

It will be recalled that one S, HK, in the present study showed characteristic elevations in response latency at the five degree points on both sides of the fovea. For a possible explanation of this finding, we may turn again to the Østerberg data. If one adds the number of rods to the number of cones at each retinal position investigated here (as we have done in table III), it can be seen that the five degree points on either side of the fovea contain the smallest number of retinal elements of any of the points we investigated here. At about one degree from the center of the fovea on either side, the number of rods and cones is approximately equal. It is possible that in the area between about $\frac{1}{2}$ degree from the center and about eight degrees from the center of the fovea, where there is less clear cut dominance of either rods or cones than at any other retinal locus, there is more variability between Ss with regard to rod and cone counts and interconnections at the retinal level than at any other point on the retina. This may serve to account

TABLE III

Approximate number of rods and
cones per $.0069 \text{ mm}^2$ at each
retinal position investigated.
(Interpolated from Østerberg, 1935)

	30°N	20°N	10°N	5°N	Fovea	5°T	10°T	20°T	30°T
Cones	75	75	100	175	1750	150	90	75	50
Rods	1775	1875	1650	1150	0	1125	1600	1825	1425
Total Receptors	1850	1950	1750	1325	1750	1275	1690	1900	1475

for the variability noted in this study and also by Lichtenstein between Ss with regard to reaction time at these points.

An artificial pupil was not employed in this study. None was used because it was reasoned that since S was dark-adapted, the natural pupil would be dilated prior to each stimulus. However, there was the risk that there might be a possible artifact introduced by some constriction of S's pupil during the course of a block of trials, especially when the more intense flashes were employed. In order to be certain that such an effect was not present, t-tests were run between the means of the combined data for the first six trials in each block for each day and each S and the mean of the combined data for the last six trials in each block. Therefore, on days when intensities A and B were used, the mean of the 54 trials representing the first six trials at all nine retinal positions was compared with the mean of the 54 trials representing the last six trials at all retinal positions. On days when the intensity was below cone threshold, only eight positions yielded data. The t-tests consisted, on these days, of the comparison between the means consisting of 48 trials, six at each retinal position.

Since the data for each S was kept separate from those for each other S, 48 two-tailed t-tests were necessary. Of these 48 blocks of trials, 23 showed faster reactions for the first half, 20 showed faster reactions for the second half, and five means were identical. None of the comparisons was significant at the .05 level. Therefore, it may be safely concluded that no significant effect was introduced by constriction of Ss pupil during the course of the trials.

SUMMARY

This study has shown flash luminance to be a critical factor in determining the relationship between the retinal locus of the stimulus and reaction time. With stimulus flashes which are above cone threshold (approximately 1.59 ml with the duration and area used in this study), reaction time is shortest when the stimulus flash is presented foveally. As the flash is moved farther out into the periphery, the reaction latencies become longer. With feeble flashes, too weak to excite the cones, reaction time to foveal stimulation is infinite. Scotopic stimuli produce the shortest reaction time at about 10 or 20 degrees on either side of the fovea. Reaction time to these dim flashes is long at the five degree stimulus position and still longer at the 30 degree positions on either side of the fovea.

We have advanced an hypothesis to account for these findings based upon the densities of retinal elements in the human eye. It is assumed that there is a distribution of latencies of retinal elements. Consequently, the more elements which are excited, the greater the probability of exciting one or more which have short latencies.

With scotopic stimuli (our intensities C and D), speed of reaction curves roughly parallel the curves of rod density vs. retinal position.

With photopic stimuli (our intensities A and B), it appears that the total number of retinal elements involved is one of the primary

determinants of reaction time. If it were possible to stimulate only the cones at different retinal positions, it is expected that the resulting speed of reaction curve would parallel the Østerberg count of cone density in the retina.

It is important to note that the findings expressed here are, in great measure, dependent upon at least two other experimental parameters: area of the stimulus patch, and duration of the flash. We used a small area (four minutes visual angle) and a brief flash (0.0230 seconds) in order to demonstrate more clearly the differences between foveal and peripheral stimulation with regard to speed of the reaction evoked.

Since the periphery is capable of both areal summation (Graham, Brown, and Mote, 1939; Graham and Bartlett, 1940) and temporal summation (Karn, 1936; Keller, 1941; Graham and Kemp, 1938) over relatively large areas and durations, it would be expected that the differences obtained in a study which investigates the effect of retinal position upon reaction time would be smaller if larger areas and/or longer flashes were employed. Since the periphery would be given more opportunity to summate the effect of the flash, it would gain some advantage over the fovea, which does not summate over such large areas and temporal durations.

REFERENCES

- Bartlett, N. R. and MacLeod, S. Effect of flash and field luminance upon human reaction time. J. Opt. Soc. Am., 1954, 44, 4, 306-311.
- Bartz, A. E. Recognition time for symbols in peripheral vision. Unpublished Doctoral Dissertation, Univ. of Ariz., 1961, 1-59.
- Froeberg, S. The relation between the magnitude of stimulus and the time of reaction. Arch. Psychol., 1907, 16, 8, 1-38.
- Galifret, Y., and Piéron, H. La transmission intra-rétinienne de l'excitation lumineuse. Année Psychol., 1948, 49, 1-19.
- Graham, C. H. and Bartlett, N. R. The relation of size of stimulus and intensity in the human eye: III. The influence of area on foveal intensity discrimination. J. exp. Psychol., 1940, 27, 149-159.
- Graham, C. H., Brown, R. H., and Mote, F. A. The relation of size of stimulus and intensity in the human eye: I. Thresholds for white light. J. exp. Psychol., 1939, 24, 555-573.
- Graham, C. H. and Kemp, E. H. Brightness discrimination as a function of the duration of the increment in intensity. J. gen. Physiol., 1938, 21, 635-650.
- de Groot, S. G., Dodge, J. M., and Smith, J. A. Factors in night vision sensitivity: the effect of brightness. MRL Report No. 194, 1952, XI, No. 11.
- Hall, G. S. and von Kries, J. Über die Abhängigkeit der Reaktionszeit vom Ort des Reizes. Archiv f. Anat. u. Physiol., 1879, Suppl., 1-10.
- Johnson, H. M. Reaction time measurements. Psychol. Bull., 1923, 20, 562-589.
- Karn, H. W. Area and intensity time relationship in the fovea. J. gen. Psychol., 1936, 14, 360-369.

- Kästner, H. and Wirth, W. Die Bestimmung der Aufmerksamkeitsverteilung innerhalb des Sehfeldes mit Hilfe von Reaktionsversuche. Psychol. Stud., 1907, 3, 361-392; 1908, 4, 139-200.
- Keller, M. The relation between the critical duration and intensity in brightness discrimination. J. exp. Psychol., 1941, 28, 407-418.
- Lemmon, V. W. and Geisinger, S. M. Reaction time to retinal stimulation under light and dark adaptation. Amer. J. Psychol., 1936, 48, 140-142.
- Lichtenstein, M. Personal communication, 1961.
- Østerberg, G. Topography of the layer of rods and cones in the human retina. Acta Ophthal., Kbh., Suppl., 1935, 61, 1-102.
- Poffenberger, A. T. Reaction time to retinal stimulation with special reference to the time lost in conduction through nerve centers. Arch. Psychol., 1912, 3, no. 23, 1-73.
- Riopelle, A. J. and Bevan, W. The distribution of scotopic sensitivity in human vision. Amer. J. Psychol., 1953, 66, 73-80.
- Sloane, L. L. Rate of dark adaptation and regional threshold gradient of the dark-adapted eye; physiologic and clinical studies. Amer. J. Ophthal., 1947, 30, 705-720.
- Steinman, A. R. Reaction time to change compared with other psychophysical methods. Arch. Psychol., 1944, 292, 34-60.
- Teichner, W. H. Recent studies of simple reaction time. Psychol. Bull., 1954, 51, 2, 128-149.
- Wertheim, T. Über die indirekte Sehschärfe. Z. Psychol., 1894, 7, 172-187.
- Woodworth, R. S. Experimental Psychology. New York: Henry Holt and Company, 1938.
- Woodworth, R. S. and Schlosberg, H. Experimental Psychology. (Rev.) New York: Henry Holt and Company, 1954.